



## A CFD Validation Ecosystem to Advance the Prediction of Low-Speed Aerodynamics

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### Abstract

Driven principally through CFD prediction workshops, efforts are well underway within the international aerospace community to advance the understanding of low-speed (high-lift) flow physics using focused and systematic Computational Fluid Dynamics (CFD) validation studies to ultimately enable a robust predictive capability. With the completion of the geometric definition of the High Lift Common Research Model (CRM-HL) in 2016, an informal consortium of organizations has been formed to create a CRM-HL “ecosystem” to design, fabricate, and test a baseline set of CRM-HL configurations in several wind tunnels over a wide range of Reynolds numbers. These data will be used to validate existing and emerging CFD technologies. This paper will discuss the original genesis of the Ecosystem concept, the requirements that drove the technical efforts, and a summary of what has been accomplished and what is expected in the future.

**Keywords:** CFD, aerodynamics, validation, experimental testing, CRM-HL

### 1 Introduction

Over the past several decades, several key imperatives around sustainable flight, lower emissions, and efficient air travel have been developed to highlight the urgent need to help mitigate the adverse effects of air transportation on climate change. Recent governmental initiatives detail specific objectives to reduce the impact of air travel on climate. In 2022, the International Civil Aviation Organization (ICAO) set the 2050 net-zero CO<sub>2</sub> goal for international aviation [1] and the Advisory Council for Aviation Research and Innovation in Europe (ACARE) introduced the “Fly the Green Deal” initiative [2] to focus attention on reducing aviation carbon footprint. Net Zero Roadmaps by the International Air Transport Association (IATA) provided greater clarity on the developments and actions needed for the airline industry to be able to deliver on its commitment to reaching net zero CO<sub>2</sub> emissions by 2050 [3]. In 2021, the United States government laid out the Aviation Climate Action Plan, which outlines a plan to achieve net-zero greenhouse gas emissions for civil aviation [4]. Likewise, NASA is sponsoring the development of the Sustainable Flight Demonstrator, which will help the United States achieve net-zero carbon emissions from aviation [5].

In support of these important studies and initiatives, there is an ongoing emphasis on the need to continually improve the efficiency, robustness, and safety of current generation and emerging air transportation systems, while reducing non-recurring development costs and risk. To achieve these goals, very efficient, accurate, and robust physics-based computational tools are needed during the all phases of airplane product development, and which can provide accurate numerical simulation when employed throughout the entire airplane flight operating envelope.

Flight characteristics at the edges of the flight envelope are particularly important as they generally size important elements of the vehicle configuration, such as structure and control surfaces, and inform robust flight control design. As described in [6], the airplane flight operating envelope defines the nominal cruise and maximum maneuvering conditions that permit safe flight, constrained to within the structural limits of the airplane as depicted on a representative “velocity-load” diagram, as shown in Figure 1. Depicted by hashed lines, aerodynamic characteristics at the nominal cruise condition are well modeled by current generation Computational Fluid Dynamics (CFD) tools and processes. However, several key aerodynamic phenomena which occur near the edge of the flight envelope, such as buffet and flutter, are inherently difficult to model accurately due to a combination of complex, interactional flow physics, multi-disciplinary coupling (e.g., aero-structures), and the inability of CFD,

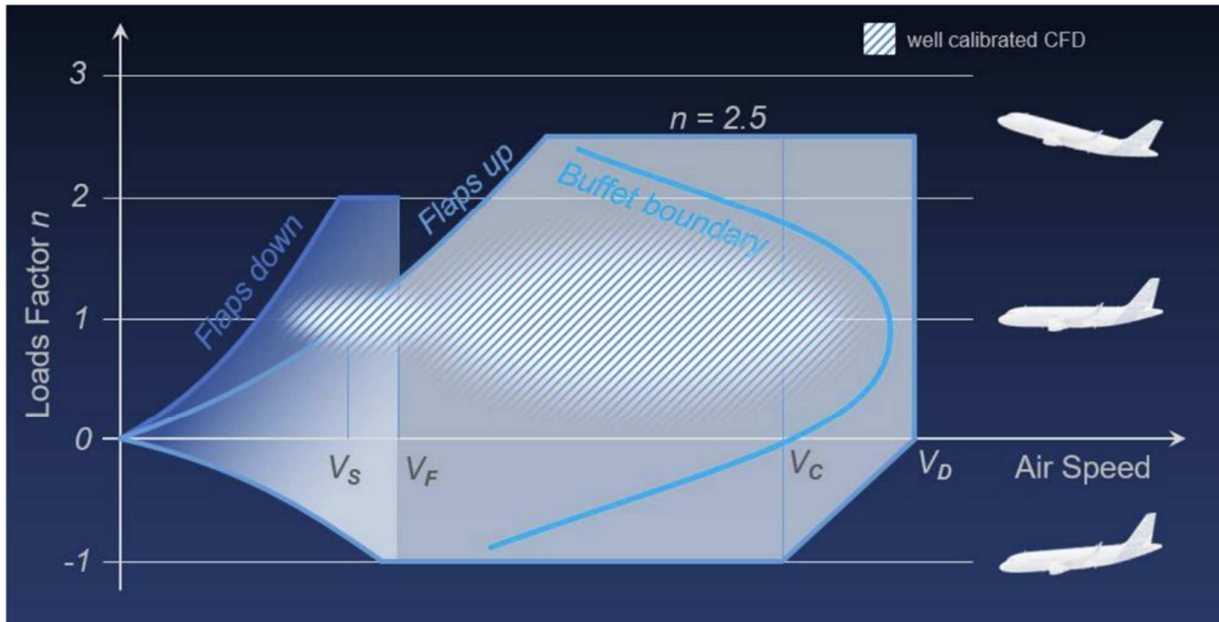


Figure 1– Airplane operating flight envelope.

particularly Reynolds-Averaged Navier-Stokes (RANS) methods, to reliably predict the effects of turbulent flow separation on configuration aerodynamic characteristics [7]. Simulation tools that can accurately predict aerodynamic characteristics in this region of the operating envelope will enable increasingly productive design iterations, enable the vision of Certification by Analysis (CbA) [8], and reduce the number of aerodynamic “surprises” routinely encountered during verification flight testing.

One of the most critical segments of flight which drives the majority of configuration development wind tunnel testing and complementary computational analysis is airplane landing and take-off performed at low-speed, subsonic flight conditions, referred here to as “high-lift”. In the high-lift configuration, the airplane deploys both leading-edge (e.g., slats) and trailing-edge (e.g., flaps) devices to increase the configuration lift via increased aerodynamic circulation. Currently, development of the high-lift system relies heavily on wind tunnel testing performed early in the design cycle to explore opportunities for aerodynamic performance improvement, address requirements from various systems integration, and collect data for initial structural loads assessments. Data from computational methods are being increasingly utilized to supplement data obtained in the wind tunnel to iterate on design trades and increase the fidelity of aerodynamic data available for vehicle sizing. CFD analysis is also expanding to address emerging requirements around aircraft icing, and to generate important data to address key low-speed design drivers due to aircraft icing. For instance, regulatory requirements for icing often size high-lift device structure, so accurately predicting the aerodynamic impacts of ice accretion on exposed surfaces is increasingly important.

High lift flow physics is inherently complex, with multiple, interfering, and unsteady flow phenomena such as turbulent boundary layers, vortex flows, wakes, etc. all interacting about a low-speed airplane configuration that is geometrically complex (see Figure 2). Appropriate mesh resolution and accurate physical modeling (e.g., turbulence models) are essential for the tools to impact vehicle design. Therefore, it is imperative that current and future CFD methods are adequately validated against relevant physical test data to understand the level of confidence that can be expected in using these toolsets in this flow regime. In the recent past, geometric simplifications and solution accuracy limitations in CFD simulations were accepted at some level to provide important insights into high-lift flow physics. However, with the advent of advanced algorithmic methods (e.g., strong linear solvers), more accurate and robust physical modeling (e.g., large-eddy simulation methods), and more powerful computing capabilities (e.g., systems with graphical processing units), the simulation of full-configuration high-lift geometry models coupled with more efficient and robust CFD flow solvers, are not only increasingly commonplace, but are also required to reliably predict the governing flow physics.

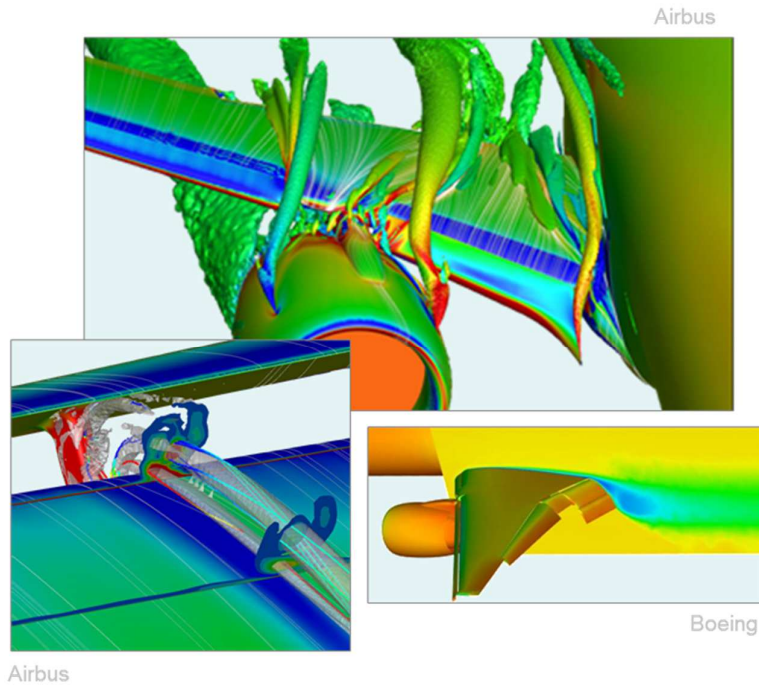


Figure 2 - High lift flow physics on full airplane configuration geometry

Emerging scale-resolving simulation methods such as Wall-Modeled Large Eddy Simulation (WMLES) offer a significant improvement in terms of predictive accuracy over current generation RANS methods, particularly in capturing the flow physics associated with turbulent flow separation [9]. The WMLES approach directly computes the turbulent eddies in most of the domain but relies on a model to incorporate the effects of the turbulent boundary layer at the wall. As an inherently unsteady simulation method, WMLES is computationally tractable mainly due to the exploitation of Graphical Processing Units (GPUs) available on current generation computing clusters, and has been particularly effective in predicting airplane aerodynamics at low-speed maximum lift ( $C_{L,max}$ ) [10]. Proper validation of WMLES tools and processes for high-lift airplane configurations at subsonic conditions is an ongoing effort and requires access to a rich set of experimental data including integrated vehicle forces and moments, surface flow visualization such as oil flows and mini tufts, and off-body velocity fields such as using Particle Image Velocimetry (PIV) techniques. Available aerodynamic datasets from previous high-lift experimental test campaigns consisted of limited or incomplete information and were generally considered insufficient for the purpose of systematic CFD validation [11,12]. More importantly, there is no path to perform future experimental testing of these models to collect additional data to supplement existing datasets if required.

Therefore, to greatly improve the accuracy of computational analysis tools for use in aerodynamic product development, a concerted effort is underway to develop and execute an integrated experimental testing campaign that is specifically designed to provide high-quality data for CFD validation of the complex flow physics associated with low-speed configuration aerodynamics. One key element of this integrated testing campaign is the development of the High Lift Common Research Model (CRM-HL) and the collaborative “ecosystem” formed around this geometry to enable consistent testing of CRM-HL models in multiple facilities around the world. Ecosystem testing of the CRM-HL configuration directly provides validation data to assess the predictive capabilities of current and emerging CFD technology, highlight shortcomings in aerodynamic modeling, identify regions in which to acquire more/better data, and to generally accelerate the maturation of advanced CFD tools for production aerodynamic design and analysis. CFD prediction workshops, typically hosted by AIAA and other aerospace societies, are commonly used as a conduit in disseminating test data from the ecosystem to the broader CFD and aerospace community.

This paper will provide a brief overview of the development of the CRM-HL concept and geometry, the genesis, formation and purpose of the CRM-HL ecosystem, the progress of ongoing ecosystem

testing campaigns, and end with some concluding remarks to provide insights into planned activities involving future CRM-HL efforts.

## 2 CRM-HL Geometry Development

Building on the successful development and testing of several high-speed common research models to provide validation data for cruise drag prediction, a similar effort was undertaken to address low-speed aerodynamics prediction. The geometry definition that was designed and developed from this effort is known as the High Lift Common Research Model (CRM-HL). The primary motivations that drove the technical development of the CRM-HL geometry definition were to (a) enable the design, development, and testing of low speed wind tunnel models, (b) enable the acquisition of high-quality low-speed wind tunnel datasets, (c) enable community CFD validation efforts, (d) provide a representative platform for high lift technology development, and (e) provide reference performance levels for a conventional high-lift system. Further discussion on the history behind the CRM-HL geometry development, as well as additional details on the general layout and specifications of the model geometry are provided by Lacy, et al., [13].

The CRM-HL geometry includes a representative low-speed wing with high-lift devices (e.g., slats and flaps) and attached pylon with a flow-through (unpowered) nacelle. The model definition is provisioned for other features (e.g., horizontal and vertical tails, nacelle chines, etc.) to provide a geometry that can be configured for a wider array of CFD validation and aerodynamic studies. During this initial geometry development, a set of positioned high-lift devices were defined for both a nominal landing (as shown in Figure 3) and takeoff configuration based on Reynolds-Averaged Navier-Stokes (RANS) CFD analysis at a representative flight Reynolds number. As will be discussed in later sections, this initial positioning was refined during subsequent wind tunnel testing to ensure that the desired high-lift performance and stall break-down mechanism was achieved [14]. The CRM-HL reference geometry definition and model configurations are available in Standard for the Exchange of Product Data (STEP) Computer Aided Design (CAD) format and have been fully documented on the NASA CRM website [15]. Geometric considerations for consistent development and experimental testing of the CRM-HL configurations are provided by Clark and Lacy [16].



*Figure 3 - Reference CRM-HL landing configuration.*

## 3 CRM-HL Ecosystem

### 3.1 Background

Once the CRM-HL geometric definition was completed, efforts began to socialize the existence of the geometry model and its specifications and energize the CFD and wind tunnel testing communities to utilize the CRM-HL geometry definition to focus primarily on CFD validation. During this period (roughly beginning in 2017) technical results and participant feedback from previous High Lift Prediction Workshops (HLPWs) and associated efforts pointed to a clear need to systematically

collect high-quality test data to help advance CFD development and mature CFD capabilities.

Previous HLPWs [17-19] relied on experimental testing of high-lift configurations/models which were often incomplete in terms of geometric detail, not readily available in usable CAD form for CFD analysis and had associated test data that was relatively sparse and with generally undefined test uncertainty. To help address this myriad set of issues, a concerted effort to utilize the CRM-HL platform was initiated. In 2018 NASA and Boeing led the formation of an informal group of interested international organizations who were involved with the development of a plan to acquire high-quality test data for CFD validation purposes. This group became known as the “CRM-HL Ecosystem” due to the inclusive and collaborative nature of the expected testing campaigns among the various partners. One of the most important selling points of the ecosystem concept was the unique opportunity to build and test multiple wind tunnel models of the same geometric configuration in multiple facilities around the world to collect corroborating and shareable CFD validation data. Per agreement within the ecosystem, data generated by each partner are owned by that partner. However, to be considered an active participant in the ecosystem, partners fund their own activities (e.g., build and/or test wind tunnel models, utilize innovative flow measurement technology, etc.) and agree to share a minimum set of results (e.g., experimental data, CFD results, etc.) either among partners and/or publicly through CFD validation workshops. Currently, several organizations from industry, government, and academia representing five countries (France, Germany, Japan, United Kingdom, and the United States) actively participate in the ecosystem.

### 3.2 CFD Validation Strategy

Early on in the evolution of the ecosystem concept and eventual formation of the informal consortium, a CFD validation strategy was developed that integrated the objectives of ecosystem testing of the CRM-HL configurations with a broader framework that incorporated a wider range of validation efforts. The objective of this framework is to assess and improve the capabilities of CFD methods and tools to predict aerodynamic characteristics of high-lift configurations at flight scale through systematic CFD validation against relevant test data. To this end, a number of steps are identified within a framework to enable systematic CFD validation:

1. Identify the **important aerodynamic characteristics and/or parameters** associated with high-lift configurations and systems (e.g., lift, drag, pitching moment, flap effectiveness, effect of power, effect of ice, etc.) and/or specific airplane performance scenarios (landing approach attitude, take-off speed, etc.)
2. Identify the **governing flow physics** of interest (e.g., turbulent boundary layers, flow separation, vortex interactions, wake confluence, shear layers, effect of Reynolds number, etc.) that affect the aerodynamic characteristics.
3. Determine the **gaps and shortcomings** in current computational methods and tools to predict the governing flow physics (e.g., inability to predict separated flows)
4. Identify a unique set of **test configurations** (e.g., landing, take-off, etc.) based on the reference CRM-HL geometry that could be built and tested in wind tunnels to collect critical experimental data (e.g., off-body velocities, surface skin friction, unsteady pressures, etc.) which are required to understand and address the gaps and shortcomings.
5. Acquire the critical experimental data, and identify and employ existing (or develop new) **data acquisition methods/techniques** (e.g., PIV, oil flow, etc.)
6. Perform **CFD validation using the acquired test data**. (This has been largely accomplished via community prediction workshops).

Given the complex nature of high-lift flow physics, the ecosystem effort is part of a much broader, integrated validation activity that includes the use of canonical or simpler configurations (e.g., ramps, bumps, etc.) to isolate specific elements of the governing flow physics (e.g., smooth body separation). Data collected from these separate efforts, and directly from ecosystem testing, are used to support CFD validation, as well as help guide improvements to CFD technology (e.g., turbulence models), provide information to refine wind tunnel wall correction methods, and help assess and mature emerging flow measurement techniques and methods. A detailed discussion about specific requirements and challenges for CFD validation utilizing the CRM-HL ecosystem is provided by Clark, et al., [20].

### 3.3 Ecosystem Outcomes and Benefits

As stated above, the main purpose of the ecosystem is to enable CFD validation of low-speed aerodynamics. To this end, the ecosystem provides the following outcomes and benefits:

- **Availability of a reference, industry-relevant, publicly available high-lift geometry.** The CRM-HL geometry was specifically designed such that numerical simulation at nominal low-speed flow conditions over a range of Reynolds numbers would exhibit the critical flow physics typically encountered on industrial airplane configurations. Test configurations based on the reference geometry are defined to study specific flow physics relevant to high-lift aerodynamics prediction.
- **Direct assessment and comparison between CFD and experimental modelling.** When both the experimental and computational models are built from the same reference geometry, disparate CFD simulation and experimental datasets, potentially from several separate and independent sources, can be effectively compared together to gain insights into CFD predictive capabilities. In this way, differences in CFD modeling can be assessed against test data in a consistent manner to mature the development of CFD tools and modeling approaches for low-speed applications.
- **Design and fabrication of nearly identical experimental models.** When consistent models are tested in different facilities around the world, systematic experimental data comparisons can provide insights into both data repeatability and model installation and/or wall effects. These insights are crucial in understanding potential differences between the experimental and computational datasets, as well as enabling the development of effective approaches to model the wind tunnel in the CFD simulations (e.g., geometry, boundary conditions, etc.) when appropriate.
- **Collaborative use of a set of challenging, open-source configurations.** Working with a common geometry enables new, and strengthens existing, partnerships to accelerate CFD technology development and application. The availability of a publicly available geometry also enables a wide range of community collaborative efforts, particularly as embodied in CFD prediction workshops.
- **Development of improved flow measurement technology.** The availability of a complex three-dimensional low-speed configuration that exhibits relevant flow physics when tested in ground-based facilities enables the development, demonstration, and refinement of advanced flow measurement and sensing techniques, particularly in response to CFD studies involving the CRM-HL configuration that highlight areas in need of additional test data.
- **Opportunity to develop and share pre-competitive low-speed aerodynamic technology.** Because the CRM-HL geometry was developed to be a representative high-lift geometry, related technologies (e.g., active flow control, noise, etc.), which are targeted for low-speed aerodynamics improvements, can be effectively explored collaboratively between external partners before proprietary efforts are initiated internally on production configurations.
- **Development of enabling technologies for indirect benefits.** Access to the CRM-HL geometry and related ecosystem activities also provides a number of indirect benefits such as the identification of requirements for improved test facility capabilities, as well as workforce and staffing development, both directly through ecosystem CFD efforts and/or experimental testing and through targeted industry/university collaborations.

### 3.4 Test Objectives

Within the CRM-HL ecosystem, a series of experimental test campaigns have been completed, are underway, or are planned to generate high-quality test data for CFD validation. To maximize the effectiveness of ecosystem testing, a set of comprehensive testing objectives was developed to help guide what data would be of highest value to obtain. In most cases, individual ecosystem partners attempt to incorporate more than one of the following target areas into their testing plan:

- **Establish reference configuration(s).** As mentioned above, key to ecosystem testing is the establishment of a set of reference configuration specifications that partners use to design and build consistent wind tunnel models. Initial determination of these specifications was informed largely using CFD, but selected wind tunnel testing was required to tune and verify certain parameters, particularly to ensure that the desired flow physics was attained. For instance, the

leading-edge slat and trailing edge flap positioning for the nominal landing configuration was explored in early testing to ensure a desired nose-down pitching moment behavior at stall was achieved. Other focus areas include nacelle chine positioning, and horizontal tail pitch angle, among others. Establishing the official ecosystem landing and take-off reference configurations informs a minimum set of test data expected to be collected and shared by ecosystem partners. Additionally, data from ecosystem testing then provides a consensus conventional high-lift system performance “yardstick” in which to compare with other aerodynamic studies.

- **Generate configuration variation data.** Of high value for CFD validation is the collection of CRM-HL configuration sensitivity data about the nominal settings developed for the reference configuration. Early on this data was obtained to help directly determine the reference configuration settings themselves, but in later testing the data has been used to provide insights into potentially interesting computational studies that stress the predictive accuracy of the CFD methods in sometimes unexpected ways. For instance, the ability of CFD tools to correctly predict the extent of flow separation on the flap at three different positions at low angle-of-attack was studied as a test case in a recent workshop. As reported from workshop results [9], all CFD simulation methods struggled to accurately predict trends in lift as observed in wind tunnel data, despite the overall good agreement generally seen with the simulations for the nominal configuration performed in the linear lift range.
- **Provide insights into high-lift flow physics.** A key ecosystem goal is to obtain high-quality experimental data in a consistent and quantitative manner to better understand high-lift flow physics, including aeroacoustics, and emerging interest around the prediction of icing effects. Requirements for specific types of experimental data are established for ecosystem testing campaigns to target quantification and characterization of the relevant flow physics, as well as to ensure data consistency between test datasets to the extent possible. Expected minimum data from ecosystem testing includes integrated forces and moments and surface pressures, but obtaining other sources of data, such as surface visualization (e.g., oilflow, tufts, etc.) and off-body data (e.g., rakes, probes, wake surveys, etc.), among others, is highly encouraged.
- **Explore Reynolds number effects.** Reliable CFD predictive capability at flight scale is increasingly necessary to design improved airplane products. To this end, another key objective of ecosystem testing is to obtain test data over a wide range of Reynolds numbers to understand how flow physics and aerodynamic characteristics change with airplane size.
- **Understand wind tunnel modeling effects.** A significant deficiency in previous experimental datasets was the lack of focused test data aimed at better understanding differences between half- and full-span testing, model mounting and installation effects, and tunnel wall corrections. For this reason, a mix of half- and full-span models installed with different mounting systems and tested in multiple facilities is a central strategy of the ecosystem effort.
- **Study secondary objectives.** In addition to basic aerodynamics, several other areas of focus are being pursued to take advantage of the ecosystem testing efforts, particularly in utilizing an open-source high-lift configuration, which the CRM-HL geometry represents. These focus areas include active flow control, artificial intelligence/machine-learning, among others.

In all cases, learnings from one experimental campaign, along with companion CFD studies, inform follow-on ecosystem testing. To facilitate learnings, members of the ecosystem are encouraged to attend partner testing campaigns when feasible. Attempts are made to ensure that each testing campaign is executed in as consistent a manner as possible relative to past tests. Appropriate data from previous testing are made available for cross-plotting purposes as a check on expected lift levels for baseline landing and takeoff configurations.

#### 4 CRM-HL Wind Tunnel Testing Campaigns

The strength of the ecosystem collaboration lies with wind tunnel testing of models built according to the established reference geometry for CRM-HL. Figure 4 shows a timeline of the various testing campaigns, arranged by partner/model type and colored coded based on testing facility, which have been identified as part of the ecosystem. In the figure, check marks indicate testing that has completed, and asterisks indicate testing campaigns that are proposed. All other tests are currently planned. “SS” indicates a semi-span model configuration, and “FS” indicates a full-span model configuration. Since the primary use of ecosystem data is to support CFD validation workshops, High

Lift Prediction Workshops (HLPWs) are included on the timelines and are denoted by red triangles.

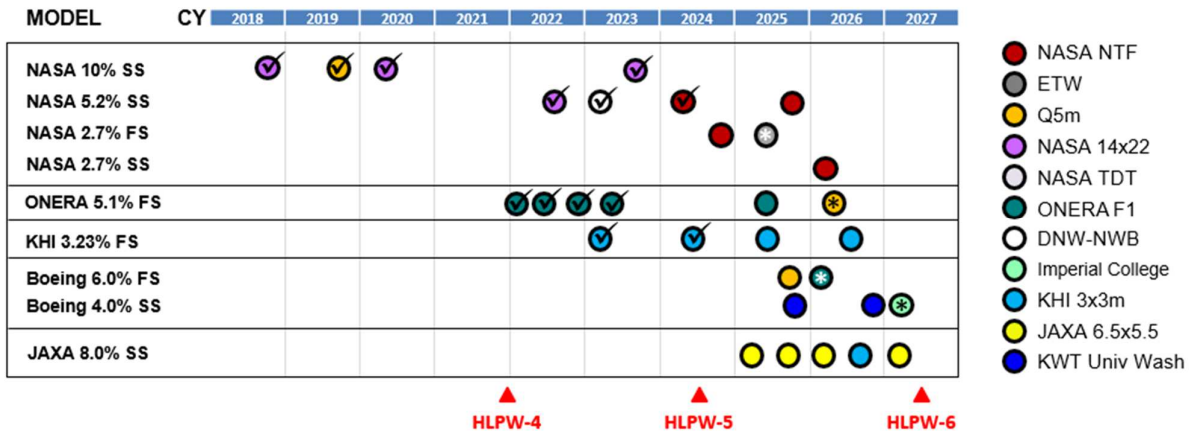


Figure 4 - Timeline of CRM-HL ecosystem wind tunnel testing campaigns.

High-level details of each of the ecosystem partner testing efforts are provided in the sections below. For each partner testing campaign, linkage to primary (green star) and secondary (black “X”) objectives and collected test data are provided in separate charts. “d” indicates technology demonstration. The intent of these charts is to show the wide range of objectives identified for CRM-HL testing, as well as the variety of test data that either has already been collected or will be collected in future wind tunnel testing campaigns. Note also that wind tunnel test campaigns at a given partner facility may include testing of a wind tunnel model from other ecosystem partners. This sharing of testing assets enables the systematic study and decomposition of facility and model differences to better understand overall flow physics.

#### 4.1 NASA

As one of the founding members of the CRM-HL ecosystem, the National Aeronautics and Space Administration (NASA) team was instrumental in strongly advocating for the initial development of the CRM-HL geometry definition, and the early development of the wind tunnel model used to properly define the reference configurations for later ecosystem efforts. NASA testing linkage to ecosystem objectives and data availability is provided in Figure 5.

NASA built and first tested a 10% scale semi-span model in the NASA Langley 14x22 Foot wind tunnel in 2018 to study Active Flow Control (AFC) technology [21], but during this testing, preliminary aerodynamic performance levels were established for the reference configuration at atmospheric conditions. In 2019, this model was then tested at the QinetiQ 5-metre wind tunnel at pressurized conditions to obtain data at higher Reynolds numbers [22], which was used to refine the nominal high-lift device positioning which then became the official reference configuration standard for all subsequent ecosystem testing. Follow-on testing of the 10% scale model focused on acoustics in 2020 [23] and a demonstration of Particle Image Velocimetry (PIV) technology in 2023.

To specifically acquire ecosystem data at the highest Reynolds numbers, NASA designed both a semi-span 5.2% scale model and a full-span 2.7% scale model for testing in the National Transonic Facility (NTF) at cryogenic conditions. The 5.2% scale semi-span model was fabricated in 2022 and was initially tested in the 14x22 Foot wind tunnel for model checkout. In 2024, the initial test of the 5.2% scale semi-span model in the NTF was completed, and a set of baseline ecosystem data for the nominal landing configuration was obtained up to 30 million Reynolds number. Additionally, a significant amount of effort was expended in acquiring data on an iced configuration to both obtain Reynolds number and Mach number sensitivities (forces and moments) to make progress toward improving computational capabilities, and to improve the Technology Readiness Level (TRL) of artificial ice shapes for use in a cryogenic environment.

A separate 2.7% scale full-span model is being fabricated with an expected completion date of summer 2024. An initial test of this model in the NTF is expected to start in winter 2024. A separate

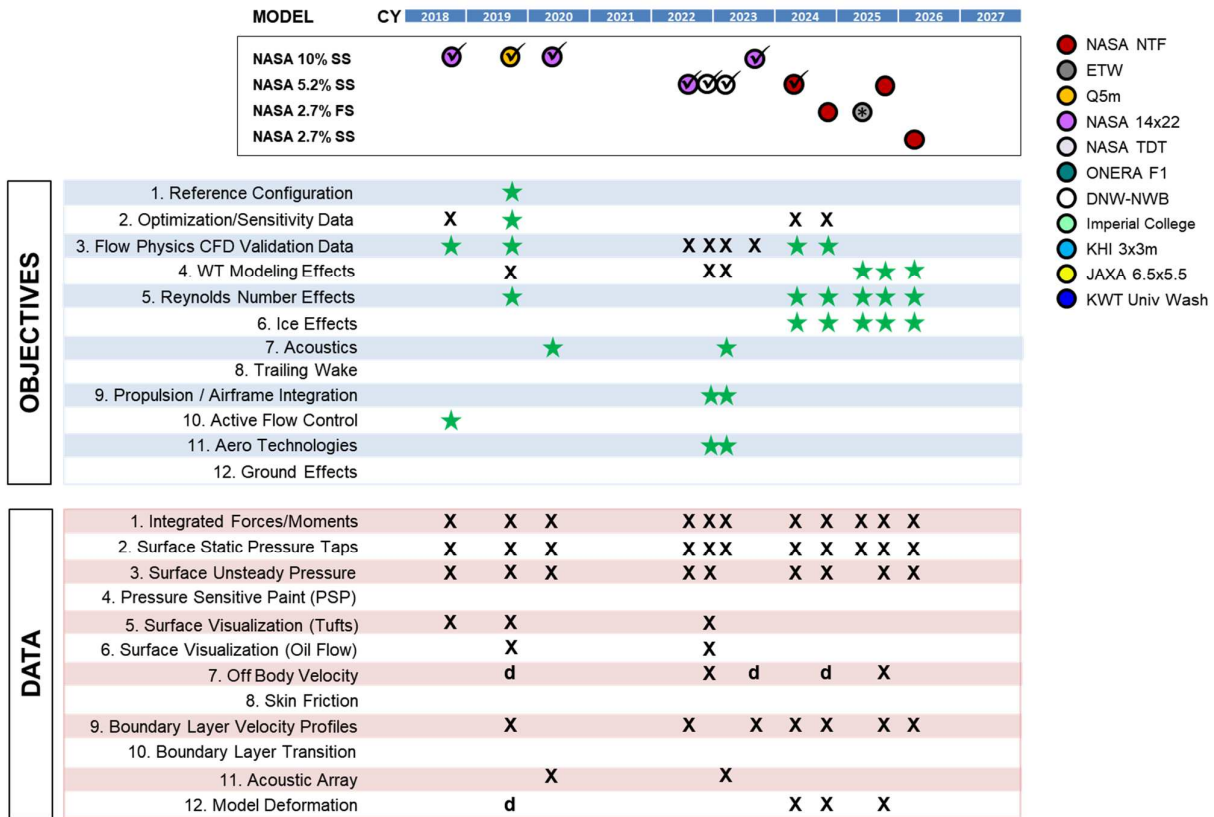


Figure 5 - NASA CRM-HL ecosystem testing campaigns.

semi-span body is also being fabricated to facilitate the testing of 2.7% scale wing and high-lift system as a semi-span model. The initial test of the 2.7% scale semi-span model is expected in 2025. The primary objectives of these tests are to confirm the aerodynamic characteristics observed on the larger 5.2% scale semi-span model across the available Reynolds number range, and to study wall interference effects and wall correction methodologies with differences in model geometry (semi-versus full-span) and geometric scale (2.7% versus 5.2%). Also, efforts will continue on obtaining iced configuration data at high Reynolds number to inform computational modeling. A companion test of the 2.7% model is proposed for the European Transonic Wind Tunnel (ETW) to obtain data on the same configuration at a second cryogenic facility.

#### 4.2 DLR

In 2023, the German Aerospace Center (DLR) tested the NASA 5.2% scale semi-span model in the Niedergeschwindigkeits-Windkanal (NWB) facility in Braunschweig, Germany, which is part of the German-Dutch Wind Tunnel (DNW) system [24]. The primary purpose of this testing was to collect test data in the open and closed test section of the tunnel to assess the impact of the test section set-up on the high lift aerodynamics and to investigate the impact of tunnel corrections. In this context, a model configuration variant featuring a vented foldable Bullnose Krüger leading edge device and an Ultra High Bypass Ratio (UHBR) nacelle was also tested for both test section types. In addition to forces and moments and model surface pressure distributions, oil flow and tufts surface visualization, boundary layer transition and PIV field data were collected (for the closed section only). For the ecosystem, data at atmospheric conditions was obtained with a focus on the nominal landing reference configuration. In addition, test runs were executed to gather acoustic wall array data next to standard aerodynamic data in both test section types with a focus on the reference take-off configuration.

#### 4.3 ONERA

Researchers at the French Aerospace Lab ONERA designed and built a 1/19.5 scale (~5.1%) full-span model of the CRM-HL reference geometry (named the “Large Reference Model” or LRM-HL) and tested the model in the low-speed F1 facility near Toulouse. Past, planned, and proposed ONERA test campaigns and their linkage to ecosystem objectives and data are depicted in Figure 6.

In 2022, the initial test entry collected data at multiple Reynolds numbers for the baseline landing configuration with and without the horizontal tail varying both angle-of-attack and angle-of-sideslip. The datasets collected included integrated forces and moments, surface pressures, oil flow surface visualization, and wing deformation information [25]. Follow-on entries in late 2022 and early 2023 focused on acoustics [26] and ground effects testing [27], including a demonstration of a Particle Image Velocimetry (PIV) system.

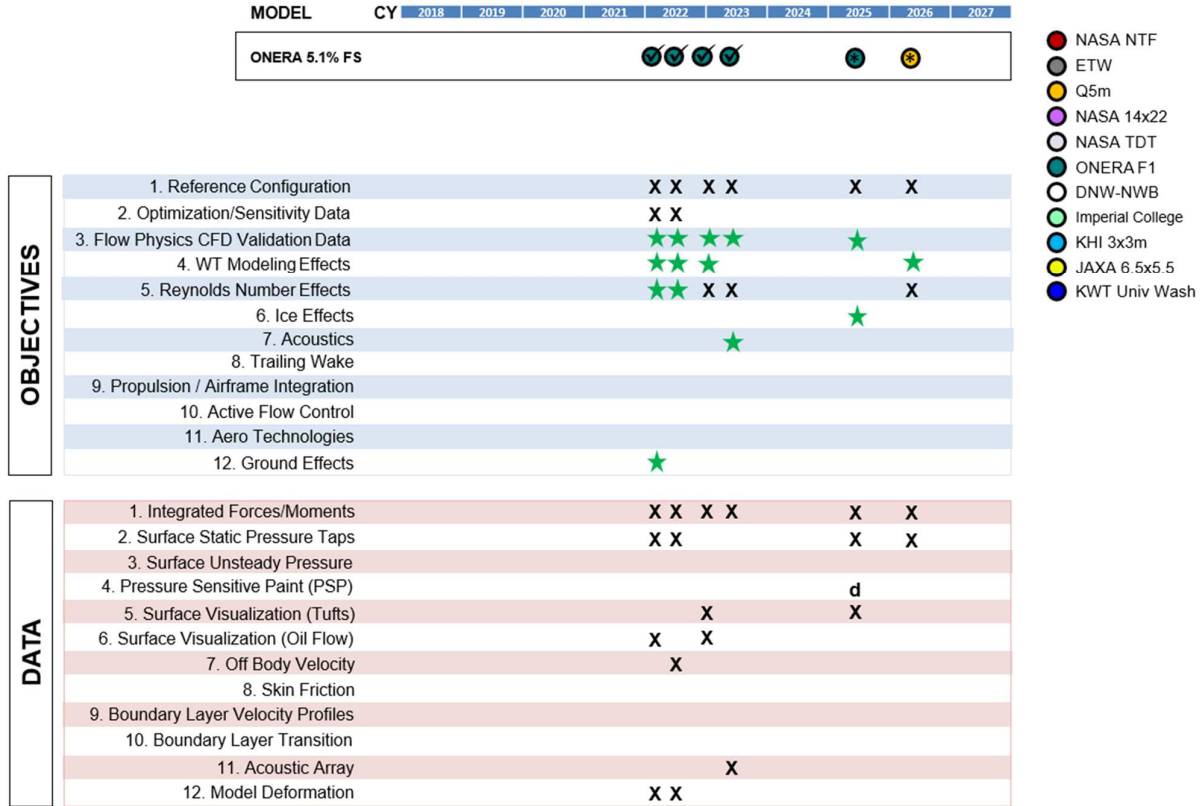


Figure 6 - ONERA CRM-HL ecosystem testing campaigns.

A proposed test in 2025 will focus on testing of ice shapes generated by multiple icing codes from a collaboration between ONERA, NASA, Boeing, and the National Research Council (NRC) in Canada within the “SUNSET III” Swept Wing Icing Project. Experimental data from the testing will help validate data generated from planned CFD simulations using the ice shapes on the landing CRM-HL reference configuration.

Additionally, to systematically study model installation and wall interference effects, the ONERA LRM-HL model is expected to be installed and tested in the QinetiQ 5-metre. Data from this test campaign will be compared to data obtained from a companion study where the Boeing full-span CRM-HL model (described below) will be installed and tested in the ONERA F1.

#### 4.4 KHI

Researchers at Kawasaki Heavy Industries (KHI) designed and built a 3.23% full-span model of the CRM-HL reference configuration and tested the model in the 3 x 3-meter Kawasaki Low-speed aero-acoustic Wind Tunnel (KLWT). KHI test campaigns and their linkage to ecosystem objectives and data are depicted in Figure 7.

The KHI CRM-HL model was developed not only to provide valuable data to the ecosystem but was also built as a check standard model to help establish benchmark facility performance data to help qualify the newly completed KLWT. In late 2022 and early 2023, separate test entries collected experimental data at atmospheric conditions up to a Mach number of 0.27 for a complete range of angle-of-attack. Data collected included integrated forces and moments, surface pressures, and some limited surface visualization information via tufts and oilflow. Configuration variation sensitivity data were collected for both the nacelle chine (on/off) and horizontal tail (on/off). Particularly important at

the lower Reynolds number that can be achieved in the KLWT, a study of boundary layer transition was also performed by removing the trip dots, which is the standard tripping mechanism used in other ecosystem testing campaigns. An initial demonstration of both a PIV and Model Deformation Measurement (MDM) system was also performed in June 2024.

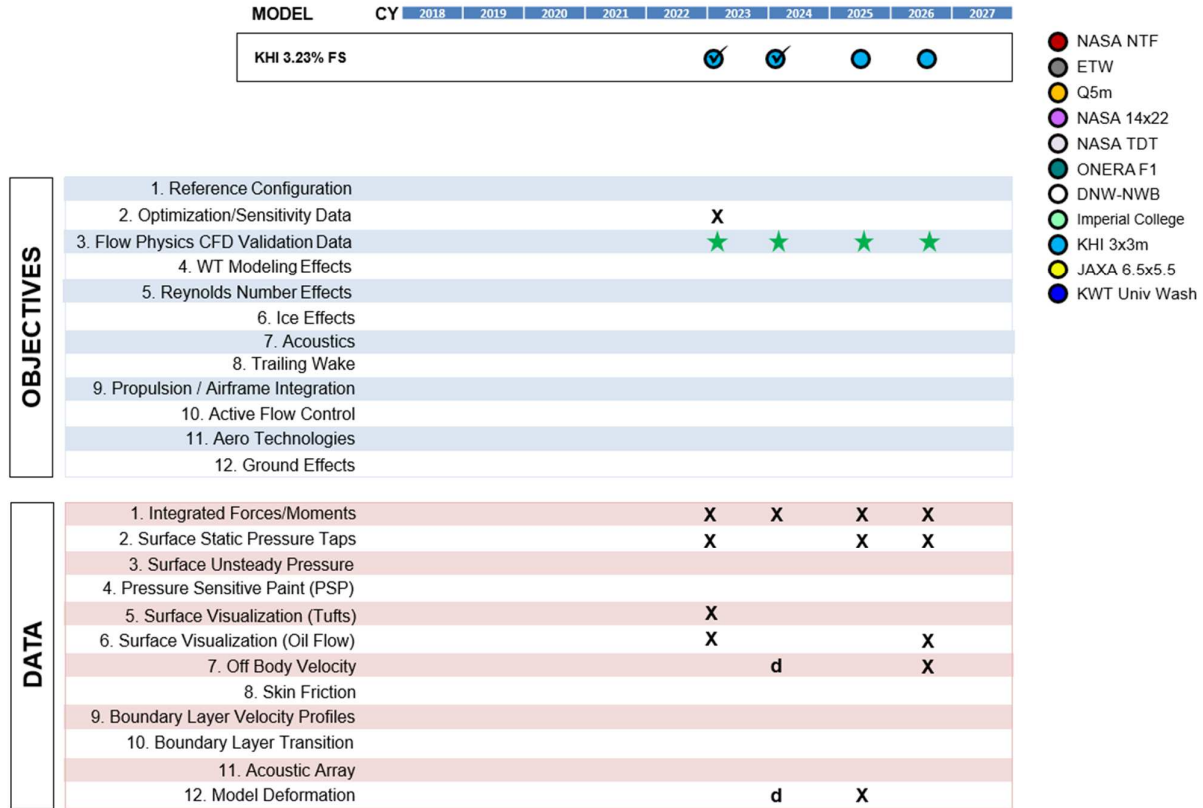


Figure 7 – KHI CRM-HL ecosystem testing campaigns.

Regular testing of the CRM-HL model in the KLWT is expected in 2025 and 2026. Ecosystem elements of these tests are expected to focus again on high-lift flow physics, but with the collection of a more robust set of test data through the expanded use of oil flow and improved PIV systems. A complete summary of the CRM-HL model development, experimental testing, and selected results is provided by Hashioka, et al., [28].

#### 4.5 Boeing

The Boeing team’s contribution to the ecosystem will be the design, fabrication, and testing of two separate CRM-HL models: a full-span 6% model and a semi-span 4% model. Planned Boeing test campaigns and their linkage to ecosystem objectives and data are depicted in Figure 8.

The 6% model is being developed for testing in a pressurized environment, principally at the QinetiQ 5-metre (Q5m) wind tunnel in Farnborough, UK, but is also for proposed complementary testing at the ONERA F1 to study wind tunnel installation and interference effects. The model design for the 6% model is complete, with fabrication underway. The initial test of this model will occur in 2025 in the Q5m. Key objectives for this test will include acquiring data on a series of build-up configurations (from cruise to landing configuration with landing gear), collecting additional higher Reynolds number data to complement the data collected by ONERA in the F1, supporting expanded efforts to better understand the aerodynamic effects of icing, as well as adding to the growing set of experimental data available to characterize high-lift flow physics. Expected datasets include integrated forces and moments, surface pressures, surface visualization in the form of both of tufts and oilflow, and a limited set of unsteady pressure measurement at locations on the upper wing surface. Both PIV and model deformation measurement capabilities will be further matured.

The semi-span 4% model was conceived as a testbed to encourage greater university participation in the ecosystem. Potential university contributions include the targeted study of specific high-lift flow



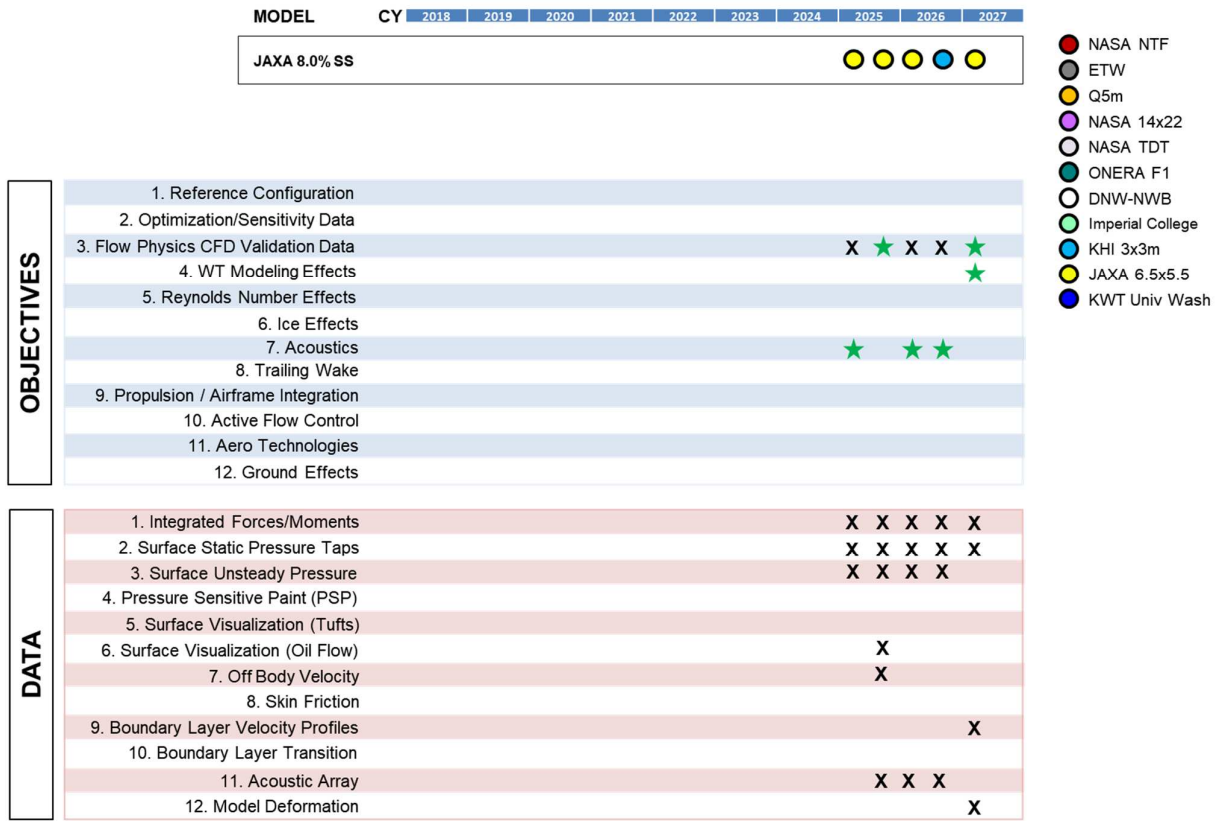


Figure 9 - JAXA CRM-HL ecosystem testing campaigns.

The model will be tested in the KHI 3 x 3-meter tunnel to measure far-field noise effects within the anechoic test section in 2026. It is expected that these intra-facility data comparisons will advance our collective understanding of effectiveness for high-lift semi-span testing and will be a significant addition to the ecosystem in this regard.

## 5 Current Status

As mentioned earlier, reference landing and takeoff configurations were first defined using RANS CFD at a nominal flight Reynolds number (~26 million based on MAC) in 2016 [13] and then refined in 2019 based on testing at the QinetiQ 5-metre wind tunnel [22] at a moderate Reynolds number (~5.5 million based on MAC). Models designed and built to these refined reference configuration specifications were subsequently tested by ONERA, KHI, and NASA in their facilities, as detailed above. Efforts are underway to thoroughly compare these datasets to establish reference aerodynamic performance levels for the nominal configurations throughout the angle-of-attack range, to both fully understand the flow physics mechanisms leading up to and including aerodynamic stall, and to characterize the flow post-stall.

Central to these overall objectives is to piece together the aerodynamic performance and flow characteristics of the reference configurations within the full Reynolds number range encapsulated by the experimental results obtained thus far. To date, existing datasets utilizing the nominal landing configuration have been collected in five Reynolds number ranges, as detailed in Figure 10. As shown in Figure 11, lift coefficient trends with increasing Reynolds number from both the ONERA F1 and NASA NTF tests are similar to one another, and exhibit the expected flow physics behavior, namely that maximum lift increases with increasing Reynolds number. However, upon closer inspection, the lift levels from data generated from the ONERA full-span model testing in the F1 are generally ~0.2 CL higher, with maximum lift occurring at a slightly higher angle-of-attack, when compared against the data from NASA semi-span model testing in the NTF at similar Reynolds numbers. At the ~3 million Reynolds number, data from the NASA 10% semi-span model tested in the QinetiQ facility tend to agree with the ONERA dataset. Data comparisons at the lowest Reynolds numbers are somewhat inconclusive and ongoing, and suggest that the stall breakdown mechanism is different

	Reynolds Number (based on Mean Aerodynamic Chord), in million				
CRM-HL Model	1.1-1.6	3.2-3.3	5.5-5.9	16	30
NASA 10%-scale SS		+	+		
NASA 5.2%-scale SS	+	+	+	+	+
ONERA 5.1%-scale FS	+	+	+		
KHI 3.23%-scale FS	+				

Figure 10 - Existing CRM-HL experimental datasets.

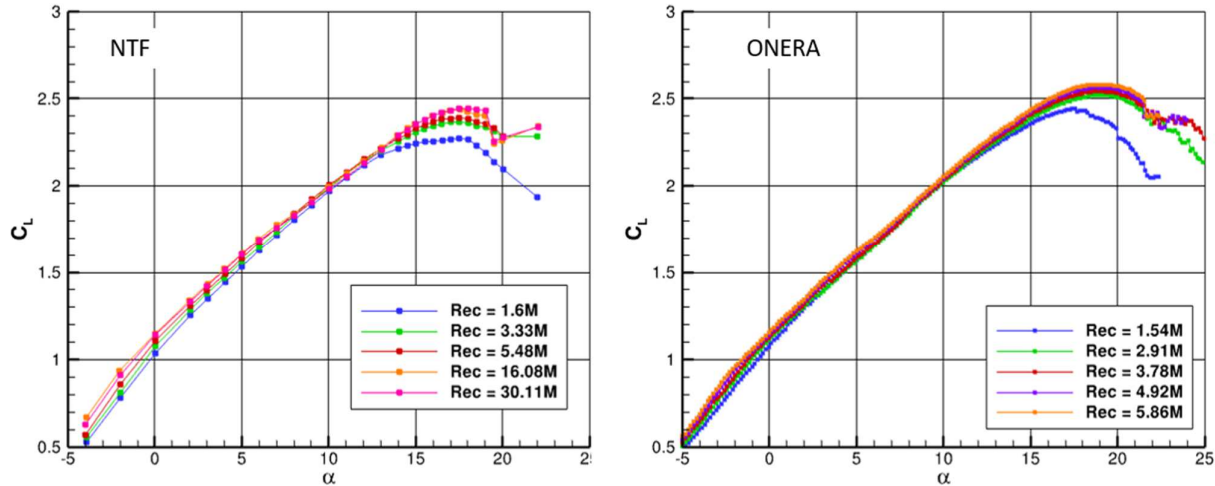


Figure 11 - Comparison of experimental lift coefficient at increasing Reynolds number for nominal landing configuration in two wind tunnels.

than what is observed at the moderate and high Reynolds numbers.

From the analysis performed to date, areas of particular focus include understanding the differences between half-model versus full-model testing, the effect of boundary layer transition particularly at lower Reynolds numbers, and the need to fully understand the assumed small aerodynamic impact of known differences in the slat bracket geometry among the various ecosystem models. To this end, future ecosystem testing will be critical in helping to isolate some of these effects and will provide opportunities to obtain key experimental data needed to better understand the underlying flow physics driving the integrated aerodynamic differences, such as surface skin friction to quantify the state of the boundary layer at a particular flow condition.

## 6 Closing Remarks

The development of the CRM-HL geometry and associated reference configurations, and the establishment of the informal ecosystem of international partners who are actively building and testing wind tunnel models based on this reference geometry, have been critical elements of a larger community focus on generating high-quality experimental data to validate CFD capabilities to predict low-speed aerodynamics. The ecosystem has spawned the development of ten unique wind tunnel models, which will be tested in at least a dozen different facilities to characterize basic configuration aerodynamics. Experimental data from ecosystem testing is already supporting community CFD prediction workshops and will do so for the foreseeable future. Interest in international collaboration is also opening new horizons to study related aerodynamic phenomena, such as the effects of icing, aeroacoustics, and novel aerodynamic concepts. Additionally, ecosystem testing is being used to demonstrate and mature emerging flow measurement techniques at several partner test facilities. These techniques will not only help benchmark the CRM-HL performance at various flow conditions but will directly lead to never-before acquired CFD validation data that will be used to advance the state-of-the-art in CFD prediction.

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