Control of Revolutionary Aircraft with Novel Effectors (*CRANE*)

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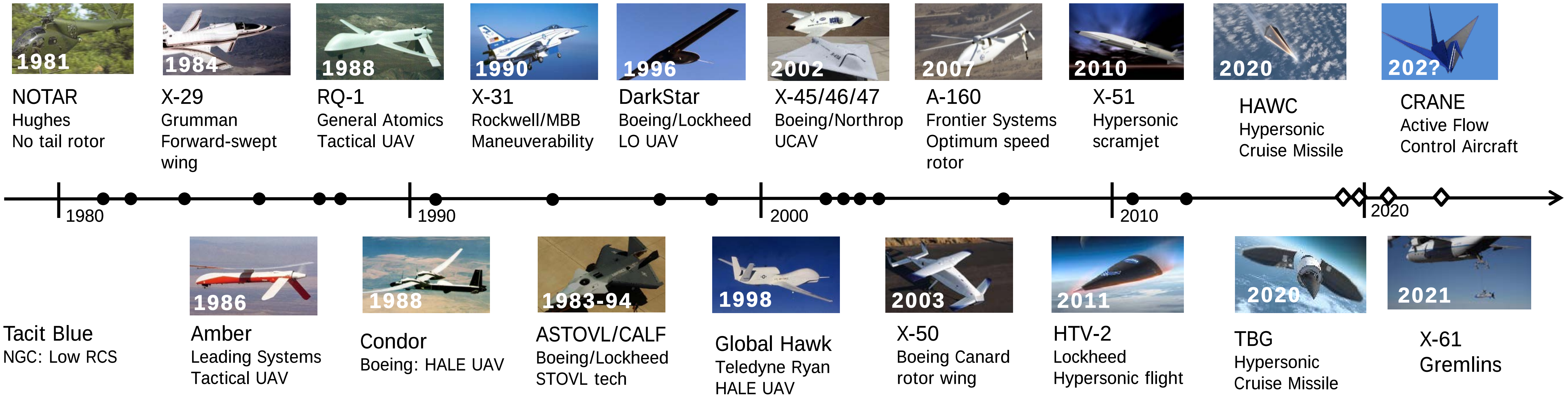
NDIA Systems and Mission Engineering Virtual Conference

December 8, 2021

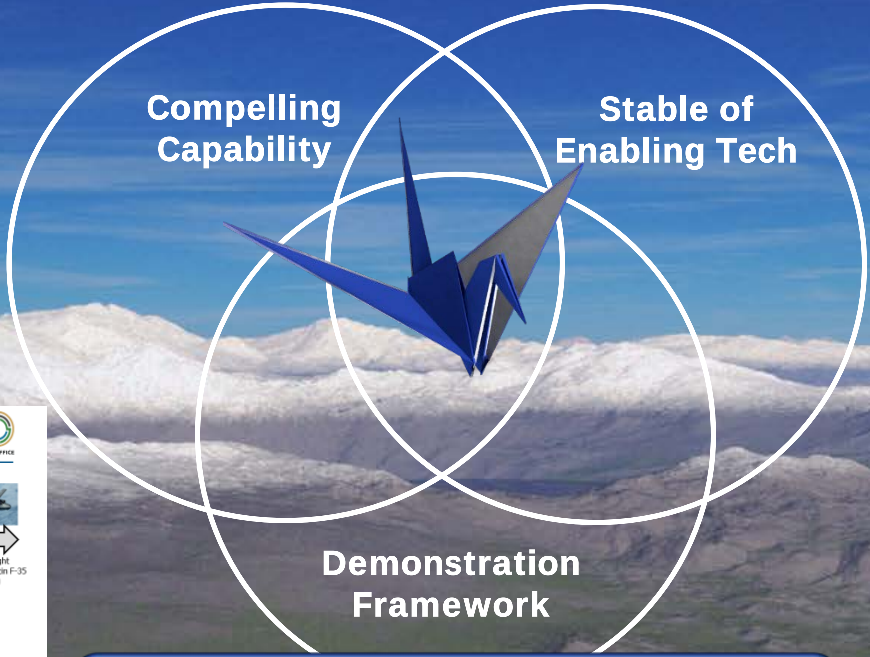
DARPA X-Planes: A Brief History



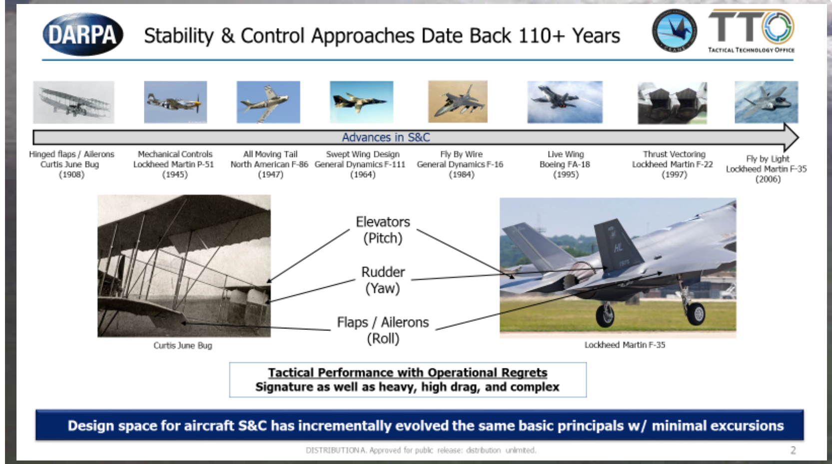
- Historically, DARPA has developed disruptive air technologies on a consistent cadence
- X-planes are technology demonstrations at convincing scale; they are not prototypes and do not always have X designation
- DARPA X-Planes arise in response to promising technology insights, not requirements pull
- Why do experimental system demonstrations?
  - Rapidly demonstrate high risk/high payoff ideas
  - Prove new enabling technologies that lead to revolutionary system concepts
  - Extend and integrate new research & technologies to achieve significant military advantage

CRANE: Program Vision

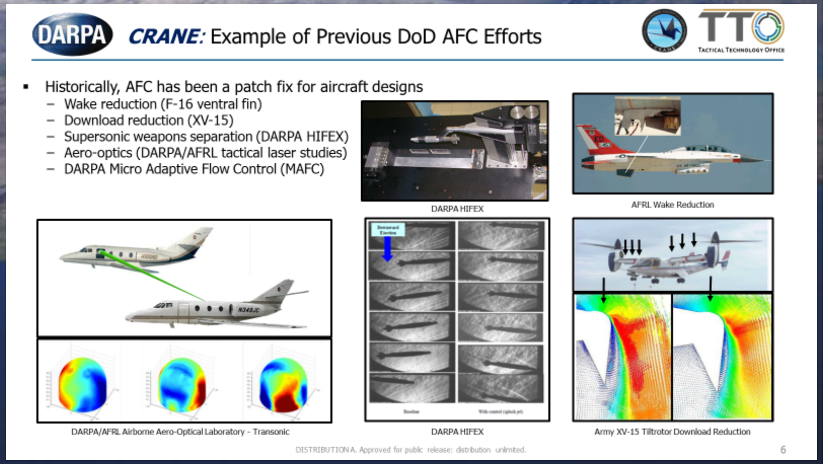
Quantify Benefits:
- Improved Survivability
- Enhanced Performance
- Novel Platforms & Geometries



Technology:
- Mature & Demonstrated Actuators
- Proven CFD Codes
- Wind-Tunnel & Subscale Demonstrations



Demonstration Framework:
- Demonstrate Relevant Performance
- Scaling to Relevant Size & Environments
- Clean-Sheet Design / Modification



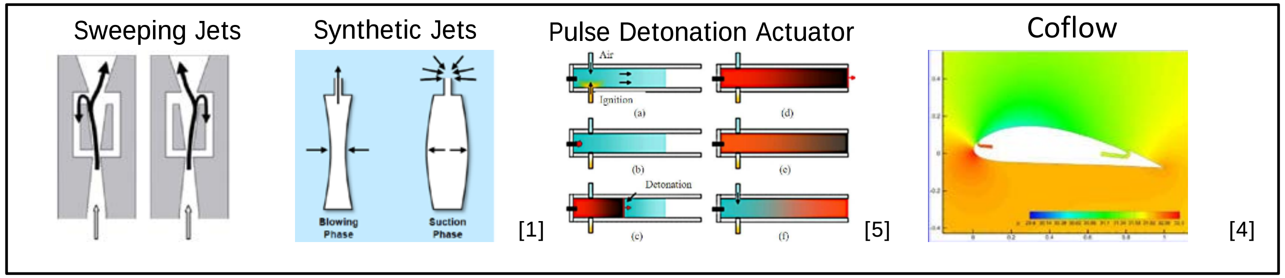
"CRANE will design, build, and flight test an X-Plane that incorporates Active Flow Control (AFC) as the primary design consideration."

Active Flow Control (AFC) Defined

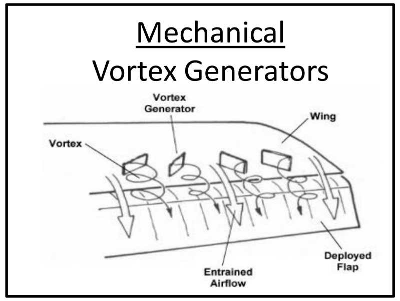
"Active flow control (AFC) is the on-demand addition of energy into a boundary layer for maintaining, recovering, or improving vehicle performance" *- NASA Definition*

- Conventional Types of Flow Control
  - Pneumatic / Fluidic
  - Mechanical
  - Plasma

  } Different actuation approaches to AFC



- AFC Affects Flows in Numerous Ways
  - Alters the boundary layer of a flow
  - Alters the boundary conditions
  - Introduces / modifies vorticity
  - Increases circulation (Lift)



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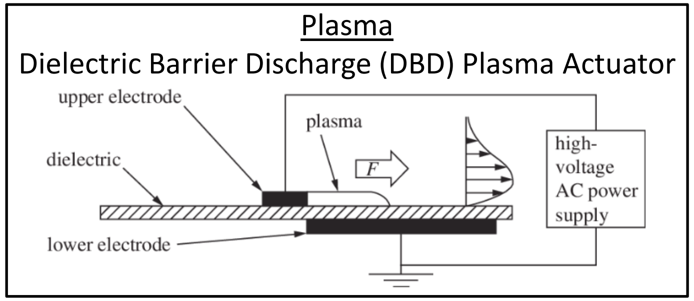


[3]

- AFC Applies to both steady & unsteady flow conditions
  - Small inputs into a flow have large 1st order effects

[1] Maines, Brant H. et. Al. "Comparison of Flow Control Actuators on a Diamond Wing Planform". Lockheed Martin Corporation, Fort Worth, Texas. 2017.
[2] www.aerospaceweb.org/question/aerodynamics/q0228.shtml
[3] www.semanticscholar.org/paper/Turbulent-boundary-layer-control-with-plasma-Choi-Jukes/93562f927c4d150b9f7a9af4df6456efacf54316
[4] Yang, et al. "Super-Lift Coefficient of Active Flow Control Airfoil: What is the Limit?" AIAA, Grapevine, Texas. 2017.
[5] Viktorovich, Bulat "About the Detonation Engine", Saint-Petersburg National Research University of Information Technologies, Saint-Petersburg, Russia, 2014.

AFC: Small inputs to the flow can impart large 1st order effects

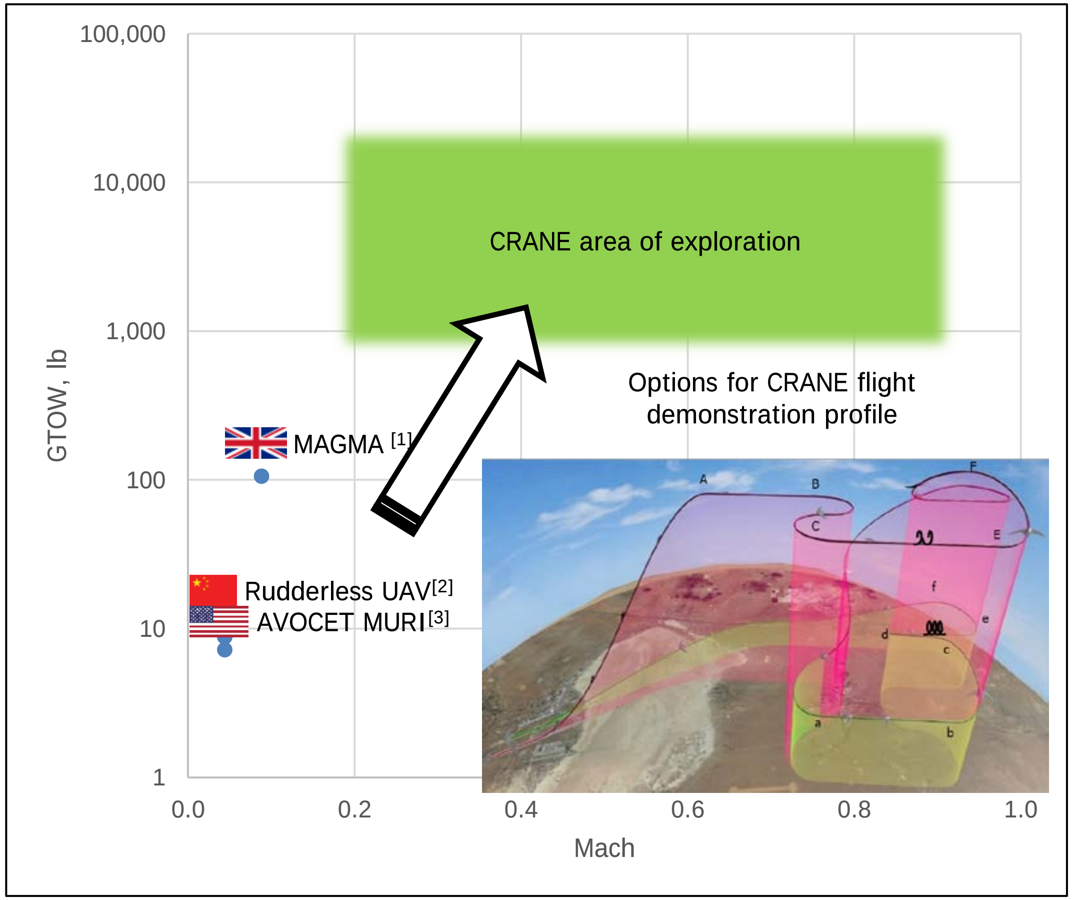
CRANE: Program Overview

1) AFC As Primary Design Consideration
   - Inject disruption tech into the A/C design process
   - Fully explore the AFC trade space
   - Address tech challenges associated w/ full scale demo
   - Early & frequent risk reduction
   - Mature the tools for aircraft configuration & design

2) Affordable Approaches
   - Leverage existing technologies / Use COTS where possible
   - Avoid developing new non-AFC subsystems
   - Systematic airworthiness approach
     - Risk based military flight release for experimental aircraft

3) Demonstration
   - Want An Innovative & Novel X-Plane Demonstration
   - Fly tactically relevant maneuvers at relevant scale

Weight vs. Speed for Previous AFC Enabled Aircraft



[1] Warsop, et Al., NATO AVT-239: Flight Demonstration of Fluidic Flight Controls on the MAGMA Subscale Demonstrator Aircraft, *AIAA SciTech*, 2019

[2]. Shi, Zhiwei, Zhu, et. Al "Aerodynamic Characteristics and Flight Testing of a UAV without Control Surfaces Based on Circulation Control" ASCE, Nanjing, China, 2019.

[3] Glezer, et Al., Dynamic Flight Maneuvering Using Virtual Control Surfaces Generated by Trapped Vorticity, AFOSR Final Report, 2010

A compelling demonstration of the art of the possible in 21st century aircraft design

CRANE: Program Approach

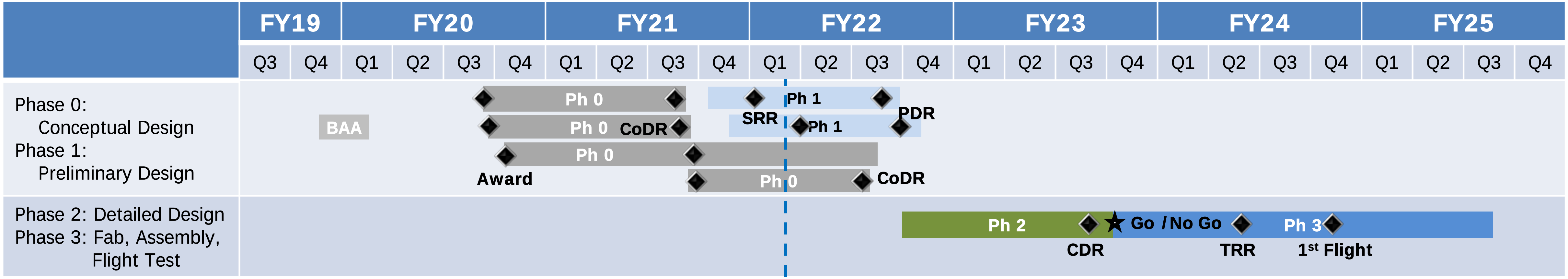
TACTICAL TECHNOLOGY OFFICE

Embedded Gov't SMEs & Engaged Stakeholders

AFRL | ONR | NAWCAD | NASA | ARL | AFOSR

ERDC ITL | ERDC

Dedicated HPC Computing Resources & SME Support



Phase 0

- *Evaluate multiple candidate configurations and flow control approaches*
- *Focus on the aircraft design process & trade space -- develop configuration agnostic design guidelines via trade studies*
- *Conceptual Design Review (CoDR)*
- *Share results widely via AFC consortium & published research papers*

Phase 1

- *Maturation of concept with component level testing, System Requirement Review (SRR), Preliminary Design Review (PDR)*

CRANE: Program Technology Challenges

1) System Design Tools: Expand Aircraft Design Tool Box to Include AFC

- ✓ Need to add AFC to Multi Domain Optimization of Alternatives (MDOA) tools
- ❑ Need to add AFC to flight control design tools

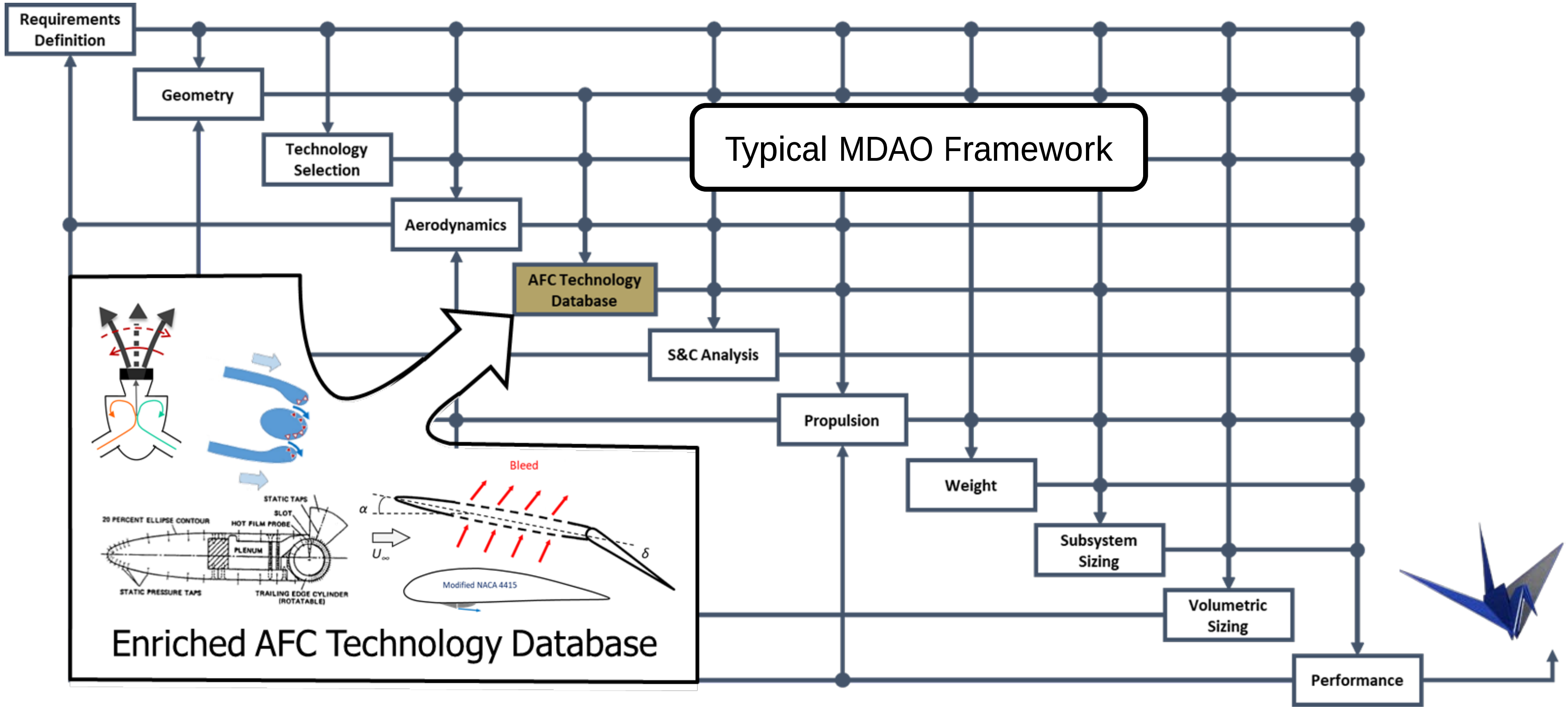
2) Full Scale Design & Integration: Design Based on AFC

- ✓ Initial design & configuration centered around AFC S&C
- ❑ AFC Airworthiness: Robust & Failure Tolerant Design

3) Incorporated AFC into Flight Controls: Basic Aircraft Maneuvers Achieved with AFC

- ✓ CFD / Wind tunnel data needs to be accurately modeled in flight control simulations
- ❑ Control loop must account for hysteresis nature of active flow control & cross coupling of effectors & transient effects

CRANE: Incorporate AFC into MDAO Processes

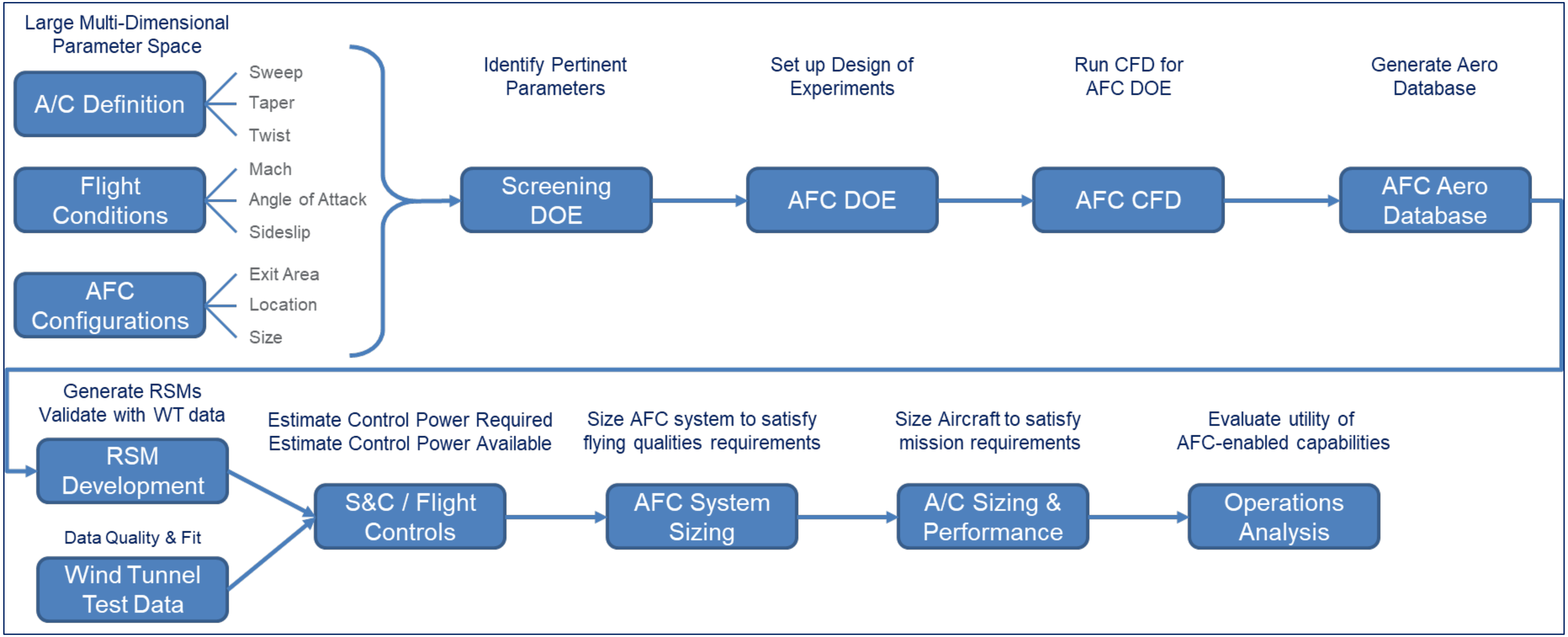


Phase 0 Major Swim Lanes

1) Systems Engineering
   - Requirements
   - Risk management
   - Technology dev planning
   - Military utility assessments
2) Design Methodology
   - MDAO methodology
   - AFC design tools
     - Aerodynamic effects
     - System level impacts
3) Configuration & Design
   - Configuration development & refinement
   - AFC based stability & control effectors
4) Verification
   - Wind tunnel
   - Sub-scale flight tests

- Phase 0 Program Management Philosophy:
  - Align Program Management Office (PMO) IPTs w/ performer IPTs
  - Keep SMEs deeply involved in design trades, test planning, & vision concept work
  - Give configurators enough time to be informed by wind-tunnel & CFD results
  - Maximize reuse of existing sub-systems – focus risk on those items tied to primary objective

Example: A Novel Approach to Exploring AFC Aircraft



Demonstrate AFC Inclusion into Aircraft Conceptual Design

CRANE: Aurora Flight Sciences – Phase 0 Overview

TACTICAL TECHNOLOGY OFFICE

Broad Empirical Database

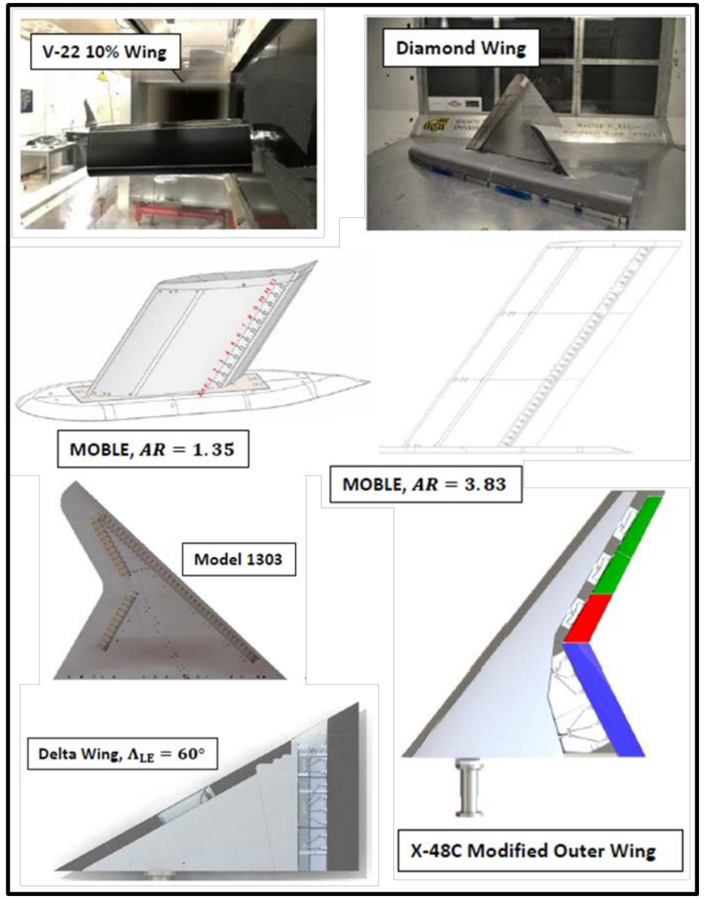
10 Wind Tunnel Test Articles
University of Arizona & Cal Tech

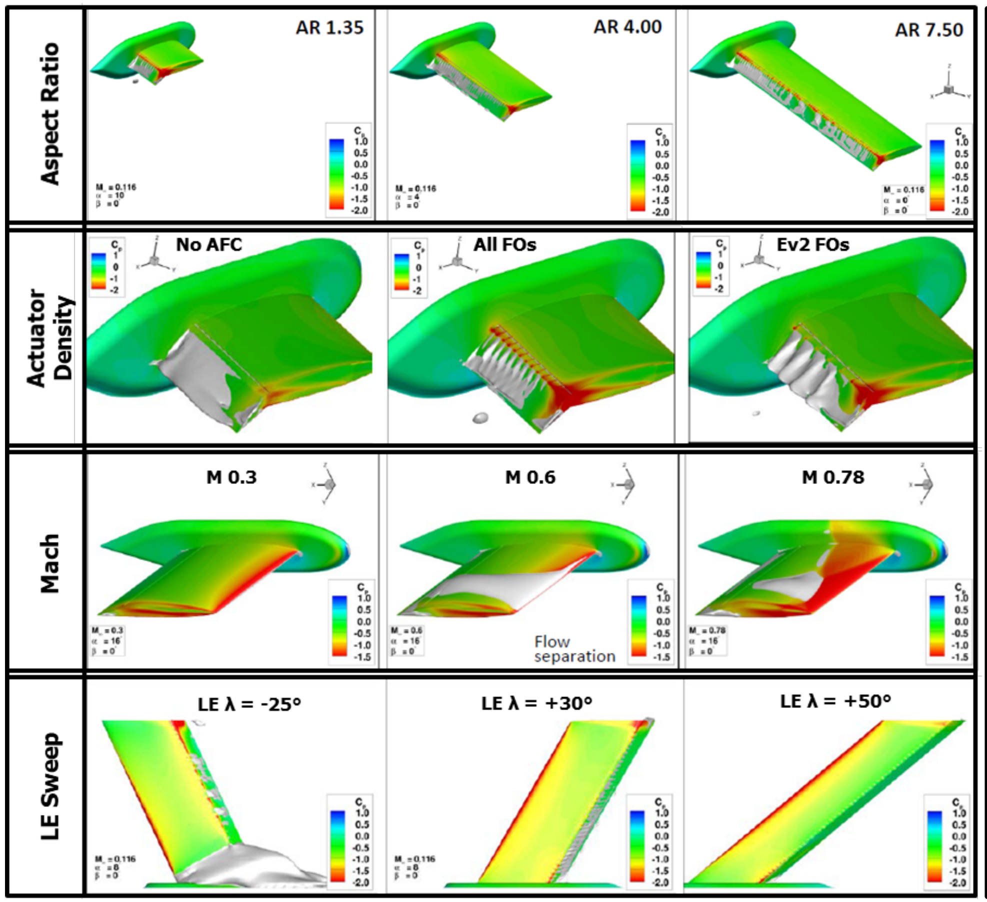
Database Enriched with CFD

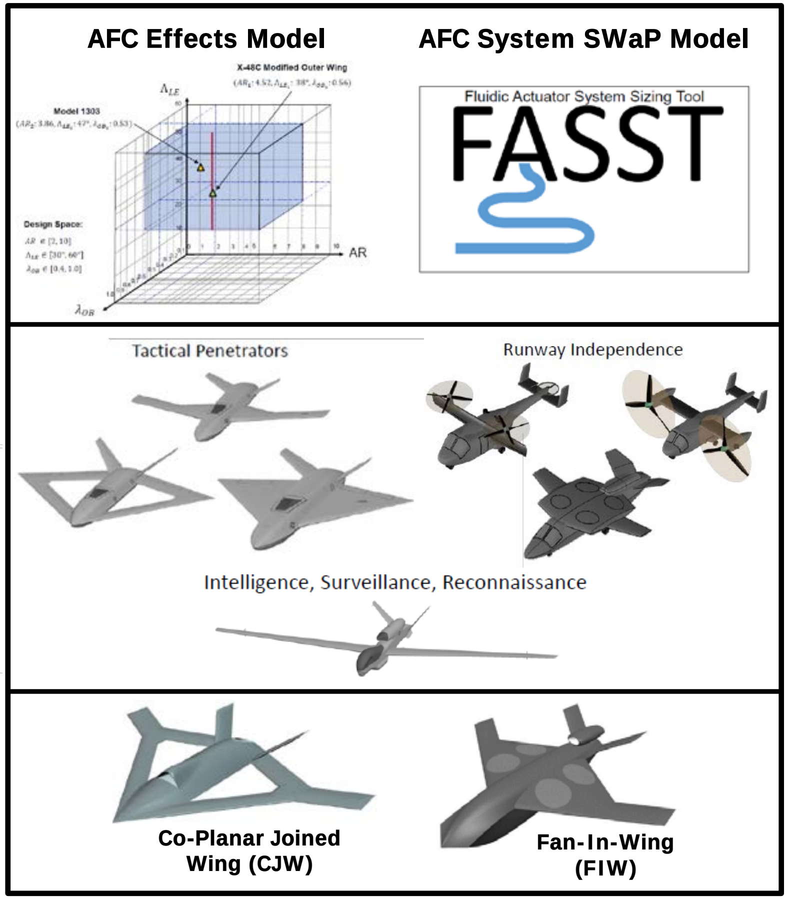
>2M CPU-Hrs of Boeing & ERDC HPC Resources
>1200 Individual Simulations

AFC Modeling and Conceptual Design Iterations

3 Major AFCIDL Releases
>7 Vision Systems Evaluated

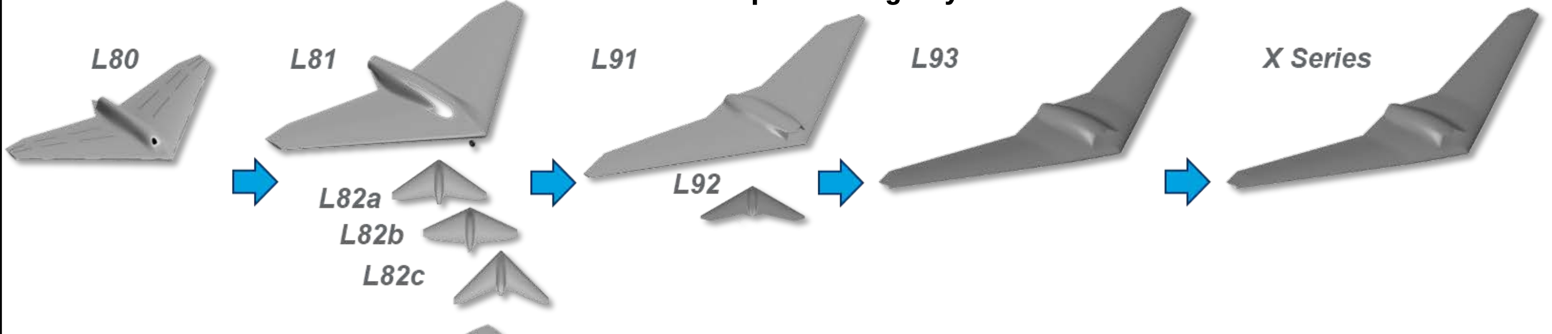


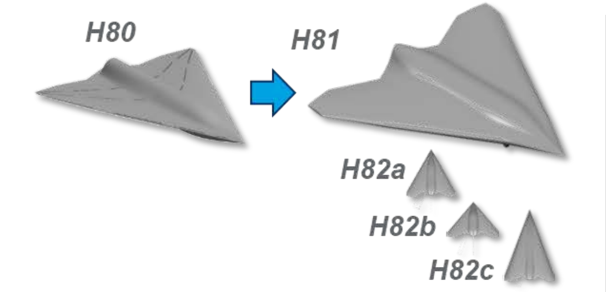




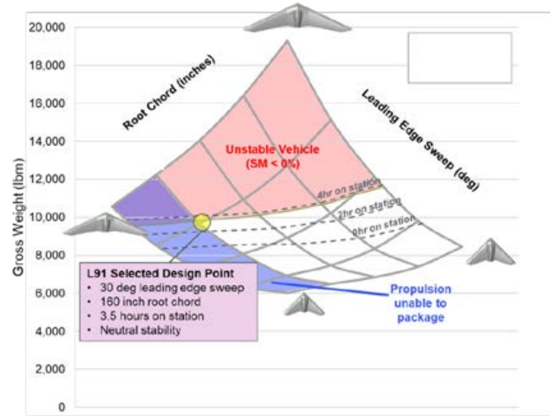
CRANE: Lockheed Martin – Phase 0 Overview

Iterative Conceptual Design Cycles





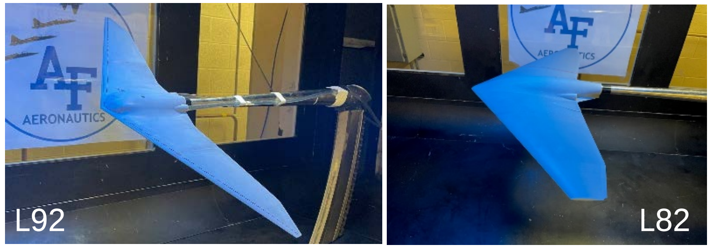
AV Sizing Analysis



AFC System Supply Trade Studies

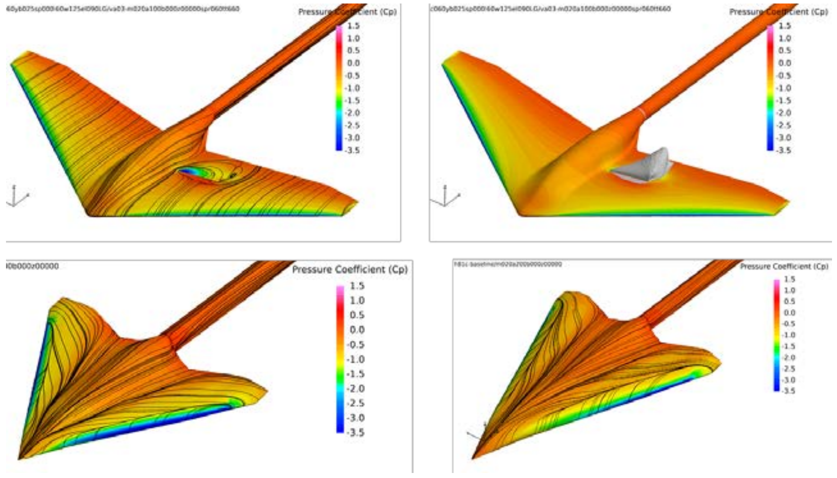
High Pressure Tanks	Aux Heavy Fuel Compressor
Engine Bleed	Auxiliary Propulsion Unit

Conducted Small (2x) and Medium (2x) Scale Wind Tunnel Tests

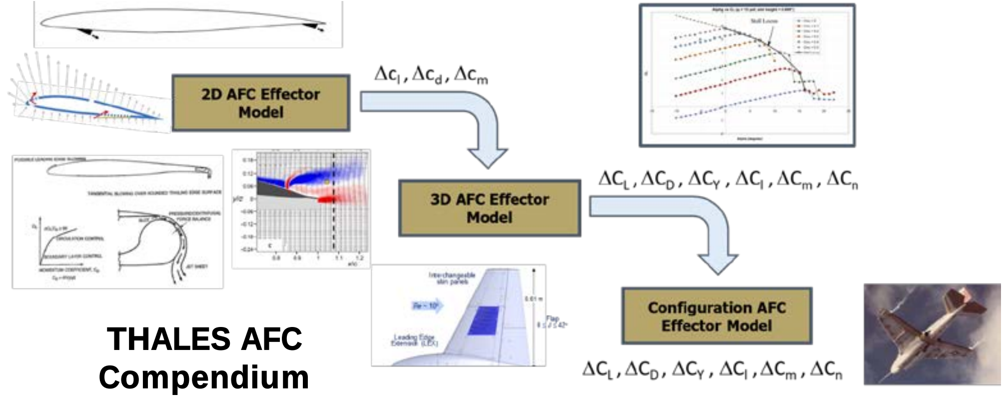


Two Fundamental Vehicle Geometries
- 8 Low Sweep, 5 High Sweep

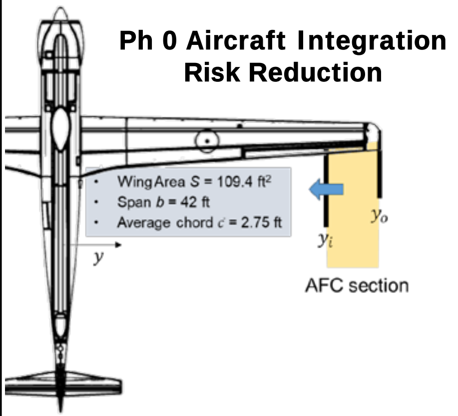
Response Surface Modeling using CFD
- >32M CPU-Hrs of LMCO & ERDC HPC

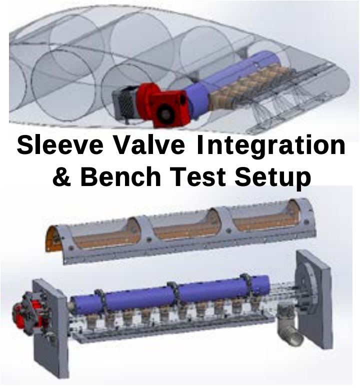


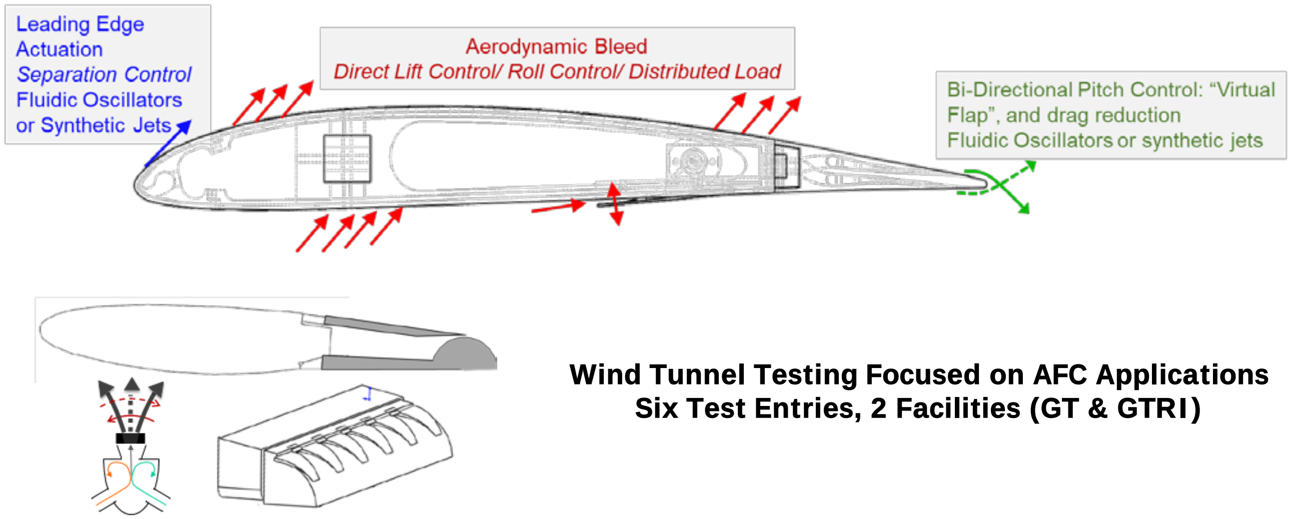
CRANE: GTRC – Phase 0 Overview



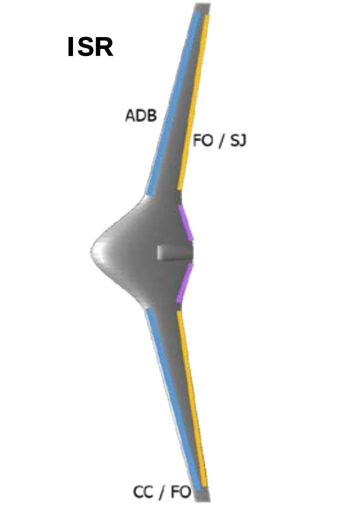
CFD Augments Literature Search & WT Testing for AFC Database
>32M CPU-Hrs of ERDC HPC Utilized

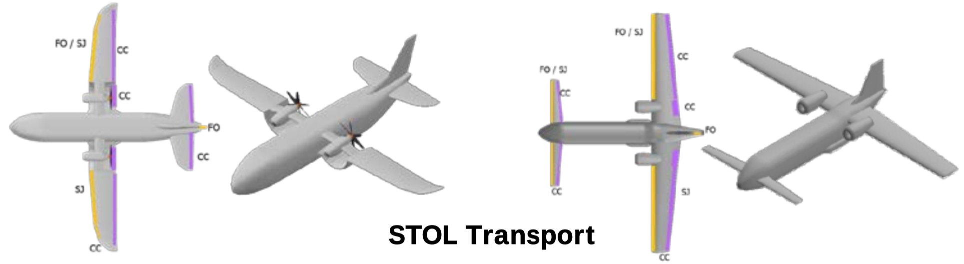


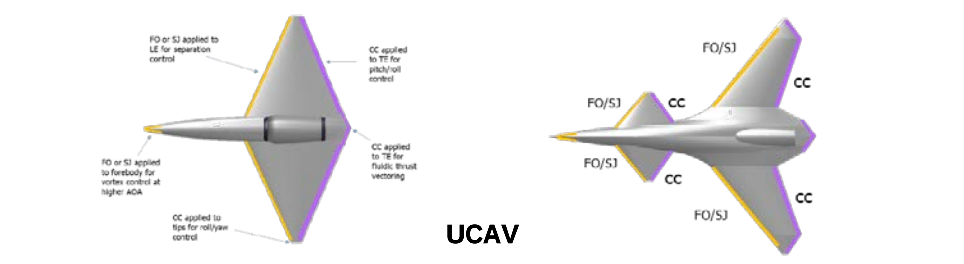




Wind Tunnel Testing Focused on AFC Applications
Six Test Entries, 2 Facilities (GT & GTRI)



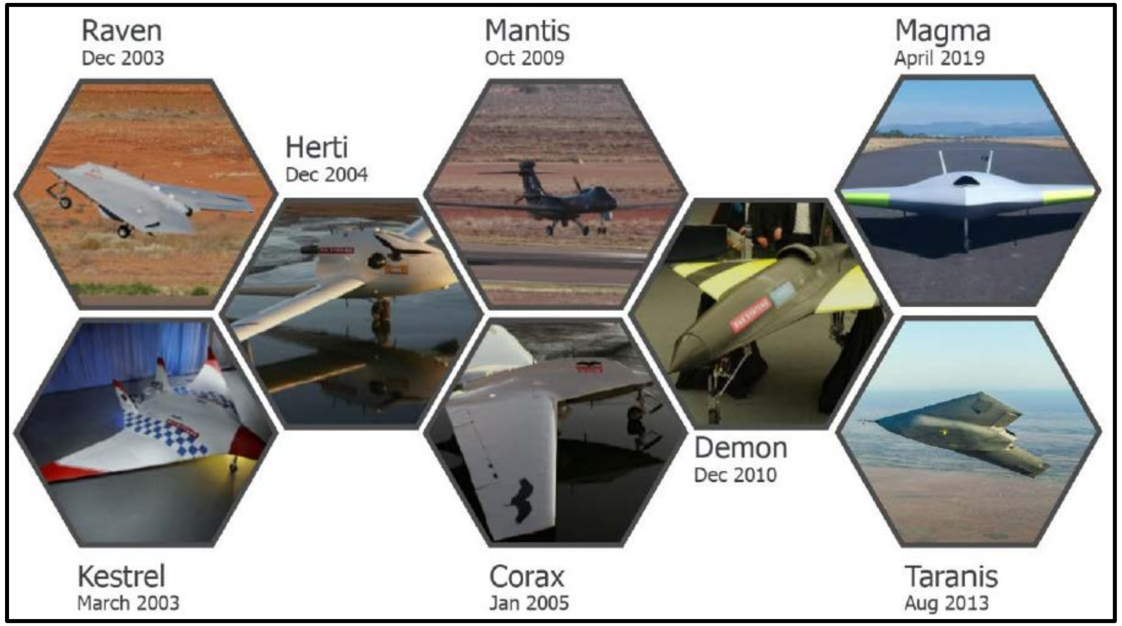




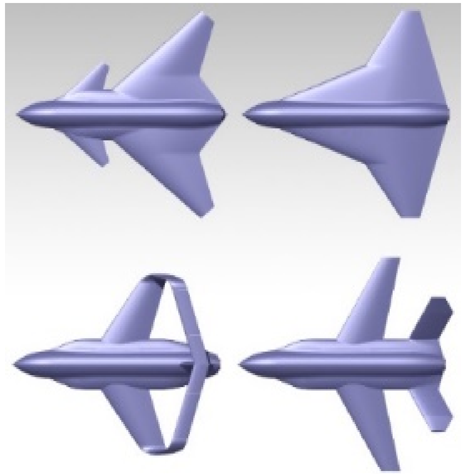
CRANE: BAE – Phase 0 Overview

AFC Conceptual Design

- Extensive AFC team experience (MAGMA, DEMON)
- Planform concepts explore high speed applications
- Transonic wind tunnel testing planned in Phase 0
- AFC Effectors under test to include:
  - Supercritical Circulation Control
  - Forebody Blowing
  - High Lift



Planform Classes Currently Under Consideration



CRANE: ERDC Impact to Phase 0

Hardware & Usage

- ~30,000 core dedicated HPC cluster for CRANE performers
- Primarily used for Computational Fluid Dynamics (CFD)
  - ❖ Rapid exploration of configuration trade space
  - ❖ Detailed trade studies on multiple AFC technologies and implementation strategies
  - ❖ Validated to CRANE Phase 0 and prior wind tunnel testing

Expert Knowledge Base

- ERDC Subject Matter Experts (SMEs) facilitated all aspects of HPC resource utilization to realize overall impact to CRANE
- Critical to success of Government provided HPC resource for CRANE Phase 0

Realized Phase 0 Benefits:

- ➢ Increased Computational Capacity
  - ✓ ~66 Million core-hours utilized
  - ✓ 200-500% increase in CFD bandwidth
- ➢ Increase Solution Speed
  - ✓ 300-1,000% speed increase due to parallelization
- ➢ Cost Avoidance
  - ✓ >$4M worth of increased productivity
- ➢ Continued usage in Phase 1+

CRANE: Summary

- CRANE currently executing with both Phase 0 & Phase 1 Performers
- CRANE Tech symposium showed breadth & depth of CRANE data to industry, academia, govt attendees
- Diverse AFC technology applications across Phase 0 and Phase 1 performers
- Finalizing development of AFC data libraries and design tools for delivery to government
- Heavy focus on digital engineering & HPC early in the program to help refine concepts & build the case for which concept shows greatest promise

CRANE To Date: By the Numbers

- ✓ >20 wind tunnel models exploring 2D & 3D applications
- ✓ 6 Different Wind Tunnel Facilities
- ✓ 3 CoDRs
- ✓ > 66M CPU-Hrs on ERDC HPC resources
- ✓ ~9000 individual CFD simulations
- ✓ 4 AFC Enabled Conceptual Design Tools

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