HIFiRE Flight 2 Unstart Reliability Analysis

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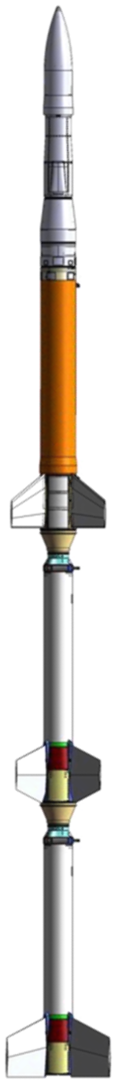
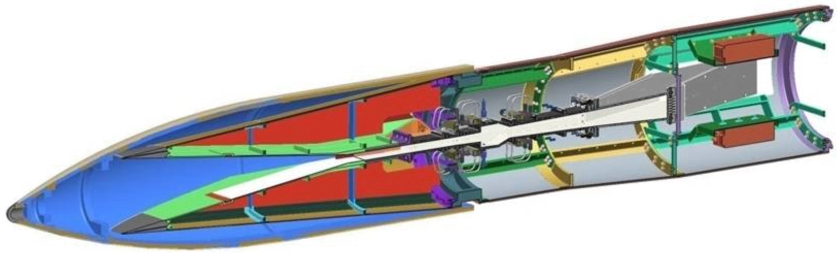
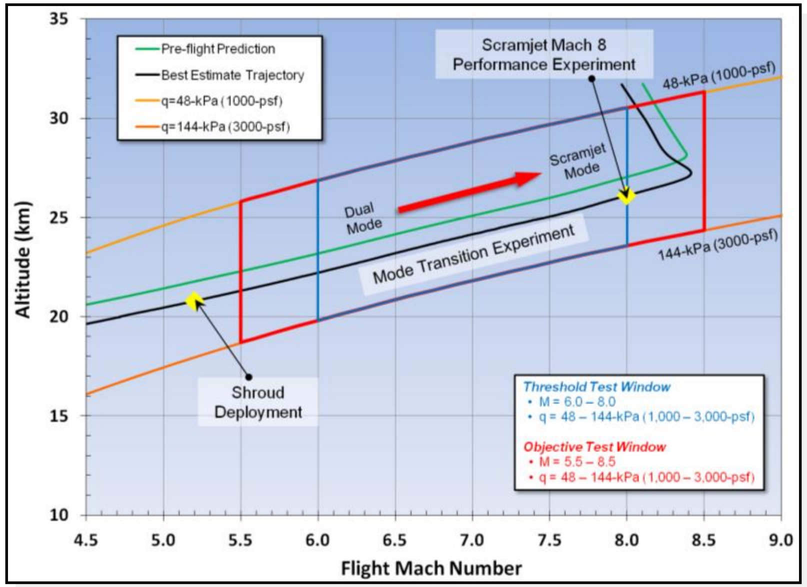
Motivation and Objective

- Air-breathing propulsion systems on hypersonic systems are some of the most complex technologies in flight vehicles
  - Complex physics with widely varying length and time scales
  - Highly sensitive to small perturbations
  - Ground testing limitations
  - Highly complex integration on vehicle platforms
- HIFiRE: Hypersonic International Flight Research Experimentation
  - Joint program between AFRL and the Australian Defence Science and Technology Organisation (DTSO) to develop/mature hypersonic technologies
  - HIFiRE Flight 2
    - Suppressed trajectory sounding rocket flight test
    - Nearly constant dynamic pressure flight
    - Mach 6 to 8+ flight
    - Hydrocarbon fueled scramjet
    - Dual-mode to scram-mode transition
    - Successfully flown on May 1, 2012
- Accurate accounting of uncertainties, especially model-form, is critical to estimate propulsion system operability and reliability to an unstart event
- Objective: Assess unstart reliability of HIFiRE Flight 2



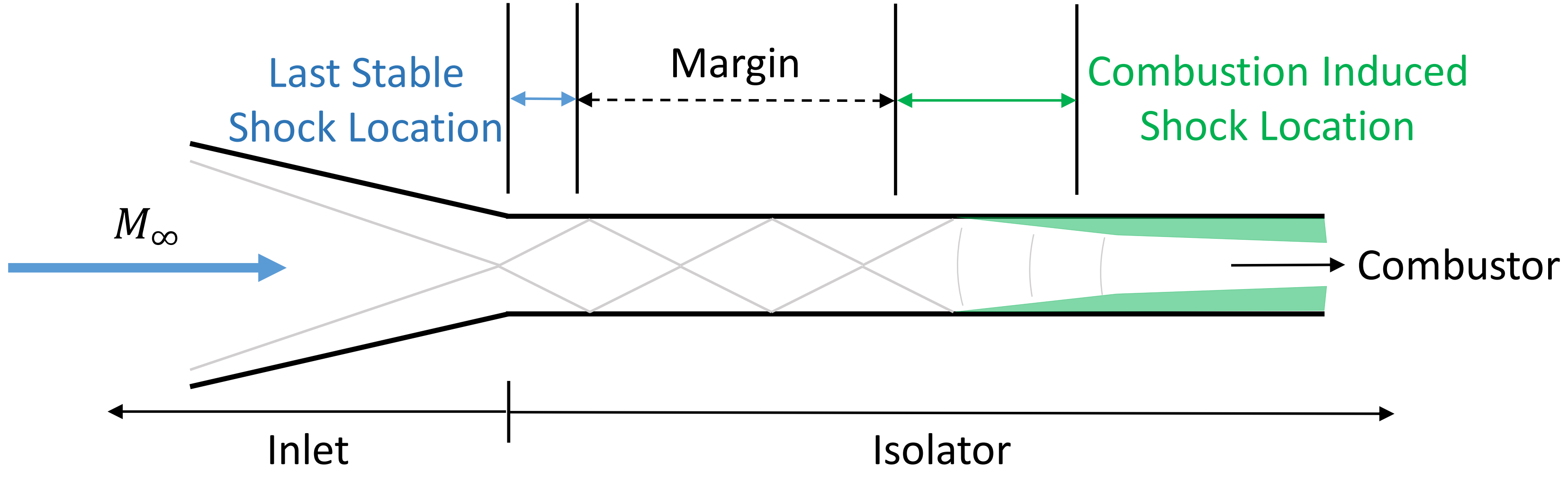




Reliability Analysis via Quantification of Margins and Uncertainties

- Quantification of Margins and Uncertainties (QMU) used to communicate relationship between system uncertainty and margin of complex systems.
- Confidence ratio (CR) defined as ratio of the margin to the uncertainty in both at a desired probability level.
- CR indicates how reliable a system may be and how much room for “unknown-unknowns” exists.

Dual-Mode Ramjet Operability

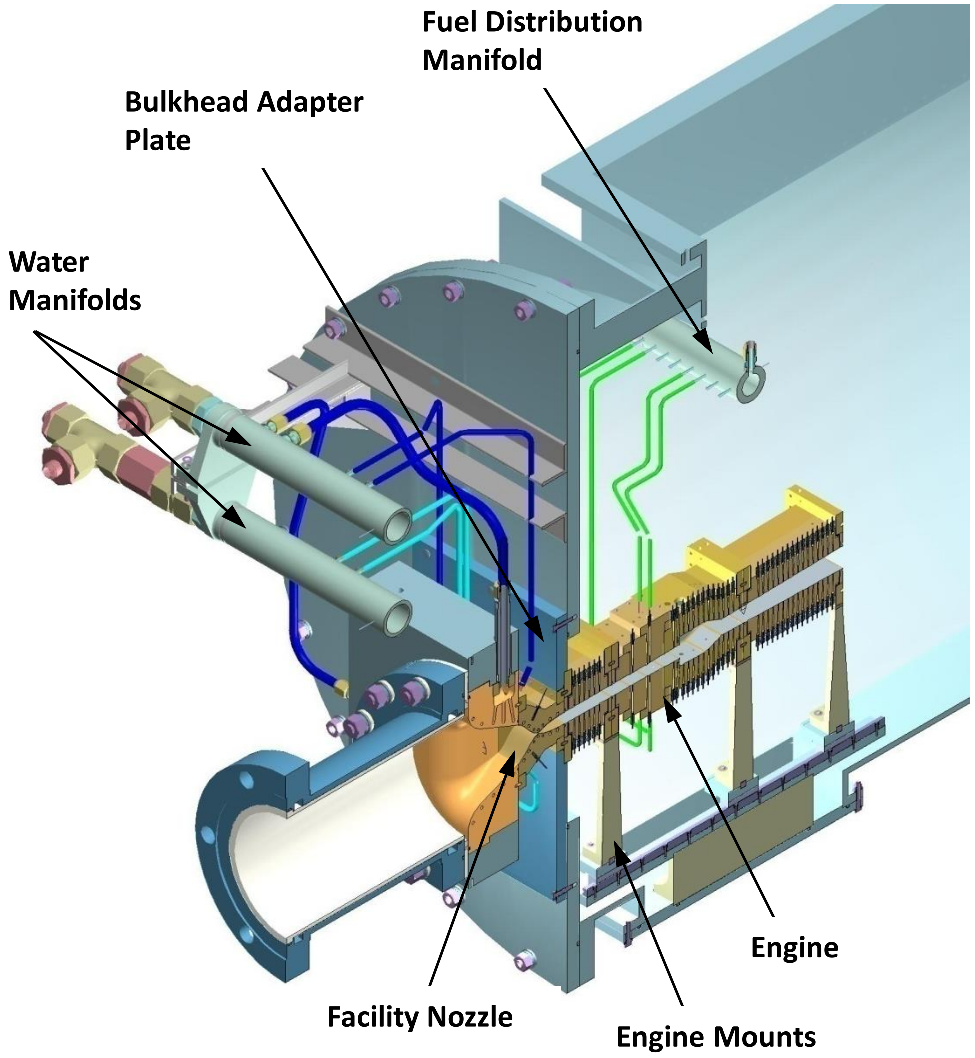


$$CR = \frac{Margin}{Uncertainty}$$

Aggregate of operating limit and condition uncertainty

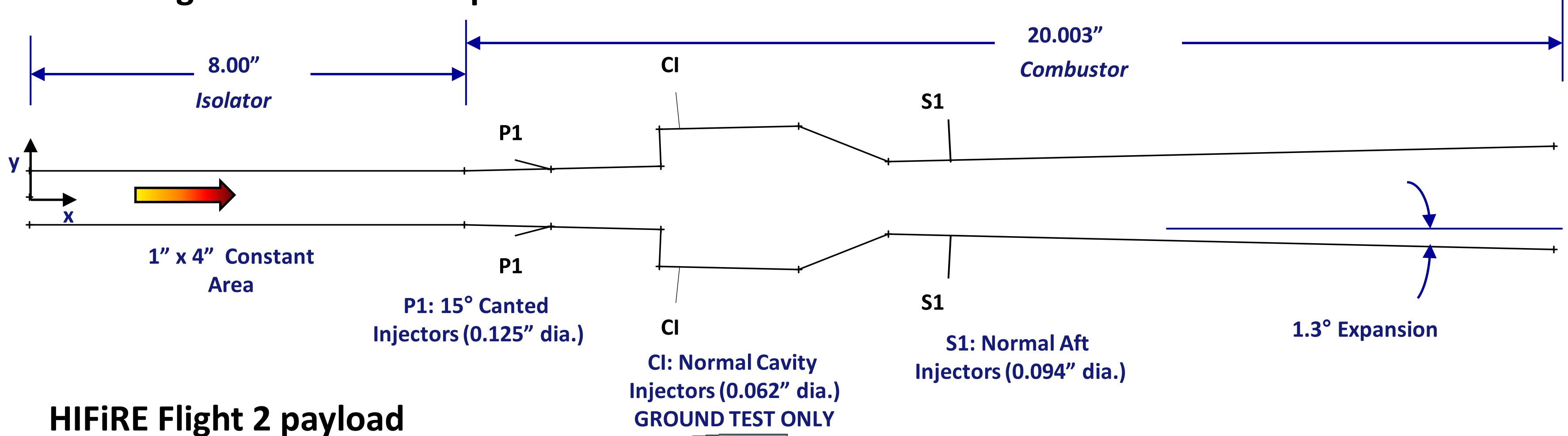
HIFiRE Direct Connect Rig (HDCR)

- Direct connect testing used to characterize combustor performance (No other propulsion system testing performed)
- HDCR is first direct-connect test in Arc-Heated Scramjet Test Facility (AHSTF) at NASA Langley
- Three facility nozzles fabricated to duplicate HIFiRE isolator entrance 1-d Mach numbers for Mach 6, 7, and 8 flight
- Copper heat sink hardware
- Flowpath
    - Modular components
    - Thermal barrier coated (TBC)
    - Heavily instrumented (nearly identical to flight instrumentation)
        - 144 static pressure taps, 23 thermocouples, 4 heat flux gauges
- HDCR is a one-to-one scale model of the flight test article isolator and combustor

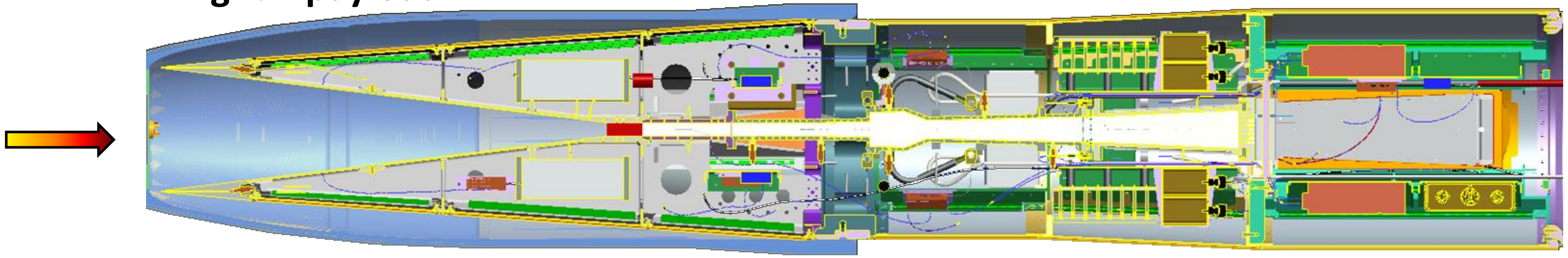


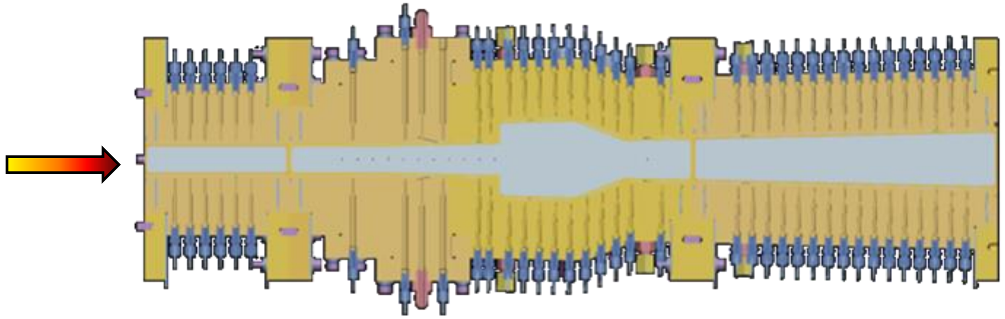
Shared HIFiRE Flight 2 and HDCR Geometry

HIFiRE Flight 2 Internal Flowpath



HIFiRE Flight 2 payload



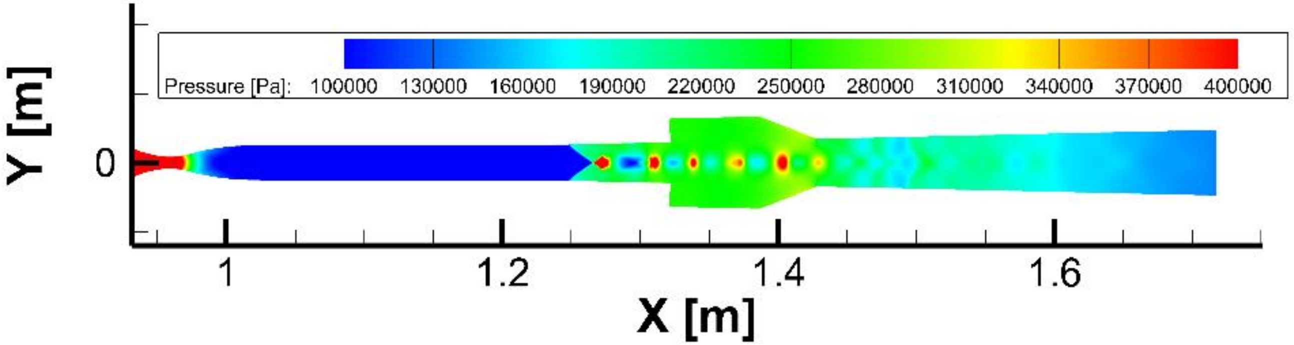


HIFiRE Direct Connect Rig (HDCR)

Computational Model (for both HDCR and HF2)

- VULCAN-CFD 7.1
- Structured, three-dimensional, cell-centered, finite volume solver
- Assumed steady state, thermally perfect flow
- Flux Scheme: Edwards Low Dissipation Flux Split Scheme (LDFSS)
- Turbulence model: Menter blended k-ω / k-ε with wall matching functions of Wilcox
- One-dimensional, wall-normal heat transfer boundary condition using experimentally obtained back-side temperatures
- Combustion model: modified version of the Eddy Dissipation Concept (EDC) model of Magnussen and Hjertager
  - Significantly lower computational cost vs. a finite rate model
  - Valid for mixing limited and well flameheld flows
- Langley Isolator Model used to determine last stable shock location for the flight vehicle

HDCR Simulation

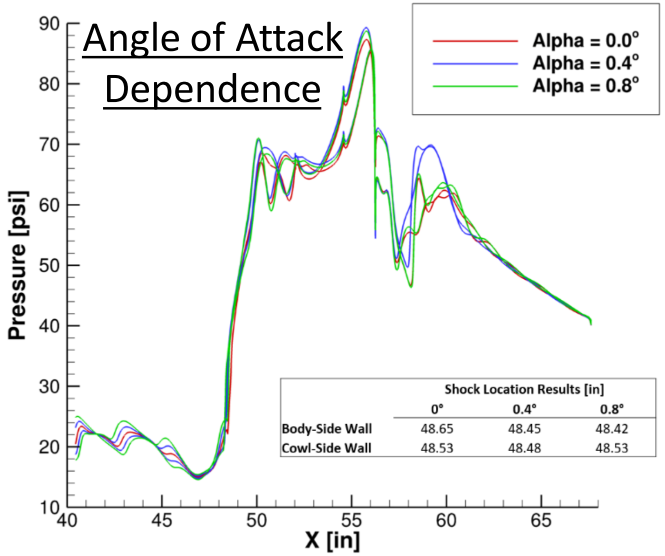


Parametric Uncertainty Sources

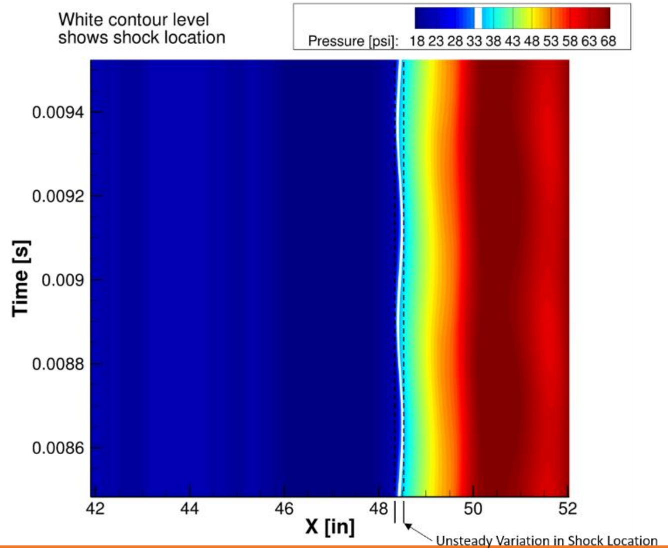
- Eight sources of uncertainty
  - Two freestream values
  - Two turbulence model coefficients
  - Four combustion model parameters
- Angle of attack determined to be negligible
  - Costly to include due to grid doubling
  - Causes unsteadiness in the solution

CFD Parametric Uncertainties

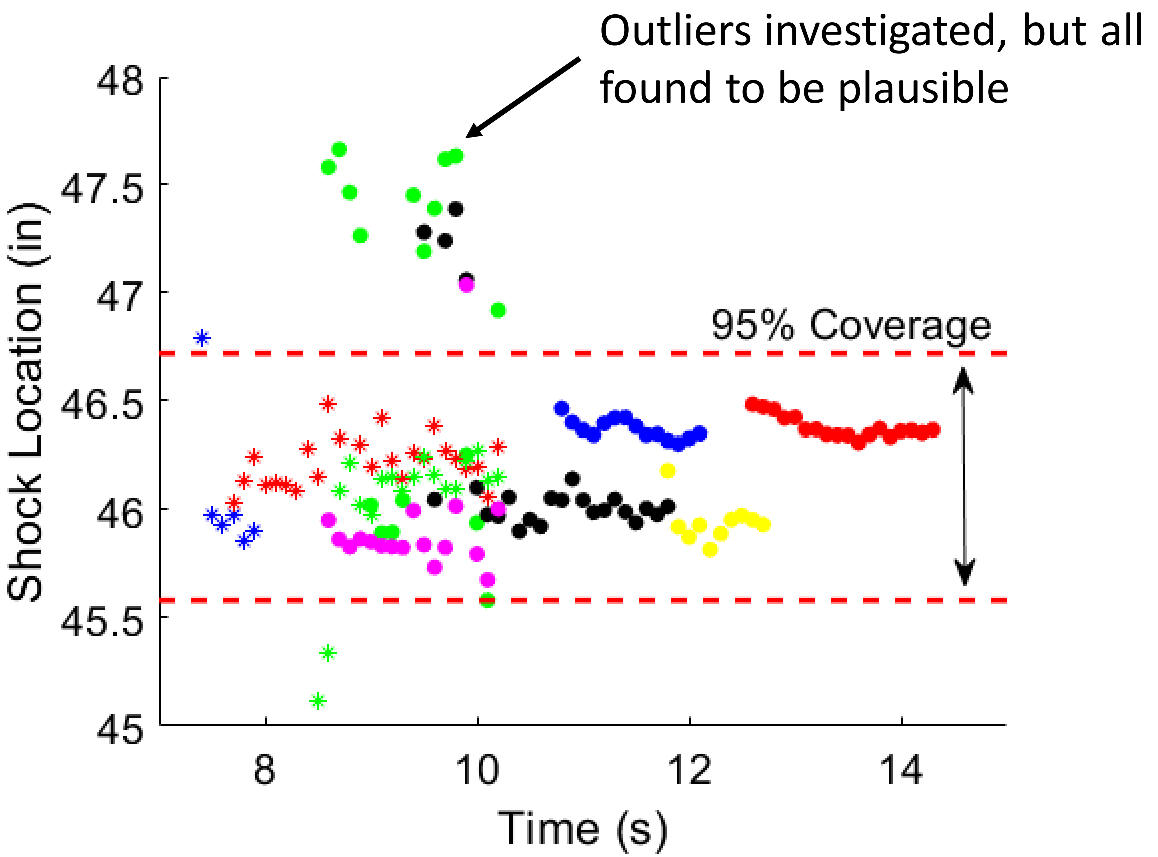
Parameter	Distribution	Mean/ Min	Std. Dev./ Max
Mach	Gaussian	6.5	0.1
q_∞ (psf)	Gaussian	2000.0	40.0
$\sigma_{\omega 1}$	Epistemic (interval)	0.3	0.7
κ	Epistemic (interval)	0.38	0.42
Sc_t	Epistemic (interval)	0.5	0.9
EDC_t (1/s)	Epistemic (interval)	30000.0	300000.0
ϕ factor	Epistemic (interval)	0.9	1.1
EDC_1	Epistemic (interval)	1.5	4.0

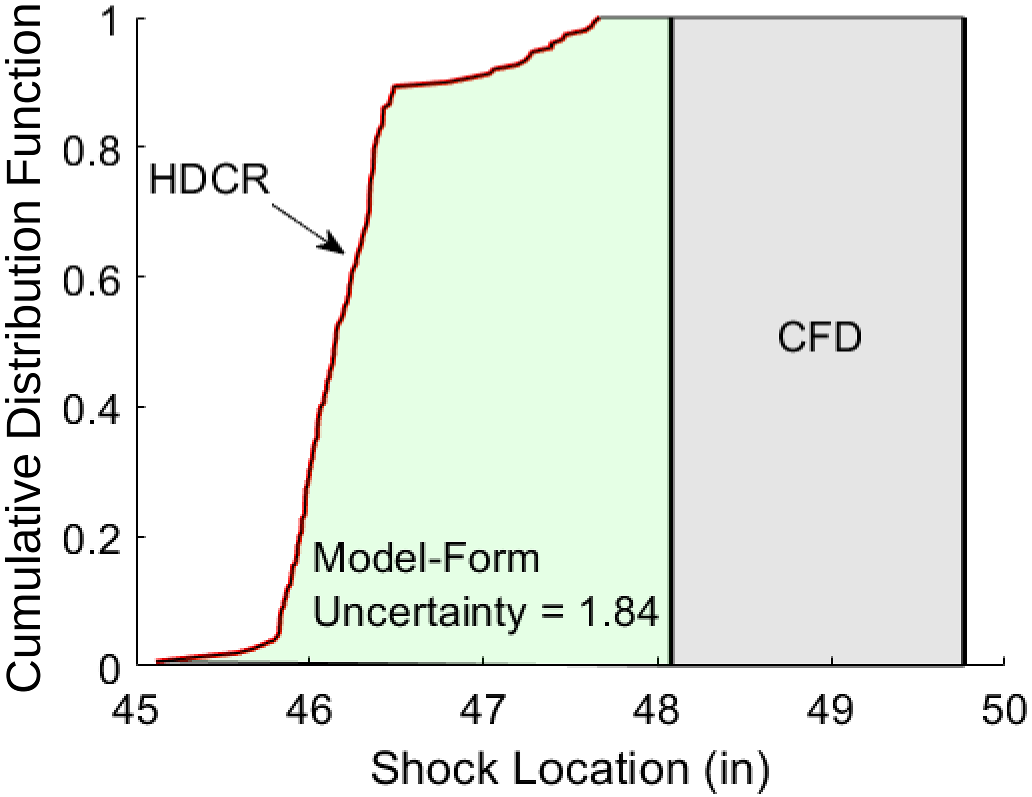


Solution Unsteadiness



HDCR vs VULCAN-CFD (Model Validation)

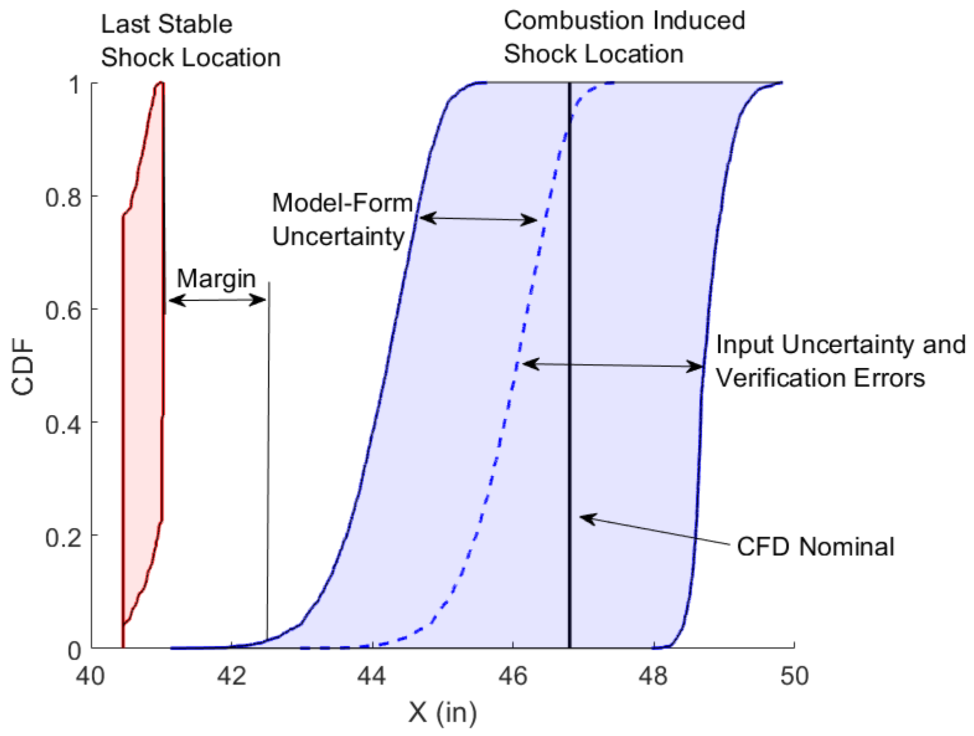




Nature/reality of the HDCR test makes comparison with CFD challenging!

HF2 Reliability Analysis

- 70 CFD simulations of the HF2 flight vehicle (2nd order Polynomial Chaos Expansion (PCE))
- Operating limit (last stable shock location)
  - Determined using the Langley Isolator Model of each simulation
  - 50% of variation due to Mach number uncertainty
- Operating condition (combustion induced shock location)
  - Extracted from each case where the combusting pressure equals 1.5 times the nominal tare pressure
  - 30% of variation due to Mach number, 45% due to turbulent Schmidt number
  - Verification errors include CFD grid error and PCE model error
- Confidence Ratio
  - Without model-form uncertainty: CR = 0.91
  - With model-form uncertainty: CR = 0.31
- Not much room for unmodeled effects, but may be sufficient
- Highly reliable in a traditional sense



HF2 Reliability Conclusion

- Analysis shows the HF2 shows system had positive margin, but significant uncertainty
  - About 30% uncertainty in combustion induced shock location due to model-form
  - Raises the question “how much CR is enough?” if the system is well characterized
- Comparison between HDCR and CFD may be questionable likely due to differences testing and modeling
- Free-jet test would be needed to better characterize model-form uncertainty
- Calibration of combustion model to reduce input uncertainties would not improve model-form uncertainty, assuming epistemic uncertainties bound the “real” solution