National Aeronautics and Space Administration

Aerodynamic Performance of a Compact, High Work-Factor Centrifugal Compressor at the Stage and Subcomponent Level

Edward P. Braunscheidel & Gerard E. Welch - NASA Glenn Research Center
Gary J. Skoch – Army Research Laboratory
Gorazd Medic and Om P. Sharma – United Technologies Research Center

United Technologies Research Center

50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference
July 28-30, 2014, Cleveland, OH

Aerodynamic Performance of a Compact, High Work-Factor Centrifugal Compressor at the Stage and Subcomponent Level

- Background and Scope
- Test Article and Facility Description
- Key Instrumentation
- Stage and Subcomponent Results
- Performance Assessment vs. Pre-test CFD
- Summary

Background and Scope

- **NASA/UTRC High Efficiency Centrifugal Compressor (HECC)** NRA cost-share contract
  - Develop HPC technologies for advanced turboshaft engines for rotorcraft
  - Challenging goal set for centrifugal compressors
  - Maintain similitude between engine scale and rig scale hardware
  - Design/Analysis, fab, assembly, test

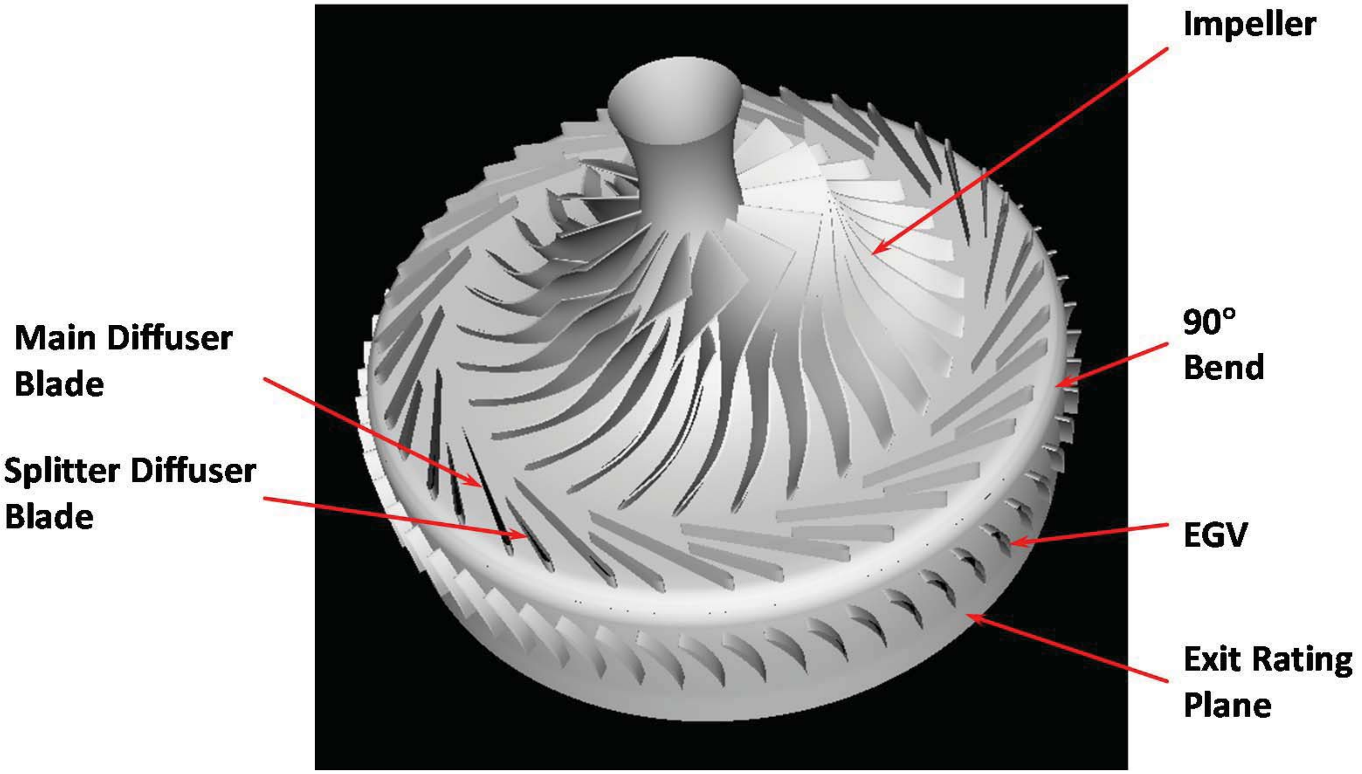
Metric	Intent (rig scale, 2x engine scale)	CFD*
Exit-corr. flow	$2.1 < \dot{m}_{c,ex} < 3.1$ lb_m/s	2.98
Work factor	$0.60 < \Delta H_0/U^2_2 < 0.75$	0.7905
$\eta_{p,tt}$ (poly)	≥ 0.88	0.888
Diam. ratio	$D_{max} / D_2 \leq 1.45$	1.45
Design SM	13%	12%
M_{ex}	0.15	0.15
α_{ex}	15^o	14^o

*Medic, G., et al., "High Efficiency Centrifugal Compressor for Rotorcraft Applications," NASA/CR—2014-218114, Sept., 2014.

HECC Stage Overview

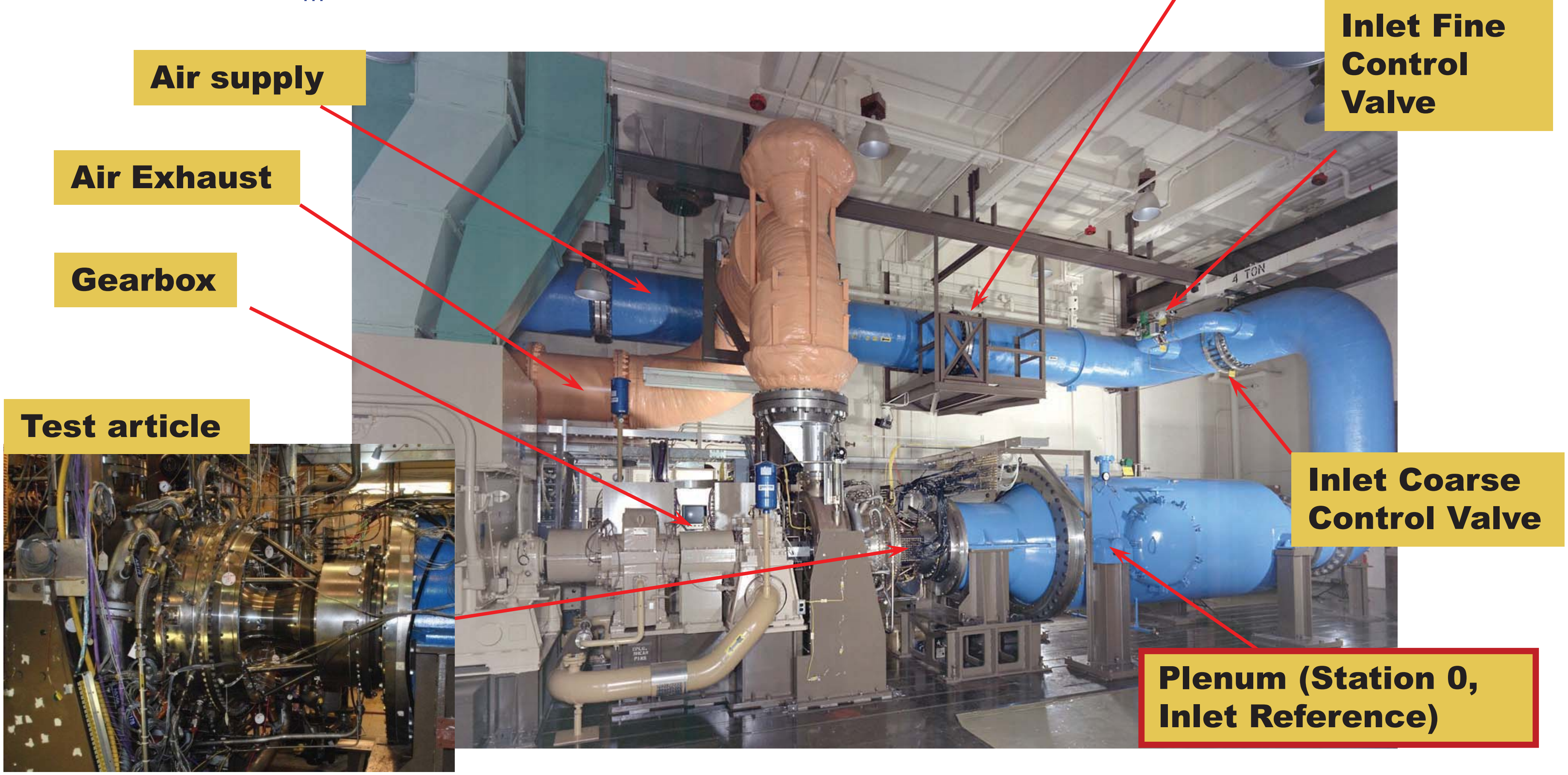
Design speed = 21,789 ft/s (Exit tip speed = 1615 ft/s)

- **Impeller**: 15 blade/splitter pairs, spanwise varying backsweep, lean, elliptical leading and trailing edges
- **Diffuser**: 20 vane/splitter pairs, with splitters offset to maximize pressure recovery
- **EGVs**: 60 cascade-style airfoils

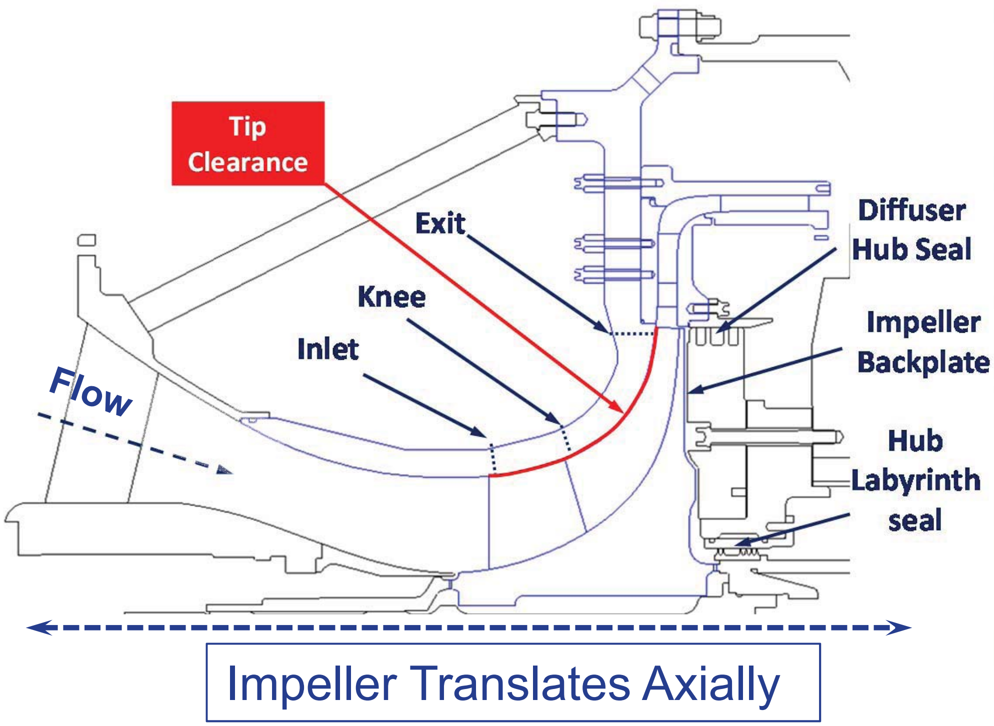


Small Engine Component Test Facility (CE-18)

- 6000 hp / 60,000 rpm / 30:1 PR / Max 20″ diameter
- Inlet pressures 2-45 psia / Inlet air -20 ºF to ambient
- Inlet flow 60 lb_m/s / Exhaust to ambient or 26 in-hg

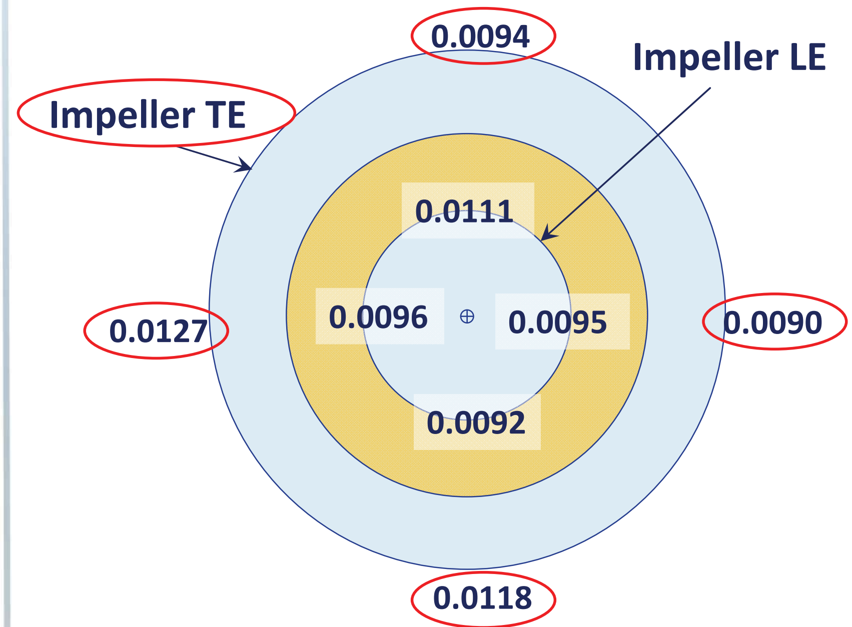


Tip Clearance System



- 4 rub probes at each station used for tip clearance calibration/alignment
- ε/b = 2% (0.012″) design tip clearance, no step in flowpath at impeller/diffuser interface

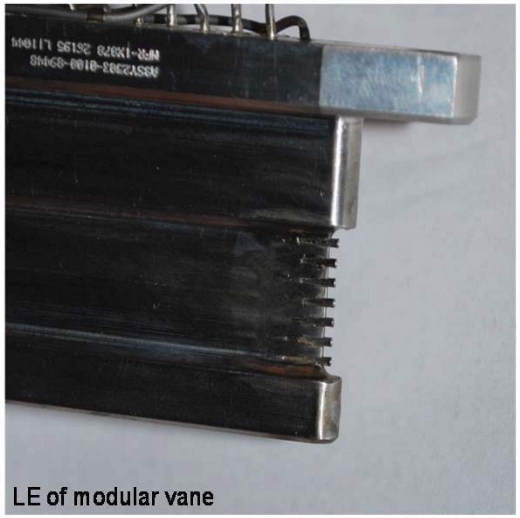
Tip Clearance Variations @ N_c = 100%



$\Delta\varepsilon/b$ *of* 0.5%, → 0.12 pt. impact on η_{tt}

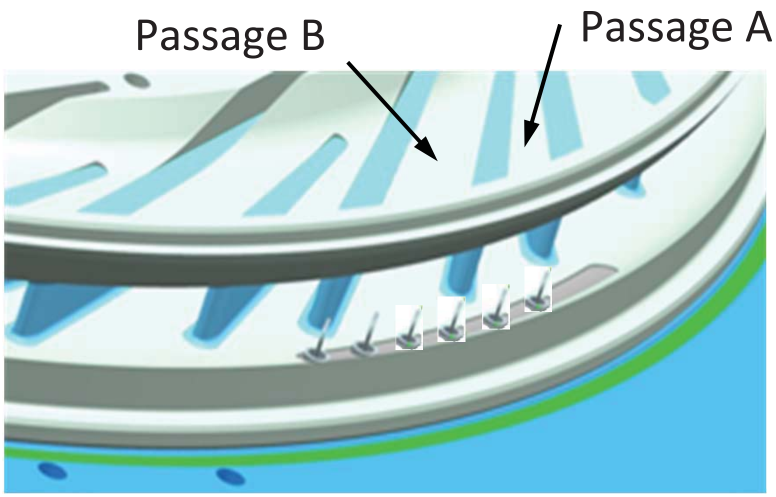
Diffuser LE and "Rake" Instrumentation

- Vane Leading Edge (2.4)
  - Two vanes with 7 Kiel head p_0 ports
  - Key measurements for impeller and diffuser performance


LE of modular vane

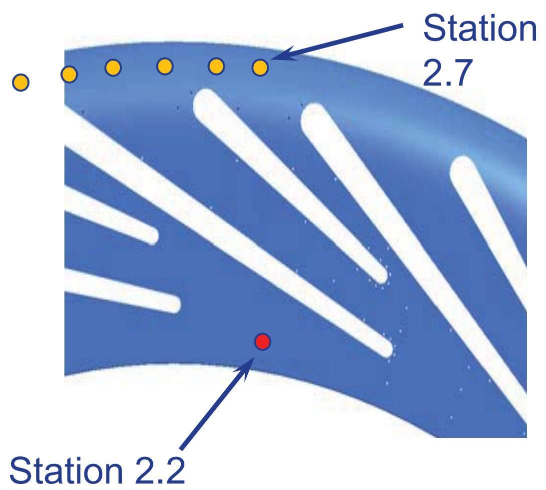

Modular vane provision

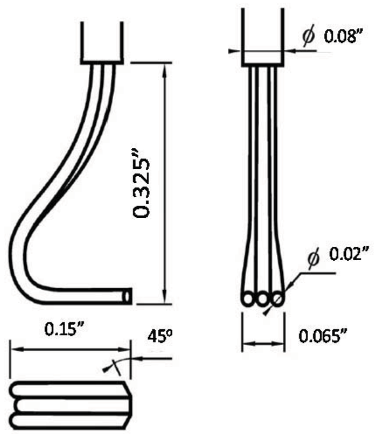
- Vane Trailing Edge (2.7)
  - 6 locations resolve one main-to-main diffuser passage
  - Miniature Cobras at immersions of 15-85%, calibrated for α and p_0

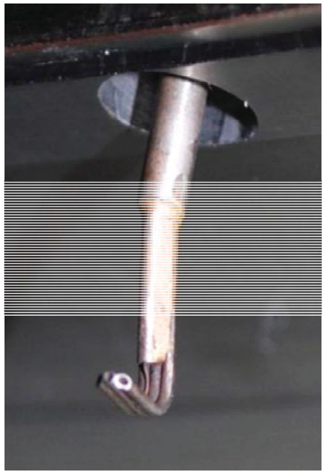


Surveys
3-Port Cobra Probe

- Vaneless Space (2.2) & Diffuser Exit (2.7)
  - Traversable spanwise, manually aligned to flow
  - Calibrated to M=0.84 (Cal. Facility limit)



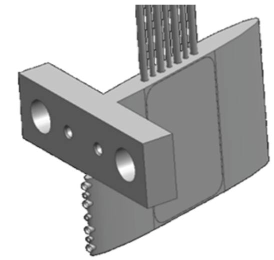




EGV Exit/Stage Rating (Station 3)

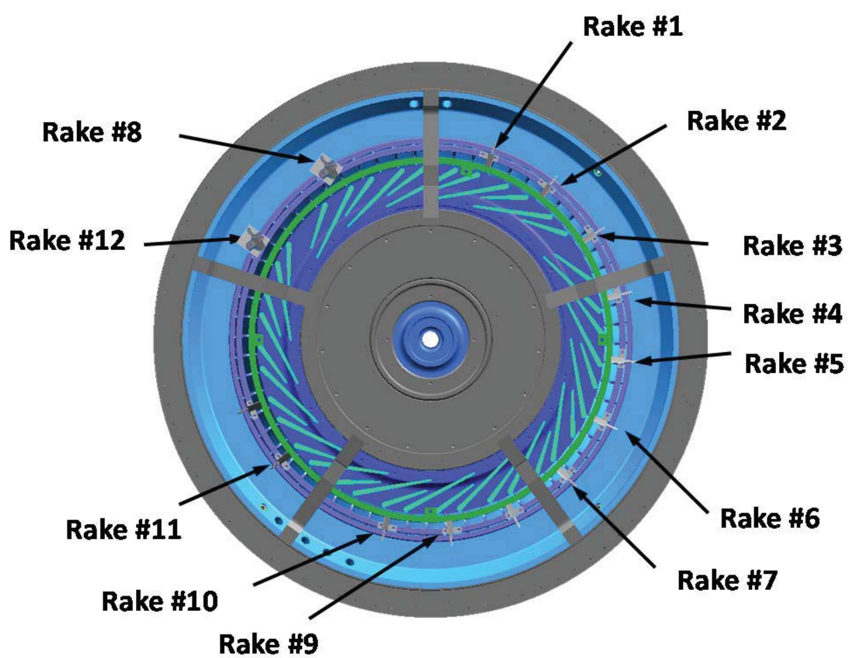
- 12 Rakes indexed to resolve one main-to-main diffuser pitch
- Kiel head p_0 and T_0 ports on area centroids

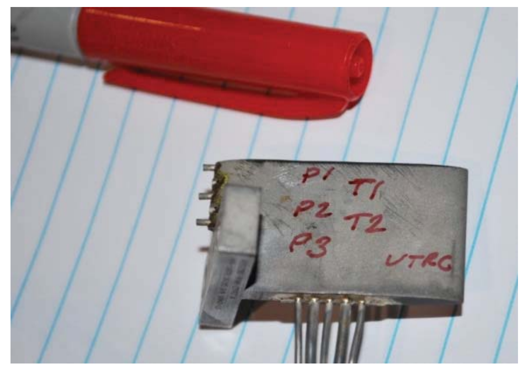
- 3 adjacent EGVs have LE Kiel head p_0 (25-75% span)



p_o x3

T_o x2

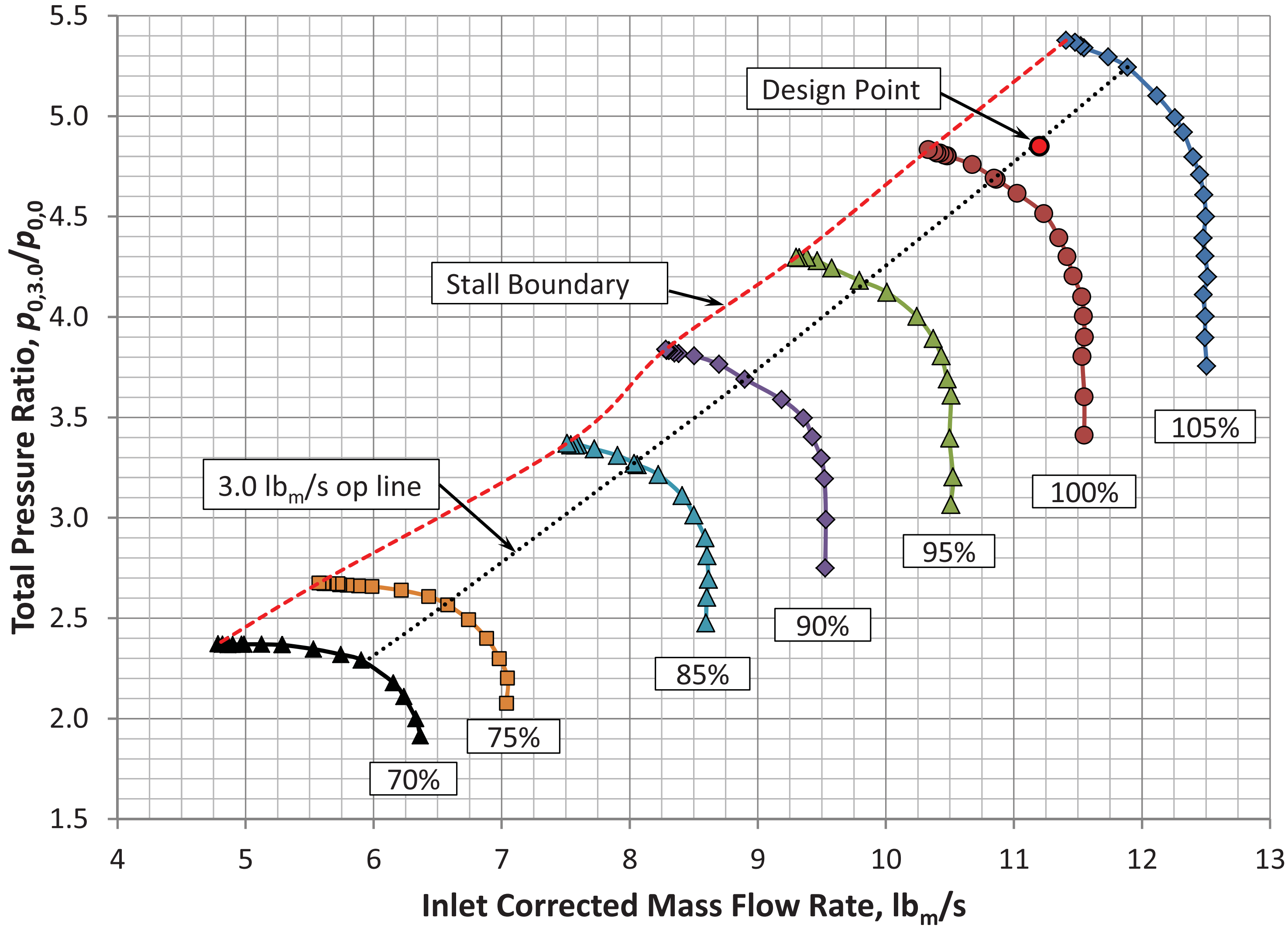




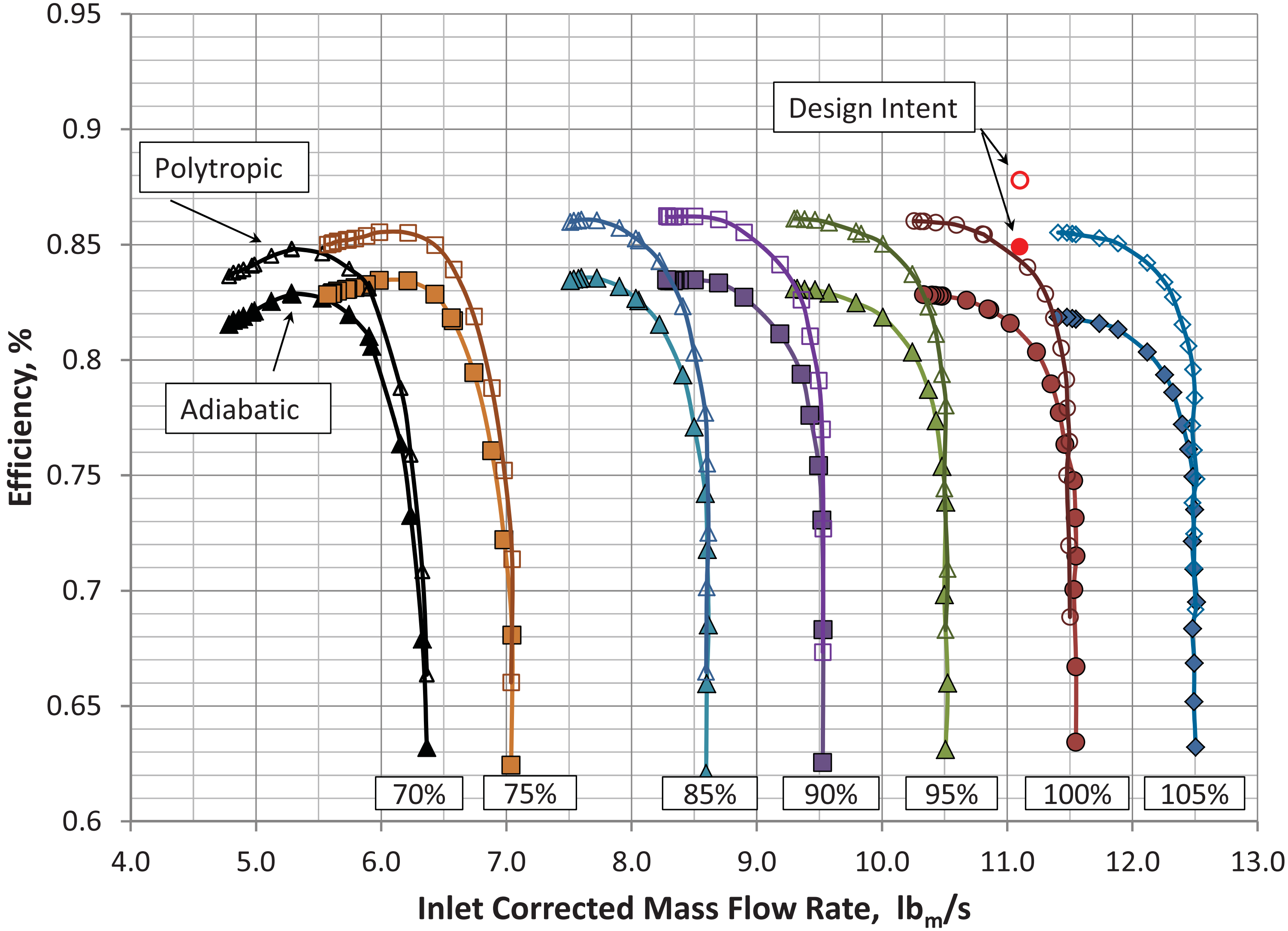
Stage and Subcomponent Results

- Compressor Maps
- Design point performance - comparison of measured vs. predicted
- Representative subcomponent measurements at N_c = 100%

Stage Pressure Ratio vs. Inlet Corrected Mass Flow Rate



Efficiency vs. Inlet Corrected Mass Flow Rate



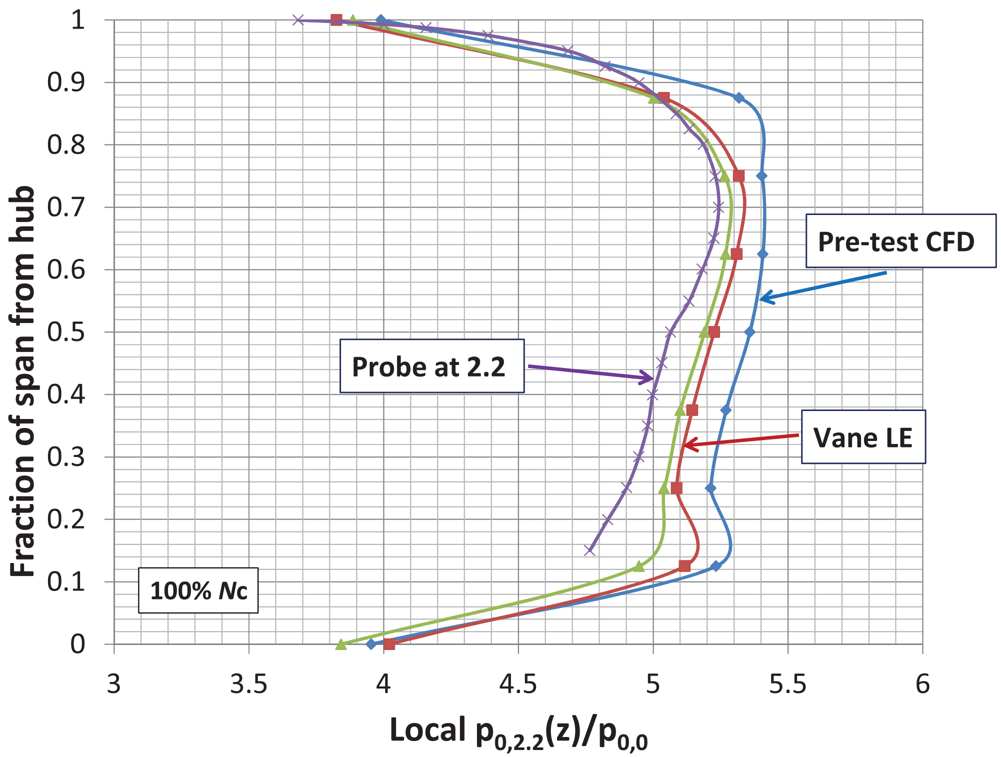
Measured vs. Predicted Performance

(N_c = 100%, $\dot{m}_{c,ex}$ = 3.0 lbm/s, design tip clearance)

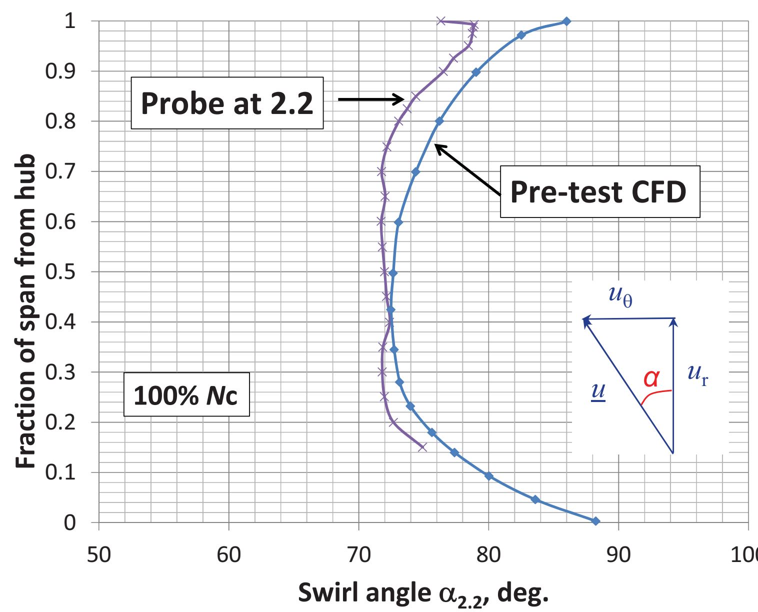
Metric	Design Goal	Rig Scale Design Intent $p_{0,0}$=14.7 psia	Rig Scale Design Intent $p_{0,0}$=11 psia	Measured $p_{0,0}$=11 psia ±Uncertainty (95% Confidence)
Pressure ratio, $p_{0,3}/p_{0,0}$		4.85	4.80	4.68 ± 0.0074
Inlet flow rate, $\dot{m}_{c,in}$, lb_m/s		11.2	11.1	10.85 ± 0.1
Exit flow rate, $\dot{m}_{c,ex}$, lb_m/s	$2.1 < \dot{m}_{c,ex} < 3.1$	2.98	2.98	2.98
Adiabatic efficiency, η_{tt}, %		0.862	0.8495	0.822 ± 0.011
Polytropic efficiency, $\eta_{p,tt}$, %	$\geq$ 0.88	0.888	0.879	0.855
Adiabatic, total pressure to static pressure, η_{ts}, %		0.852	0.8396	0.805
Exit Mach number, M_{ex}	0.15	0.15	0.15	0.18
Exit flow angle, α_{ex}, deg	15°	14°	14°	34.3°
Stability Margin, SM, %	13	12	12	7.5
Work factor	$0.60 < \Delta H_0/U_2^2 < 0.75$	0.7905	0.793	0.81
Diameter ratio	$D_{max}/D_2 \leq 1.45$	1.45	1.45	1.45

Impeller Exit (2.2) and Diffuser Vane LE (2.4)

(N_c = 100%, $\dot{m}_{c,ex}$ = 3.0 lb_m/s)



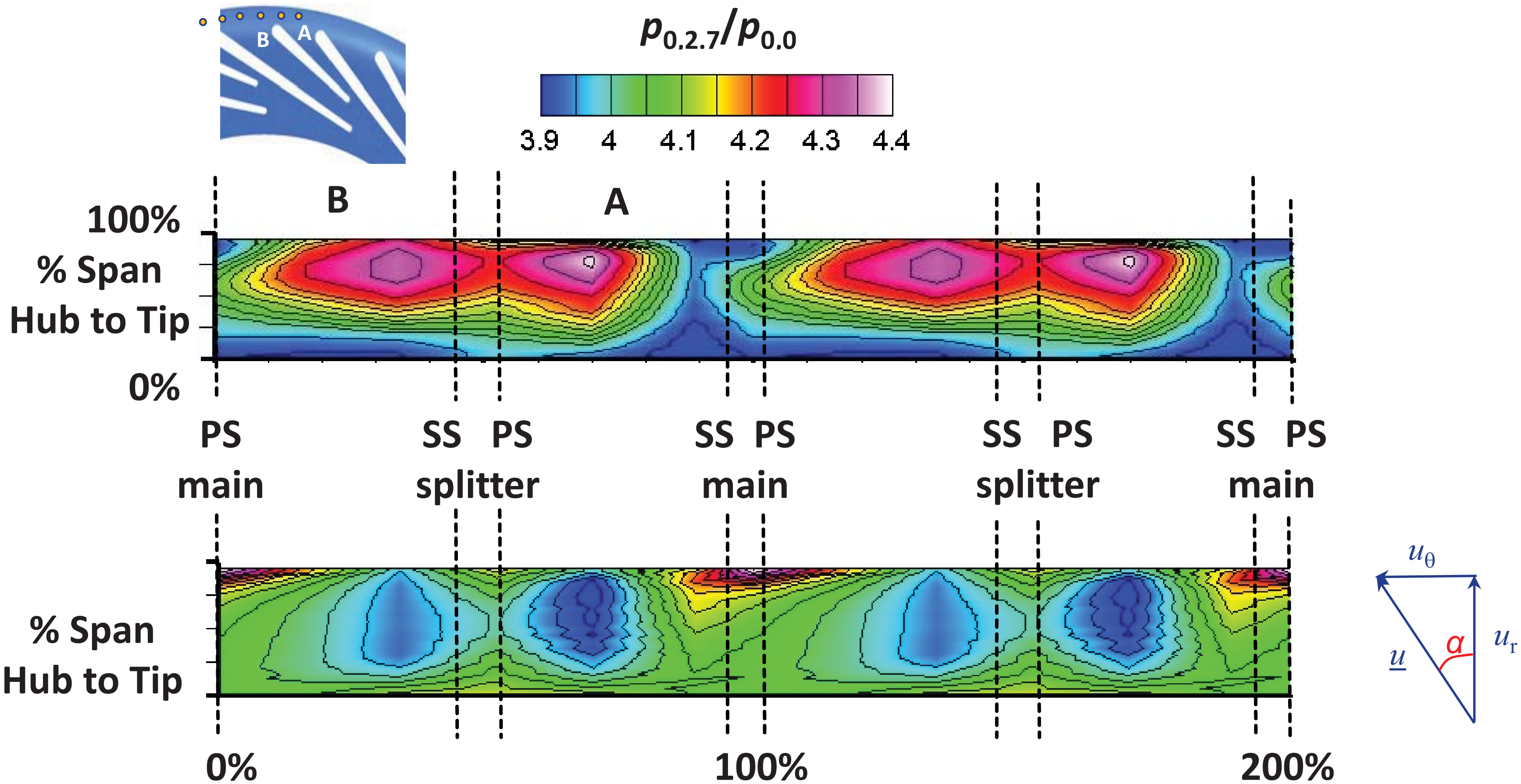
- Measured swirl angle in relatively good agreement



- Vane to vane agreement very good
- Vane LE and CFD in good agreement
- Probe p_0 (at 2.2) lower than vane LE, probe does not adequately resolve the pressure flow field
- Probe (2.2 vaneless space) data only used qualitatively

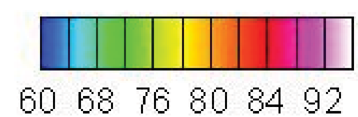
Diffuser Exit Probe Survey Data (2.7)

(N_c = 100%, $\dot{m}_{c,ex}$ = 3.0 lb_m/s)



Flow Angle, Deg.

% Pitch, Main to Main



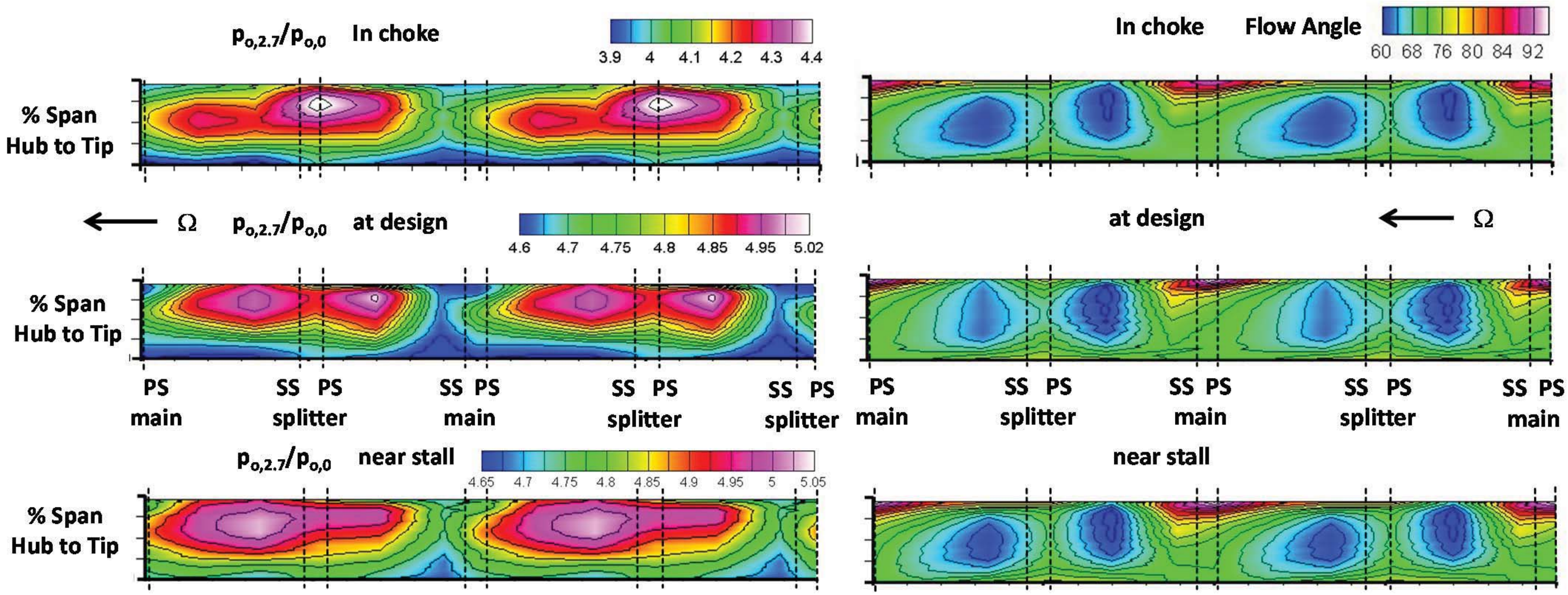
TE Mean Camber Angle

Main = 51 deg

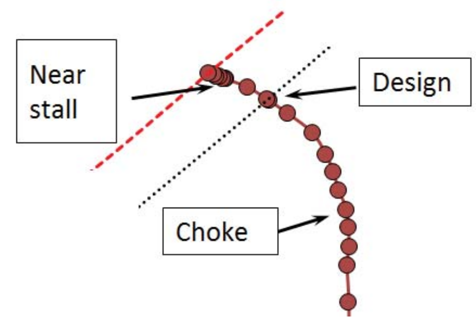
Splitter = 52 deg

← Ω

Diffuser Exit Survey Results vs. Operating Condition (N_c = 100%, Choke, Design, Near-Stall)

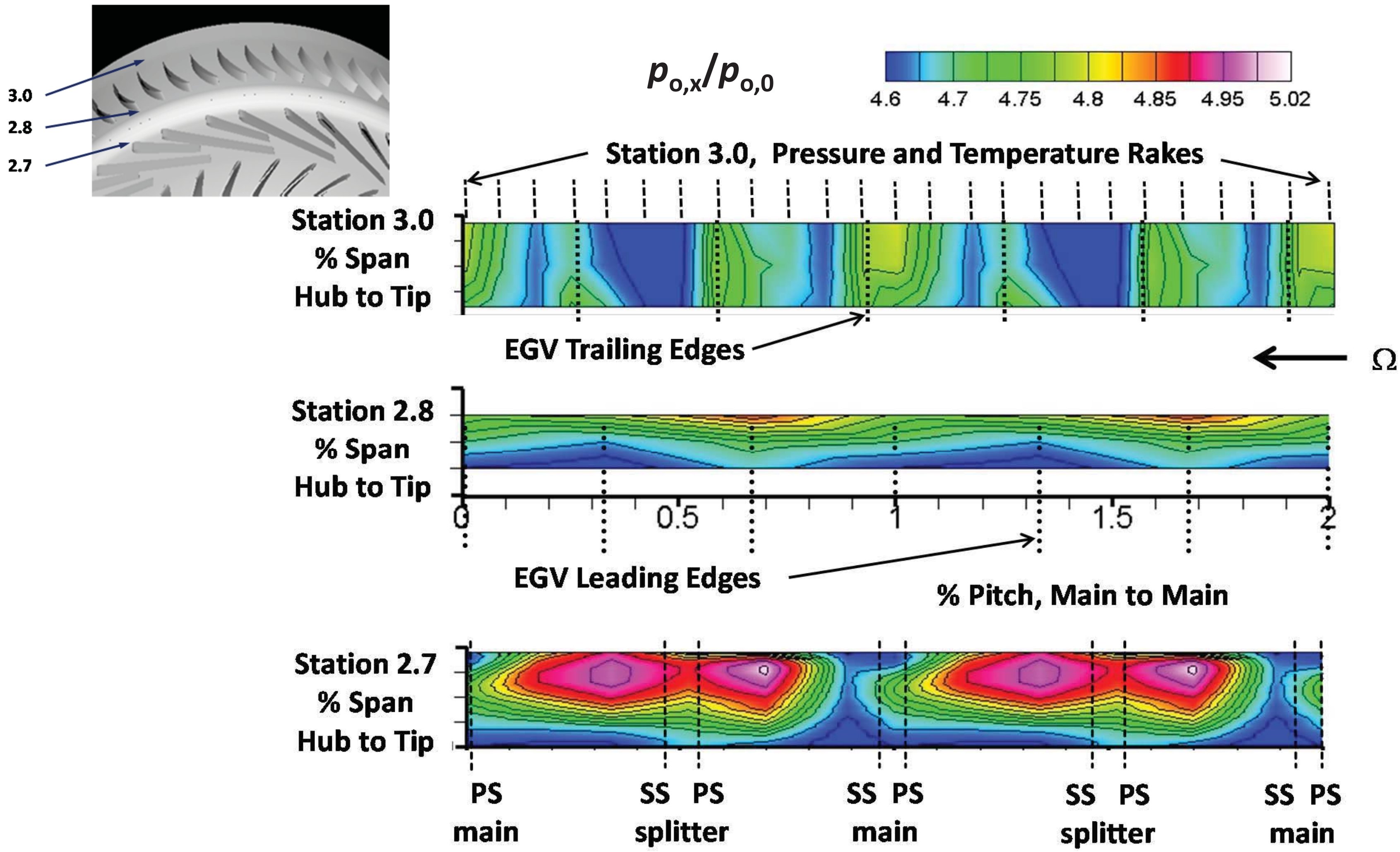


- Flow redistributes as stage is throttled
- High swirl angles at SS main vane could indicate separated flow

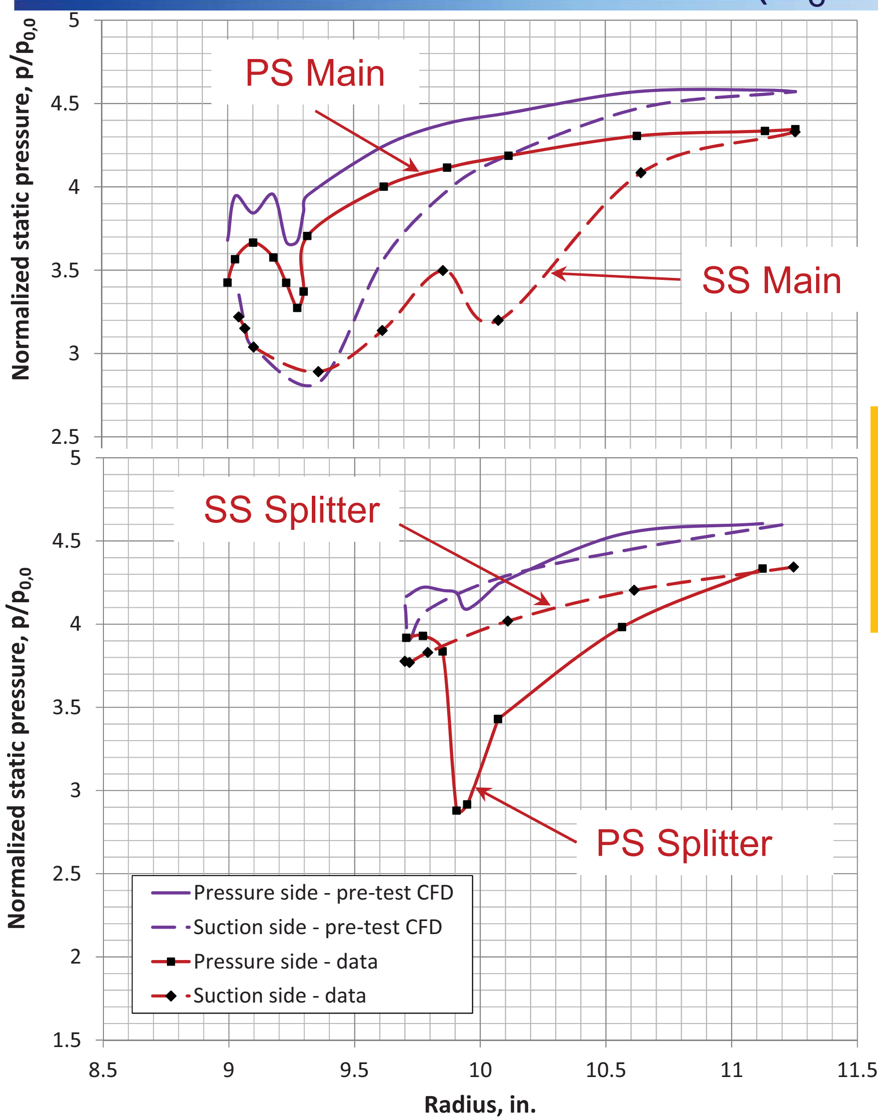


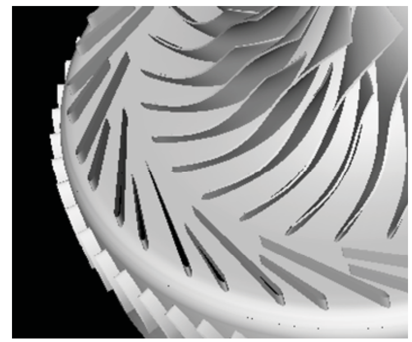
Pressure Contours at Stations 2.7, 2.8, 3.0

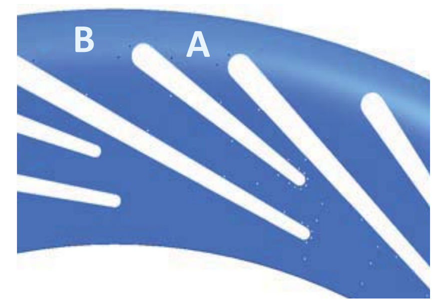
(N_c = 100%, $\dot{m}_{c,ex}$ = 3.0 lb_m/s)



Diffuser Vanes Loading Diagrams-Shroud Static Pressures (N_c=100, near design point CFD)

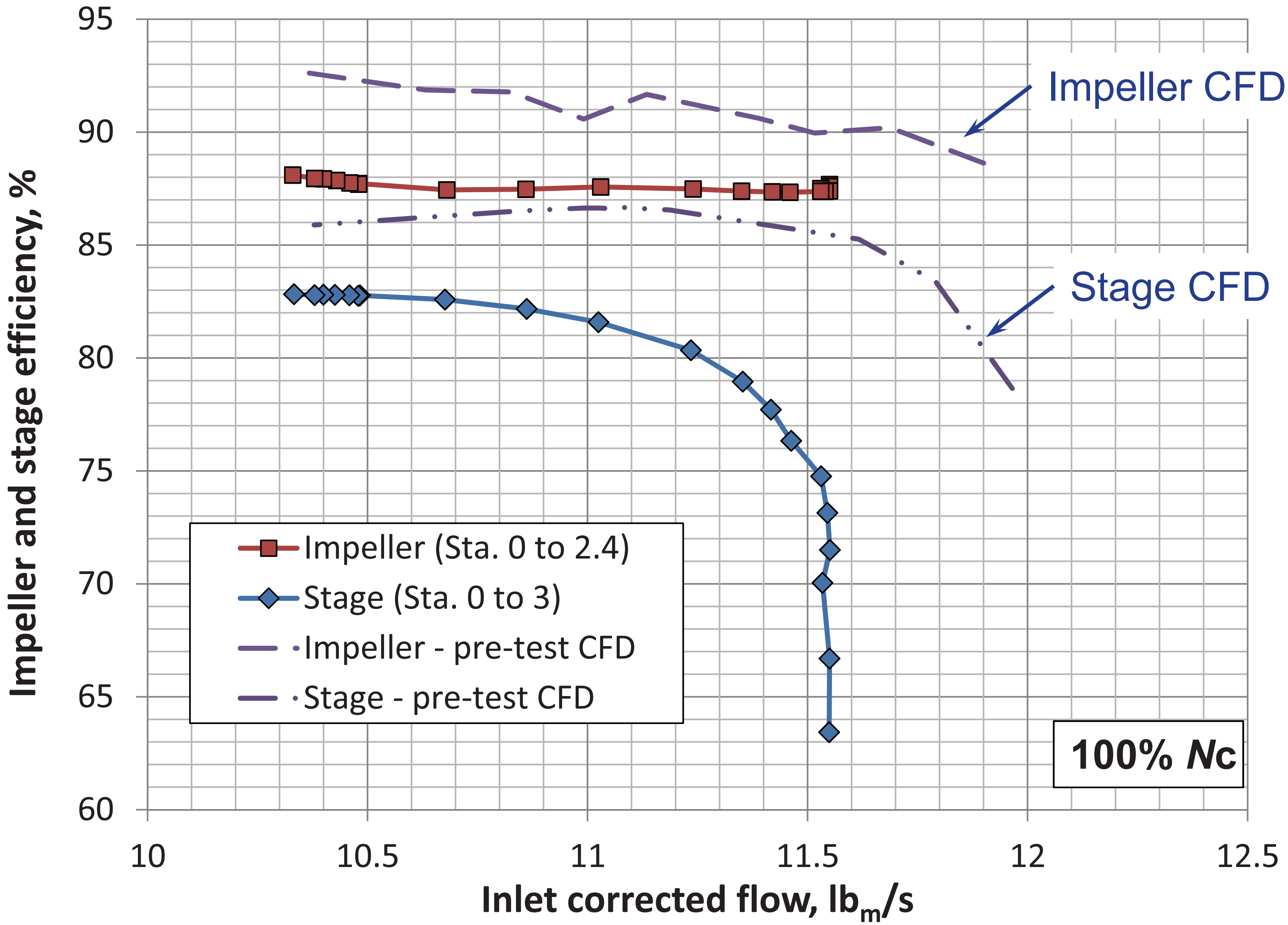






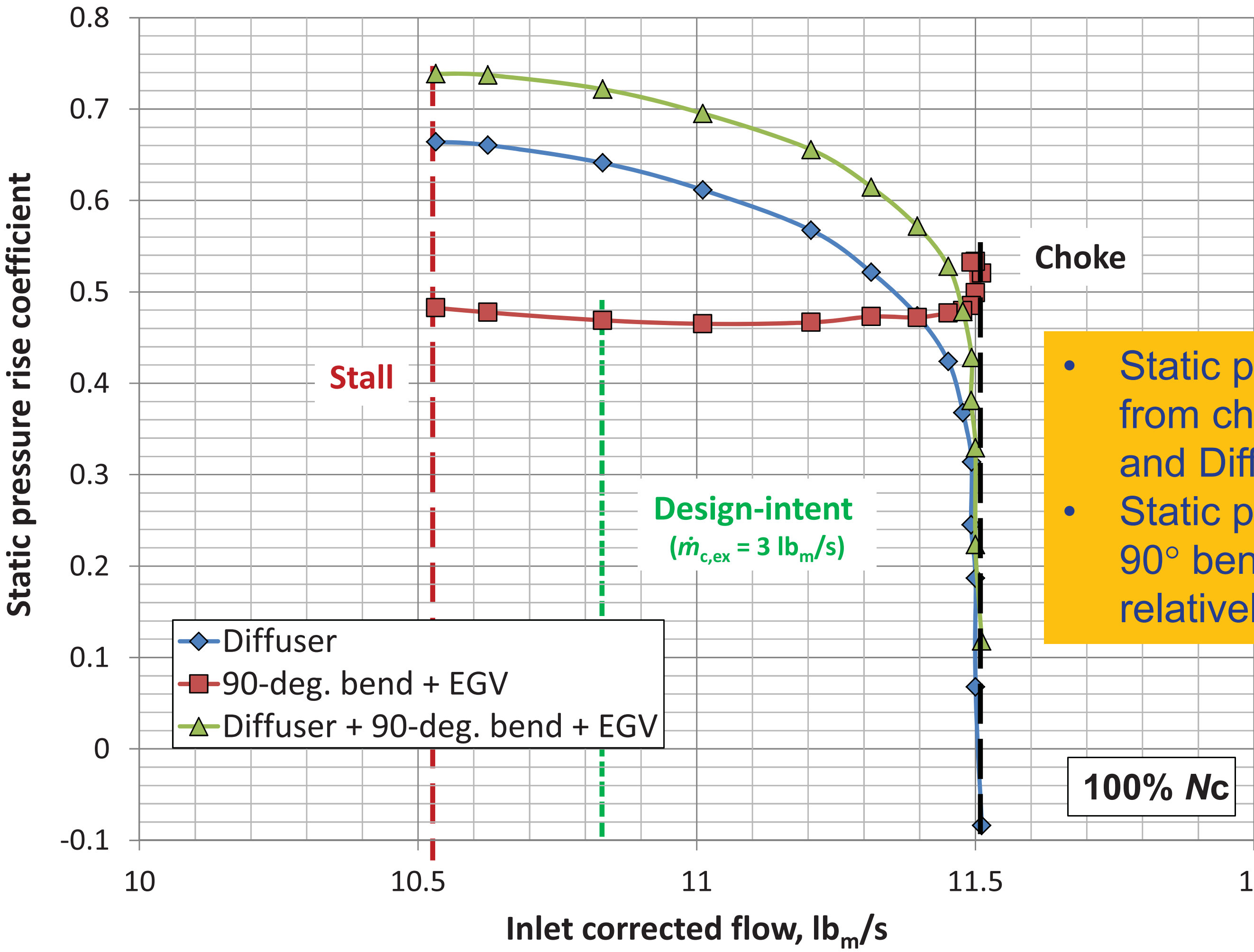
- Overall pressure rise lower than predicted
- Negative loading on splitter indicates operating at large negative incidence vs. lightly loaded design intent

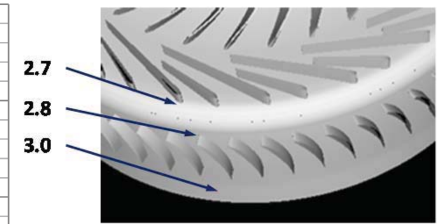
Stage and Impeller Adiabatic Efficiency



Diffusion System Static Pressure Rise

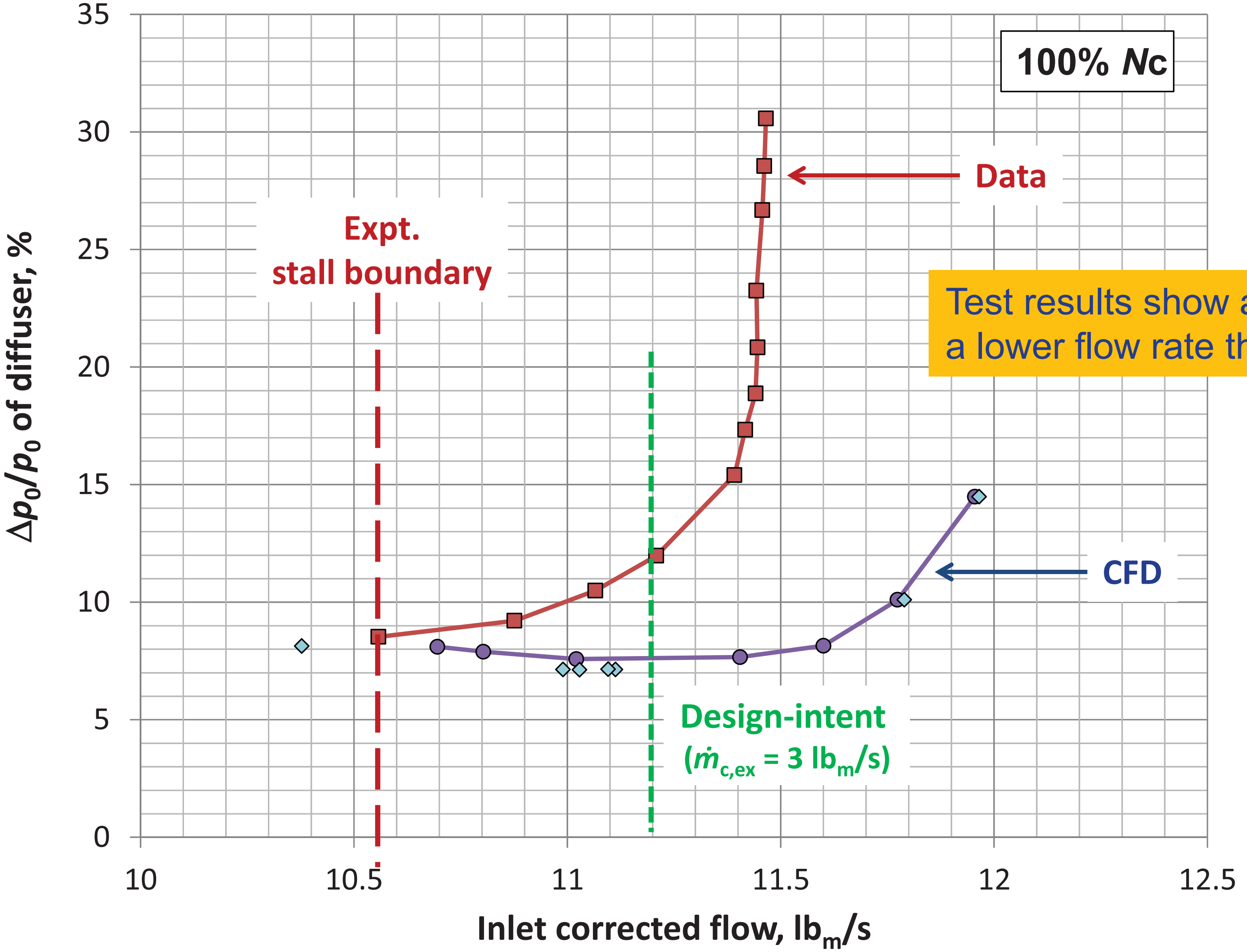
$$c_p = (\bar{p}_{ex} - \bar{p}_{in})/(\bar{p}_{0,in} - \bar{p}_{in})$$





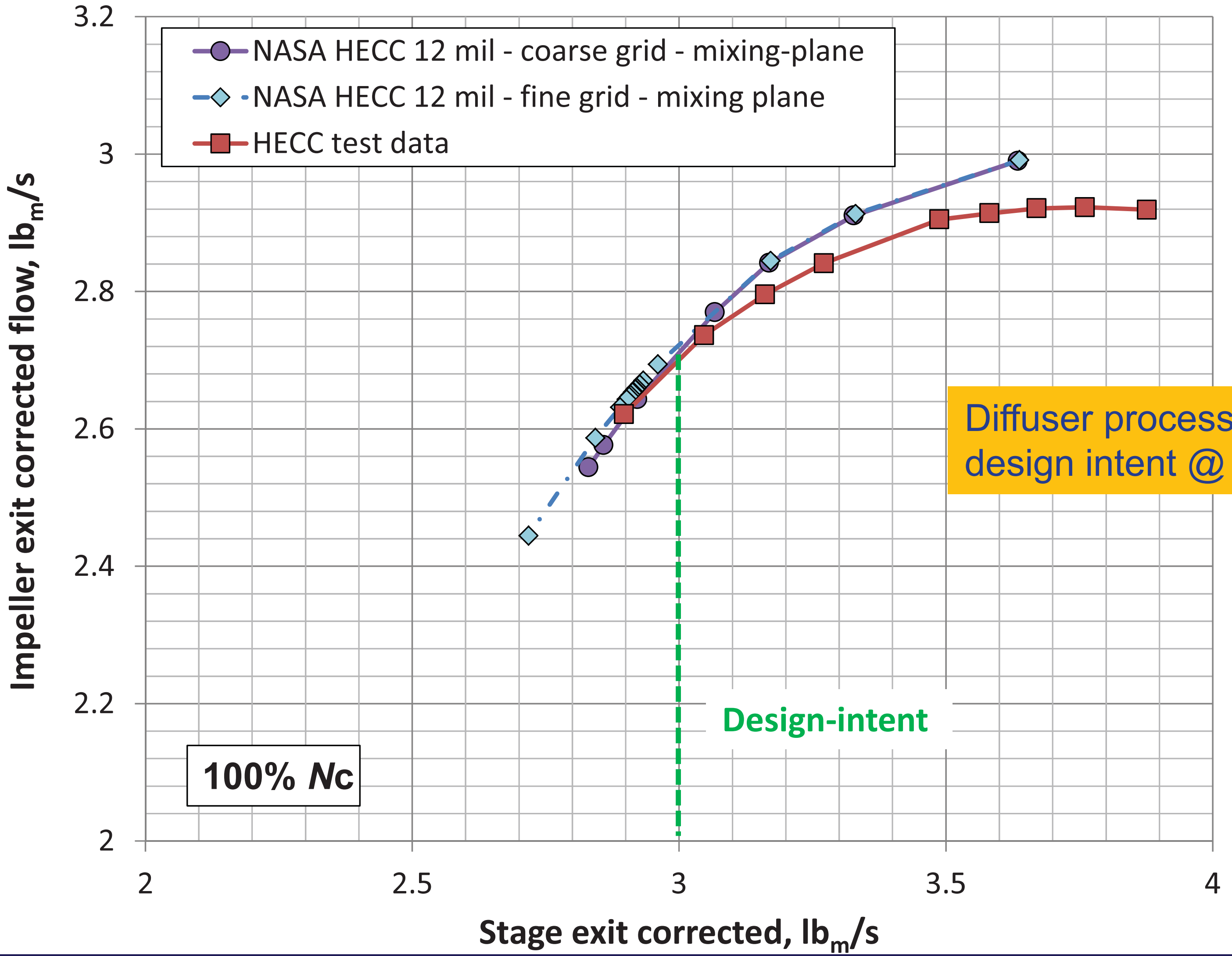
- Static pressure rise increases from choke to stall (Diffuser and Diffuser+Bend+EGV)
- Static pressure rise across 90° bend and EGV is relatively constant

Diffuser Loss Bucket



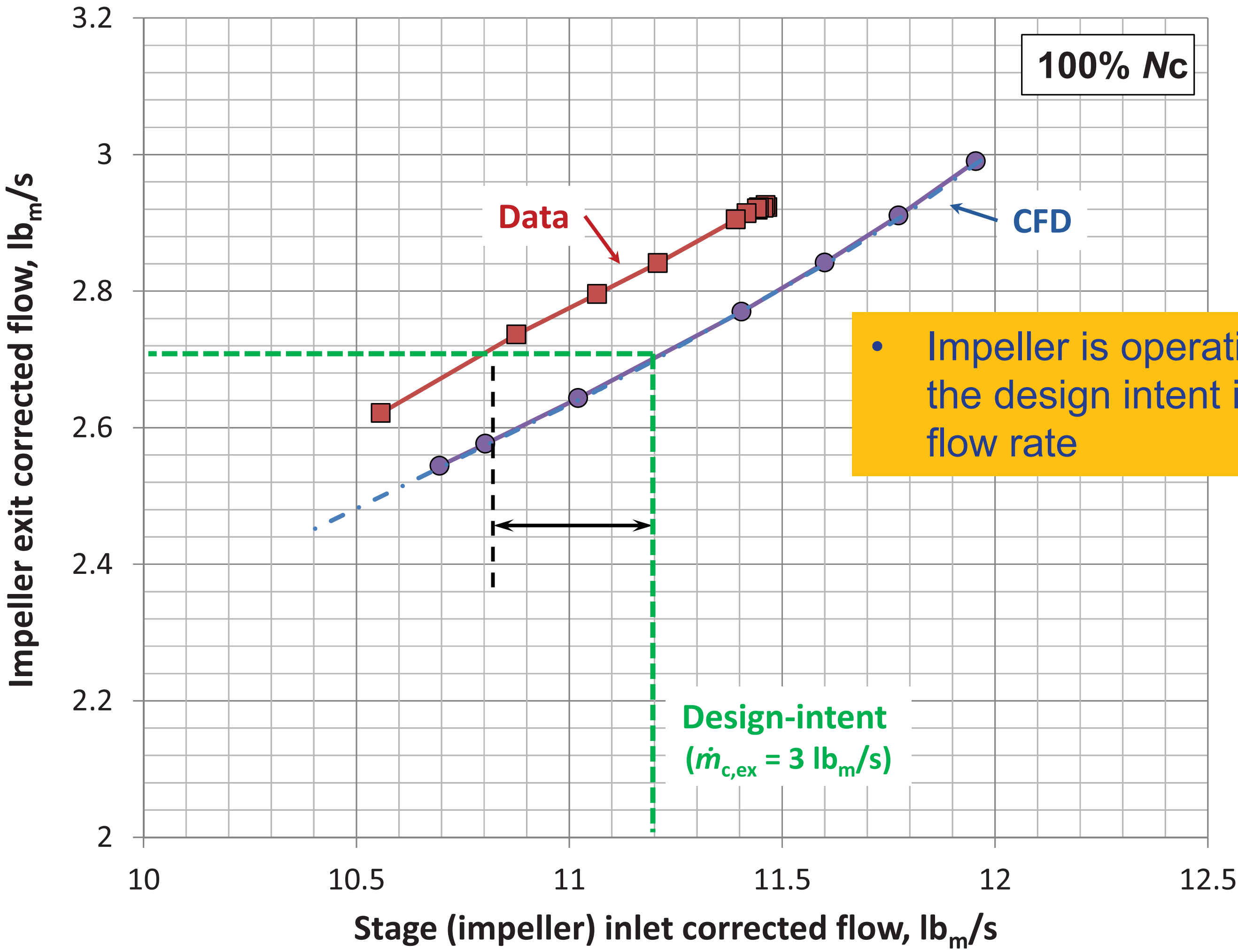
Test results show a minimum loss at a lower flow rate than design intent

Diffuser Corrected Flow Characteristic



Diffuser processes flow as per design intent @ $\dot{m}_{c,ex}$=3.0 lb_m/s

Impeller Corrected Flow Characteristic



- Impeller is operating at a lower $\dot{m}_{c,in}$ at the design intent impeller exit correct flow rate

Summary

- Aerodynamic performance of an advanced, compact, high work-factor centrifugal compressor stage was presented
- Stage performance and stability were lower than design intent
  - Adiabatic Efficiency by 2.75 pts., mass flow by 2.25%, and Stability Margin by 4.5 pts.
- Differences in predicted and measured impeller efficiency, impeller flow characteristics, and diffuser loss buckets were observed.
- Root-cause-analysis of the performance shortfall was initiated within the NRA contract. Analyses continue with intent to guide future design efforts.

Comprehensive data sets and geometry to be made publically available

Acknowledgements

United Technologies Research Center

Drs. Joo Jongwook
Larry Hardin
Duane McCormick
William Cousins
Brian Holley
Paul Van Slooten
Elizabeth Lurie
Aamir Shabbir

NASA

Dr. Michael Hathaway
Mark Stevens
Jonathon Mitchel
Jozsef Puskas
Adam Redding
David Haydu
Richard Senyitko

Design Review Team

ARL, Air Force Research Laboratory, AATD, NAVAIR