Summary of Recent Inducer Testing at MSFC and Future Plans

2003 Thermal and Fluids Analysis Workshop

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NASA/Marshall Space Flight Center

Agenda

- Water Flow Test History
- Water Test Facility
- Recent
  - Inducer Hydrodynamic Forces
  - RS-83 Main Lox Inducer Performance
- Current and Future
  - RS-84 Main Lox Inducer Performance and Blade Loads
  - Pump Dynamic Transfer Functions: Mass Flow Gain and Cavitation Compliance
- Test Team

Water Flow Test History

1987 to 1988: SSME Fuel Pump Inlet Tests, Passive and Active

1990: SSME Lox Pump Radial Sideloads

1992: Inducer Test Loop (ITL) Operational

1992: SSME High-Pressure Lox Inducer Synchronous Vibration

1995: Pump Test Equipment (PTE) Operational

1995 to 1998: Alternate SSME Fuel Pump Impeller (6 Designs)

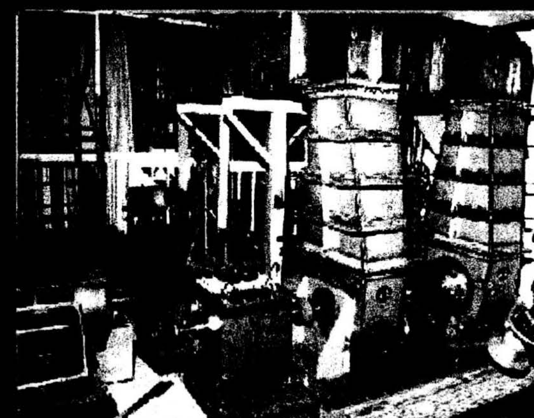
1995: SSME High-Pressure Lox Inducer Blade Loads

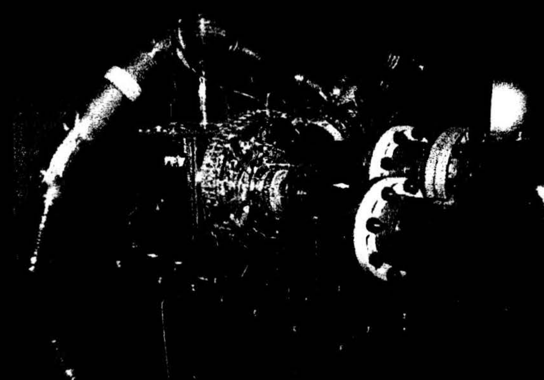
1996: SSME High-Pressure Lox Inducer Tip Clearance Effects

1997 to 1998: 2nd Source Lox Inducer and Modified Inlet Vane

SSME High-Pressure Fuel Pump Inlet

SSME Lox Pump Radial Sideloads





SSME High-Pressure Lox Inducer

Instrumented SSME High-Pressure Lox Inducer

Water Flow Test History

1999: Fastrac/MC-1 Lox Pump

2000: Simplex Lox Pump Inducer

2000 to 2001: Baseline Unshrouded Impeller Tip Clearance Effects

2001: Advanced Unshrouded Impeller Tip Clearance Effects

2001: Cavitation-Induced Hydrodynamic Forces

2002: Inducer Test Loop Upgraded

2002: RS-83 Main Lox Pump Inducer

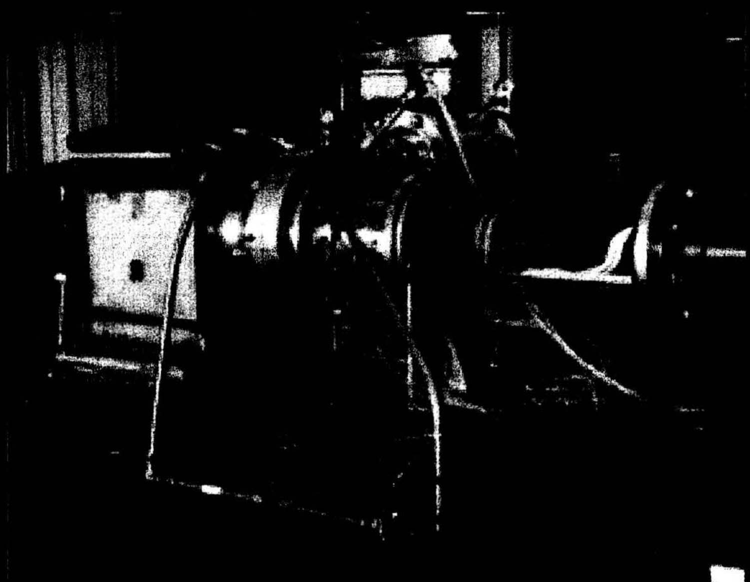
2003: COBRA Low Pressure Lox Pump

2003: RS-84 Main Lox Pump Inducer

2004: RS-84 Main Lox Inducer Blade Loads

Simplex Inducer

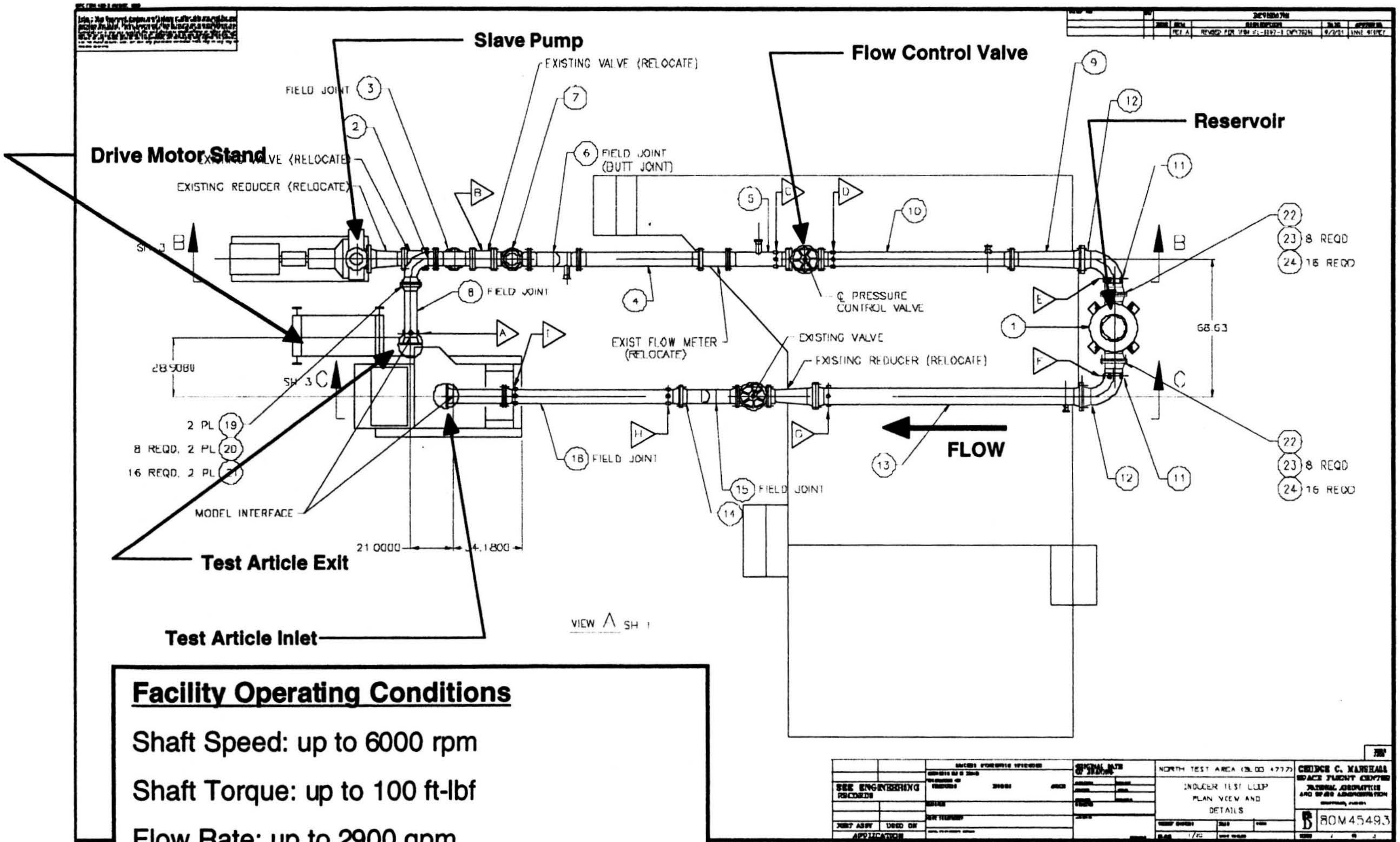
SSME High-Pressure Lox Inducer



Fastrac/MC-1 Lox Pump

Water Test Facility

Water Test Facility



Facility Operating Conditions

Shaft Speed: up to 6000 rpm

Shaft Torque: up to 100 ft-lbf

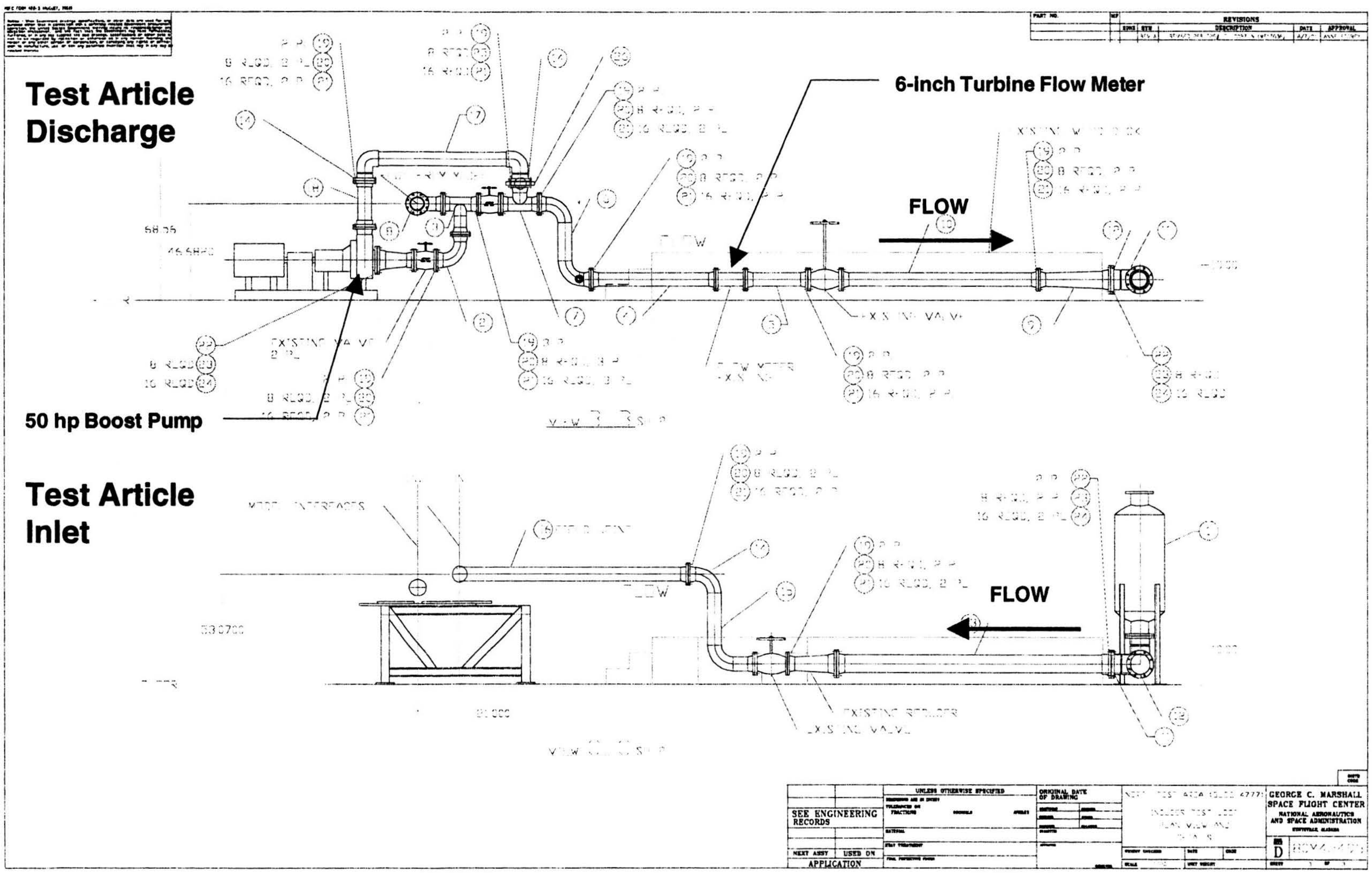
Flow Rate: up to 2900 gpm

Inlet Pressure: 3 to 50 psia

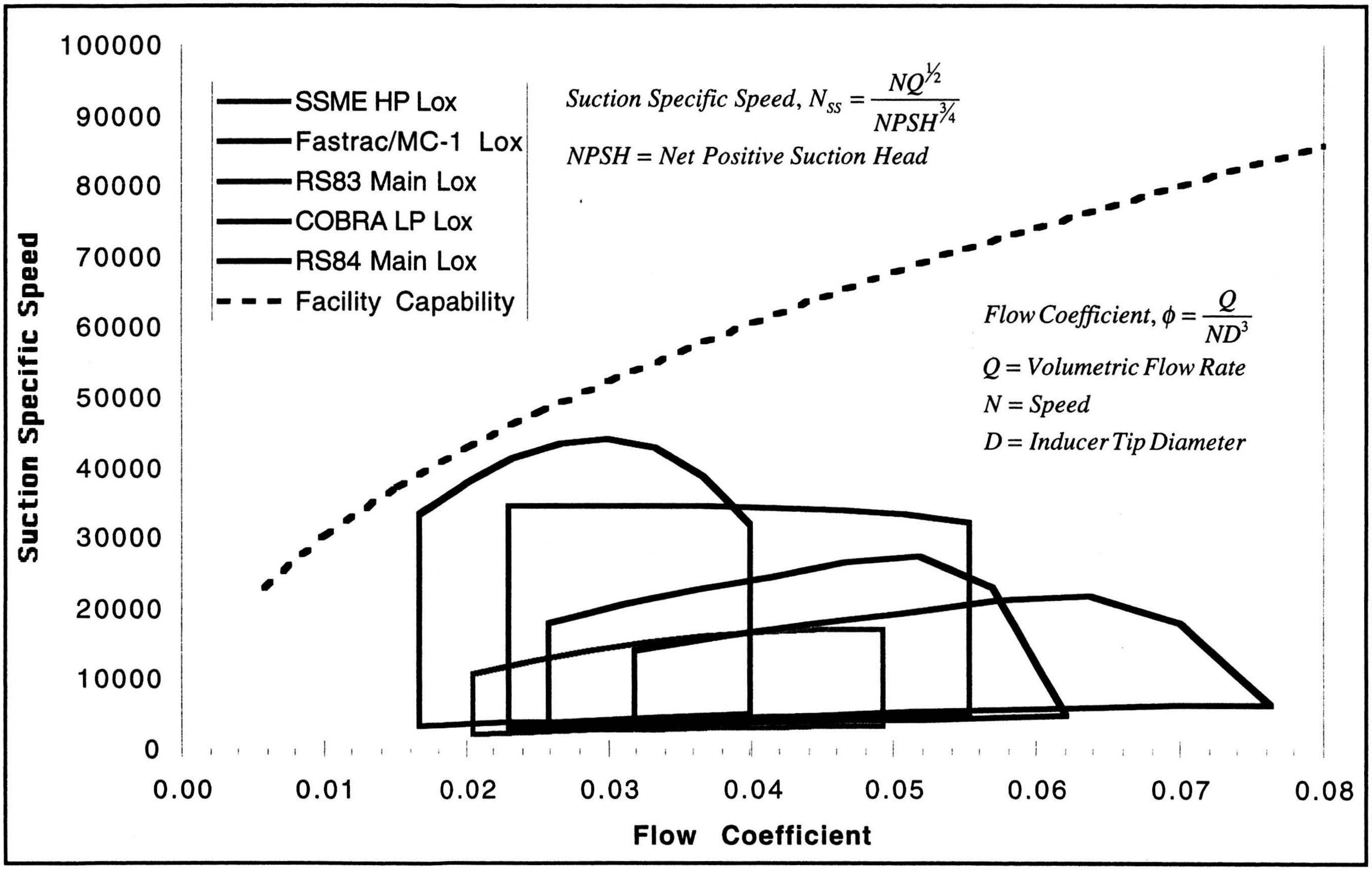
Discharge Pressure: up to 375 psia

Water Temperature: 60 to 120 deg F

Water Test Facility

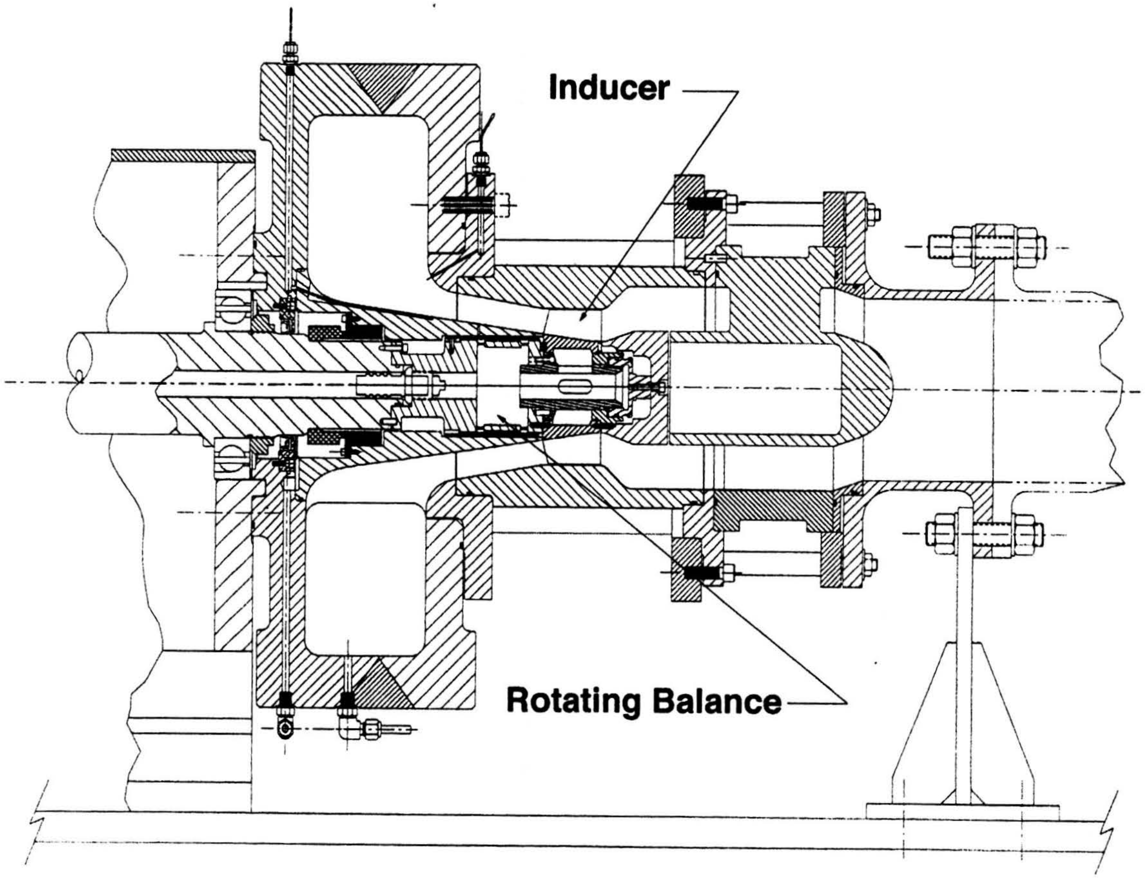


Water Test Facility

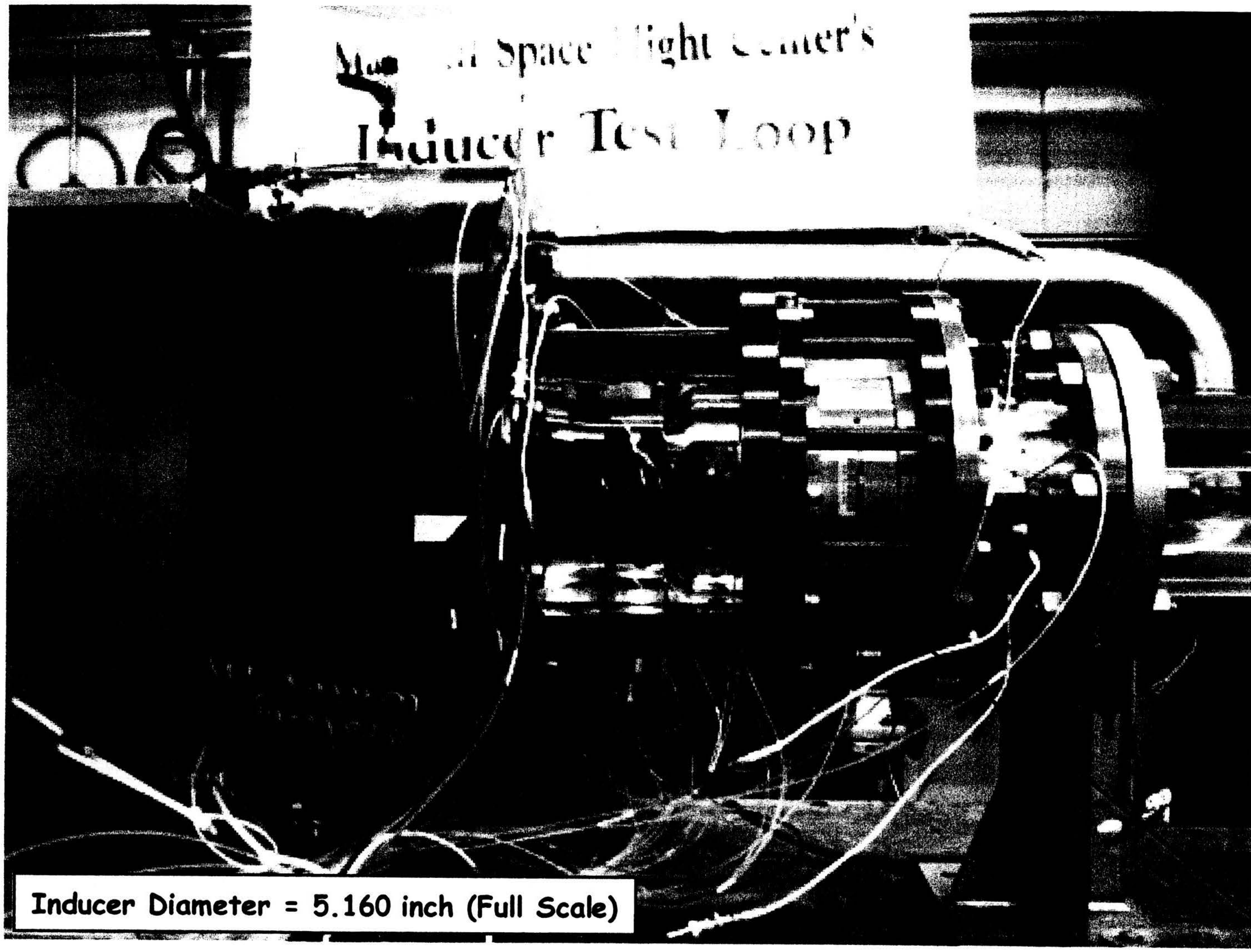


Inducer Hydrodynamic Forces

- 6-component force and moment measurement device ("Rotating Balance") validated in water at engine-equivalent operating conditions with the SSME high-pressure Lox inducer.



Inducer Hydrodynamic Forces

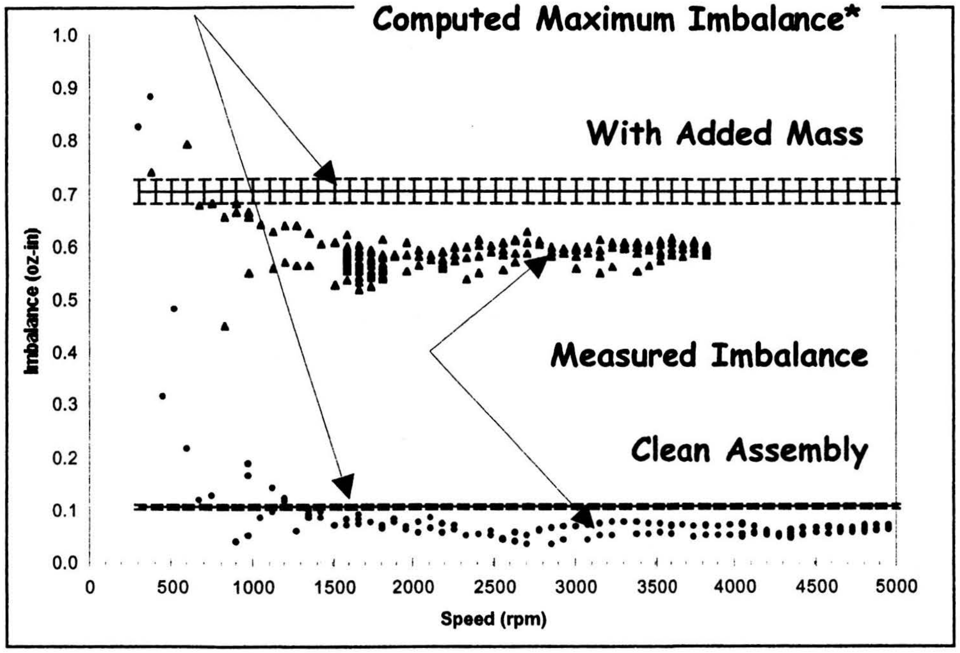


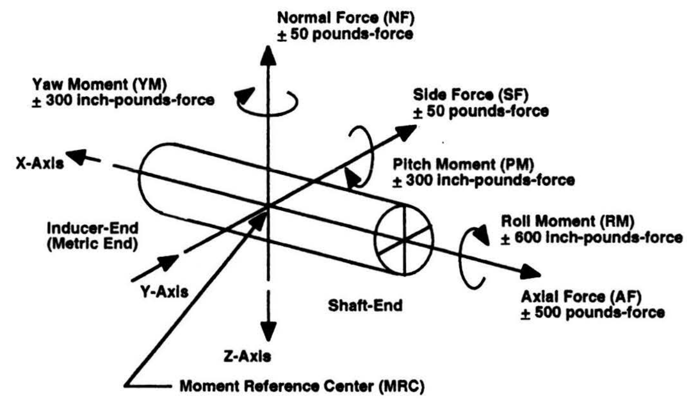
Inducer Diameter = 5.160 inch (Full Scale)

Inlet guide vane assembly used to simulate volute exit condition (proper radial velocity gradient and incidence) in axial configuration.

Inducer Hydrodynamic Forces

- Sensitivity confirmed by directly measuring imbalance in air and buoyancy in water.

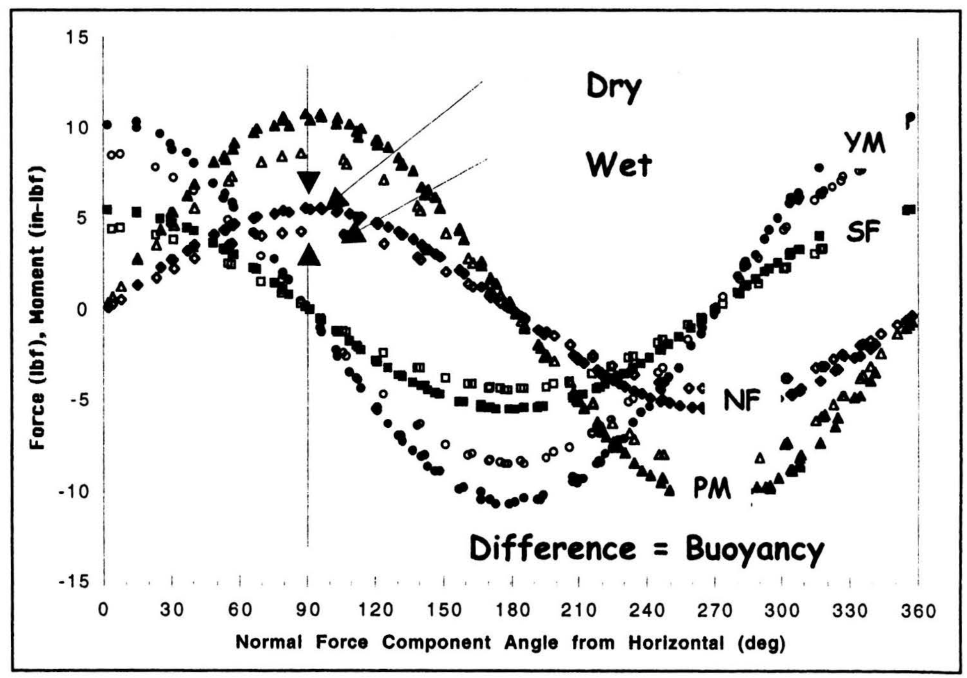




Measured Imbalance = 0.058 ± 0.015 oz-in
Difference (Added Mass - Clean) = 0.596 ± 0.023 oz-in
Expected Difference = 0.596 ± 0.022 oz-in

*Includes piece-part allowable imbalance, assembly misalignment, etc.

Measured buoyancy = 1.12 ± 0.26 lbf
Computed buoyancy = 1.27 lbf

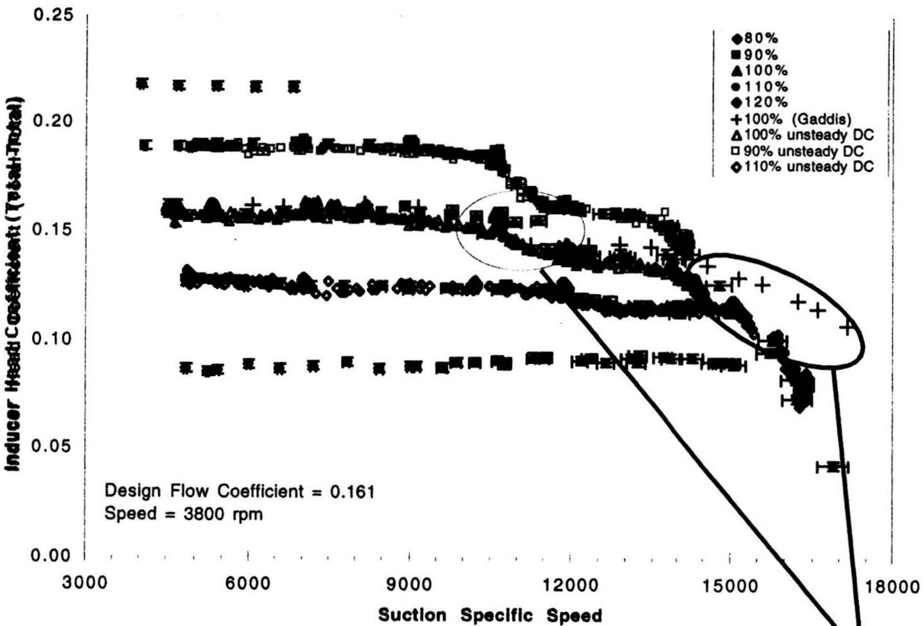


Inducer Hydrodynamic Forces

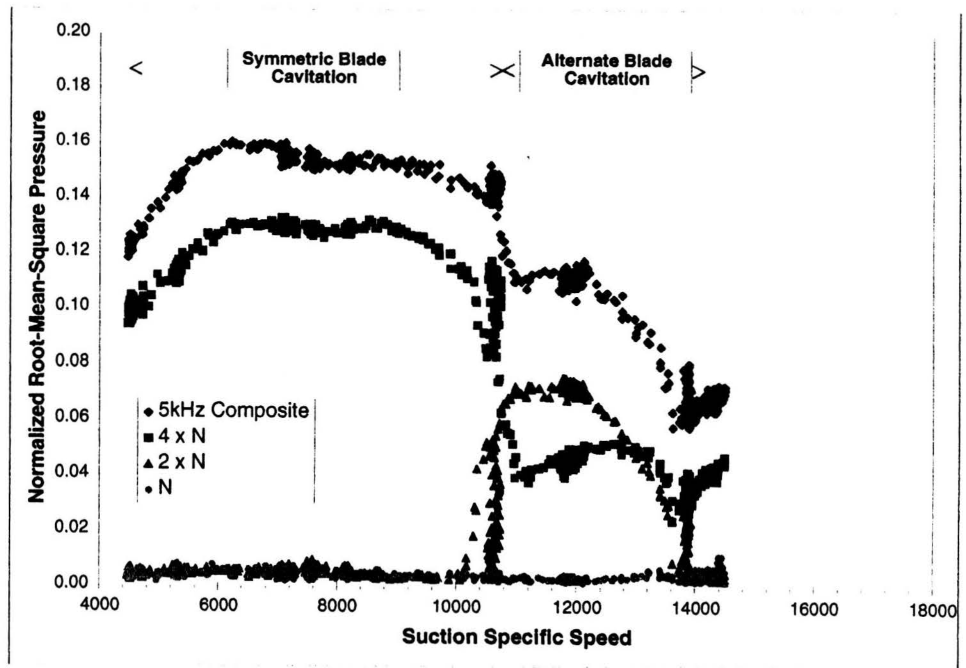
- Inducer steady and unsteady performance consistent with previous experimental tests.
- Observed cavitation modes for the 4-bladed inducer: symmetric tip vortex, alternate blade, and indications of "higher-order" cavitation.

$$Head\ Coefficient = \frac{Total\ Pressure\ Rise}{\rho U_{Tip}^2}$$

$$Normalized\ Flow\ Coefficient = \frac{\phi}{\phi_{Design\ Point}}$$



Slight difference on onset of alternate blade cavitation and slope attributed to inlet condition - guide vane simulator versus "baby pants" inlet volute.



Inducer Hydrodynamic Forces

- Cavitation modes captured on strobed SVHS and high-speed video tape.

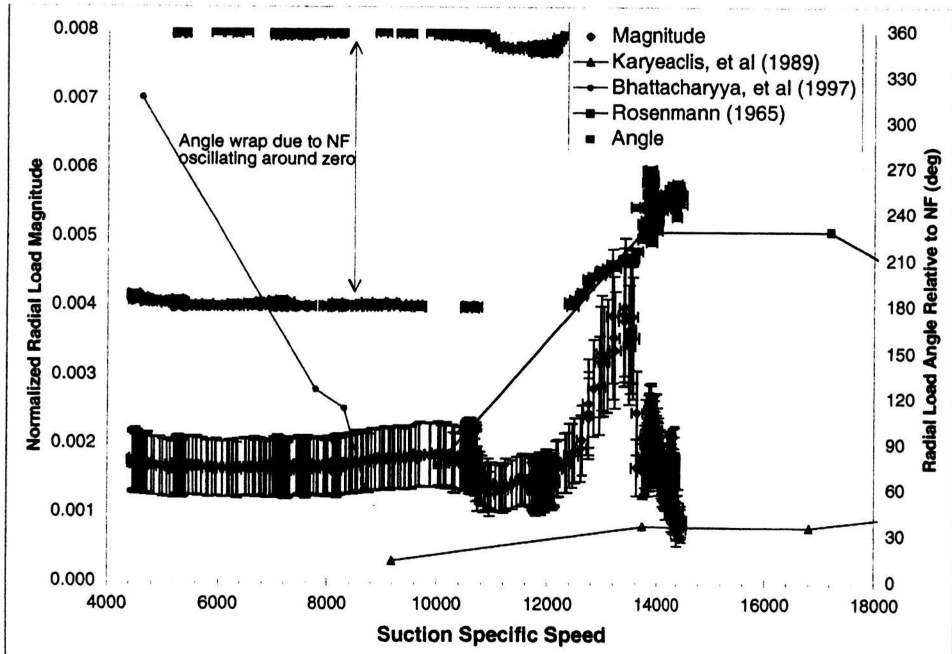
FLOW

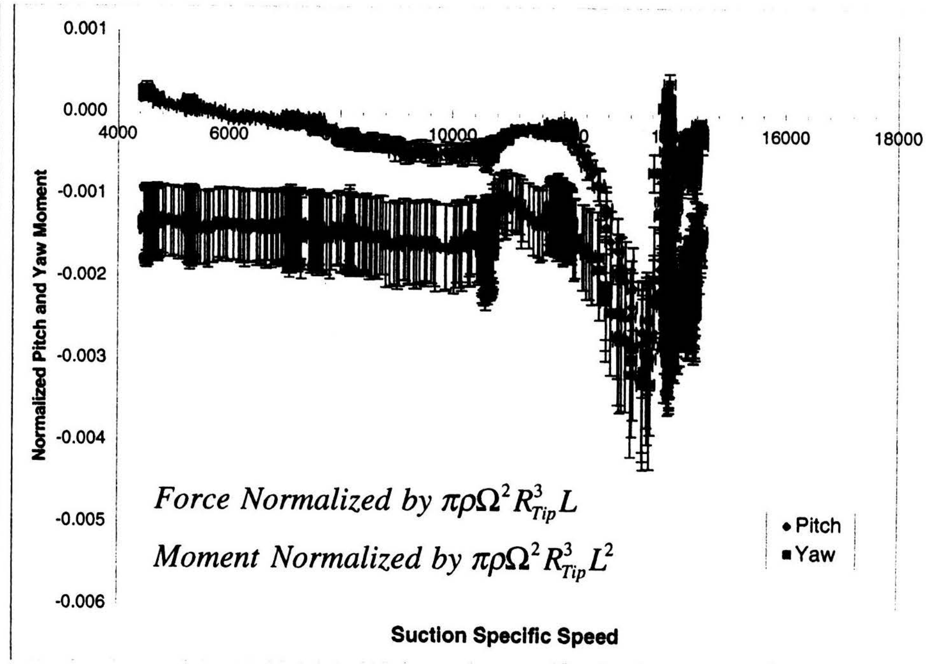
Direction of Rotation

Frame Rate = 30 fps
Speed = 4200 rpm

Inducer Hydrodynamic Forces

- Radial force magnitude and angle relative to inducer sensitive to cavitation mode.
- Radial force magnitude comparable to similar experimental investigations of 3 and 4-bladed inducers.
- Shifting pitch and yaw moment consistent with leading edges "unloading" and center of pressure moving axially with increasing cavitation intensity.

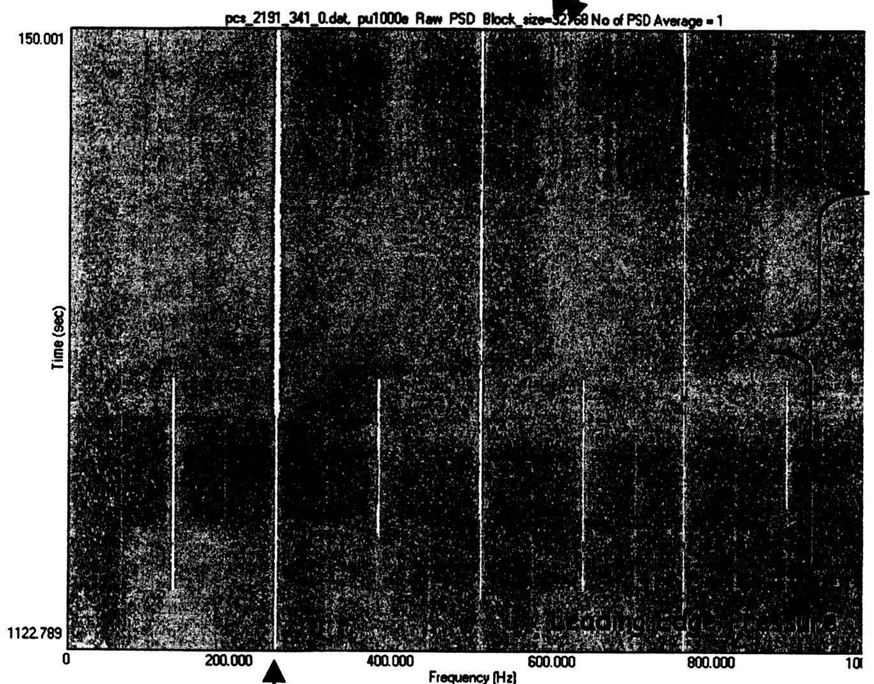




Inducer Hydrodynamic Forces

Simultaneous Single-Cell Rotating Disturbances at 8.7N and 10.2N Moving in Opposing Directions "Higher-Order Cavitation"

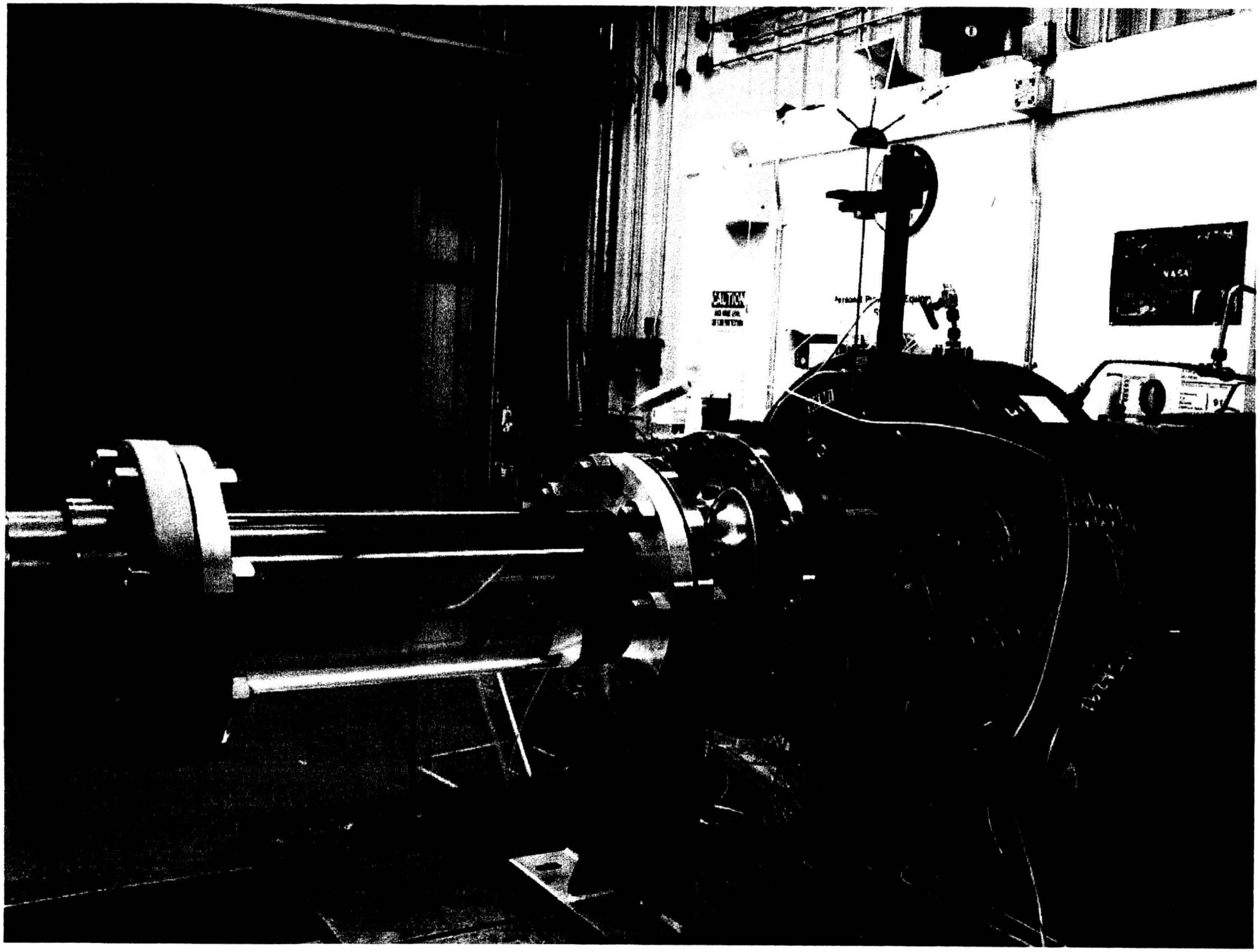
Structural Bending Mode "Split" with Forward and Backward Propagation



4 x Blade Pass (4N) in Stationary Frame

7 x Blade Pass (7N) in Rotating Frame

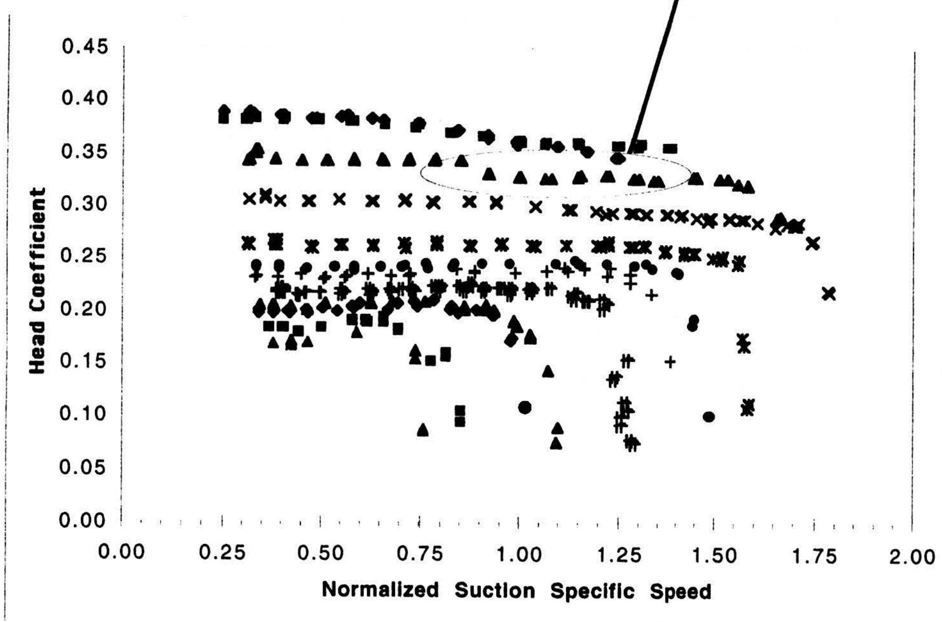
RS-83 Main Lox Inducer



RS-83 Main Lox Inducer

- Objectives: Measure Head Rise, Exit Swirl, Hydraulic Efficiency, Suction Capability, and Unsteady Environment versus Flow Coefficient.

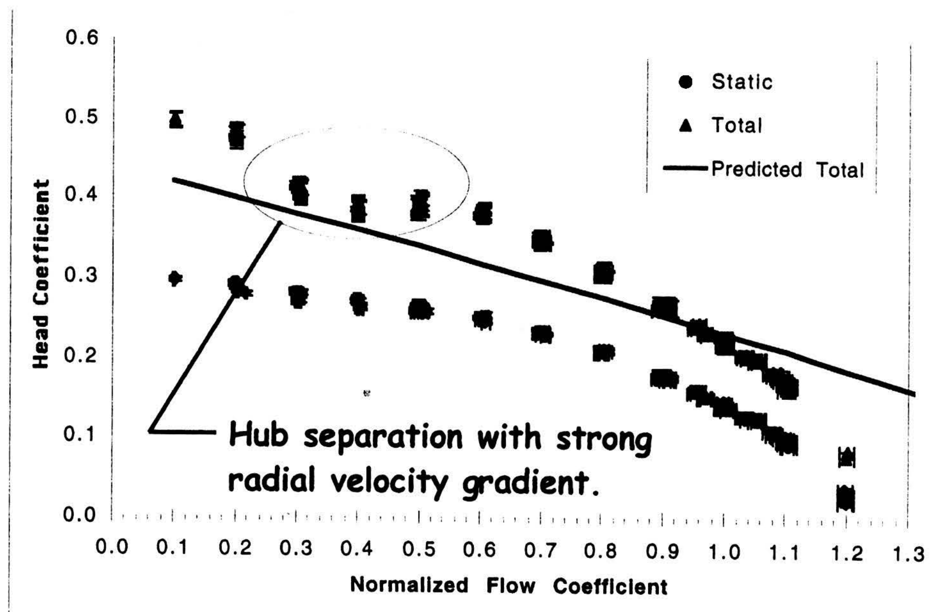
Rotating cavitation appeared as a 5% drop in inducer steady-state head rise.



$$Normalized\ Suction\ Specific\ Speed = \frac{Nss}{Nss_{Design\ Point}}$$

$$Head\ Coefficient = \frac{Total\ Pressure\ Rise}{\rho U_{Tip}^2}$$

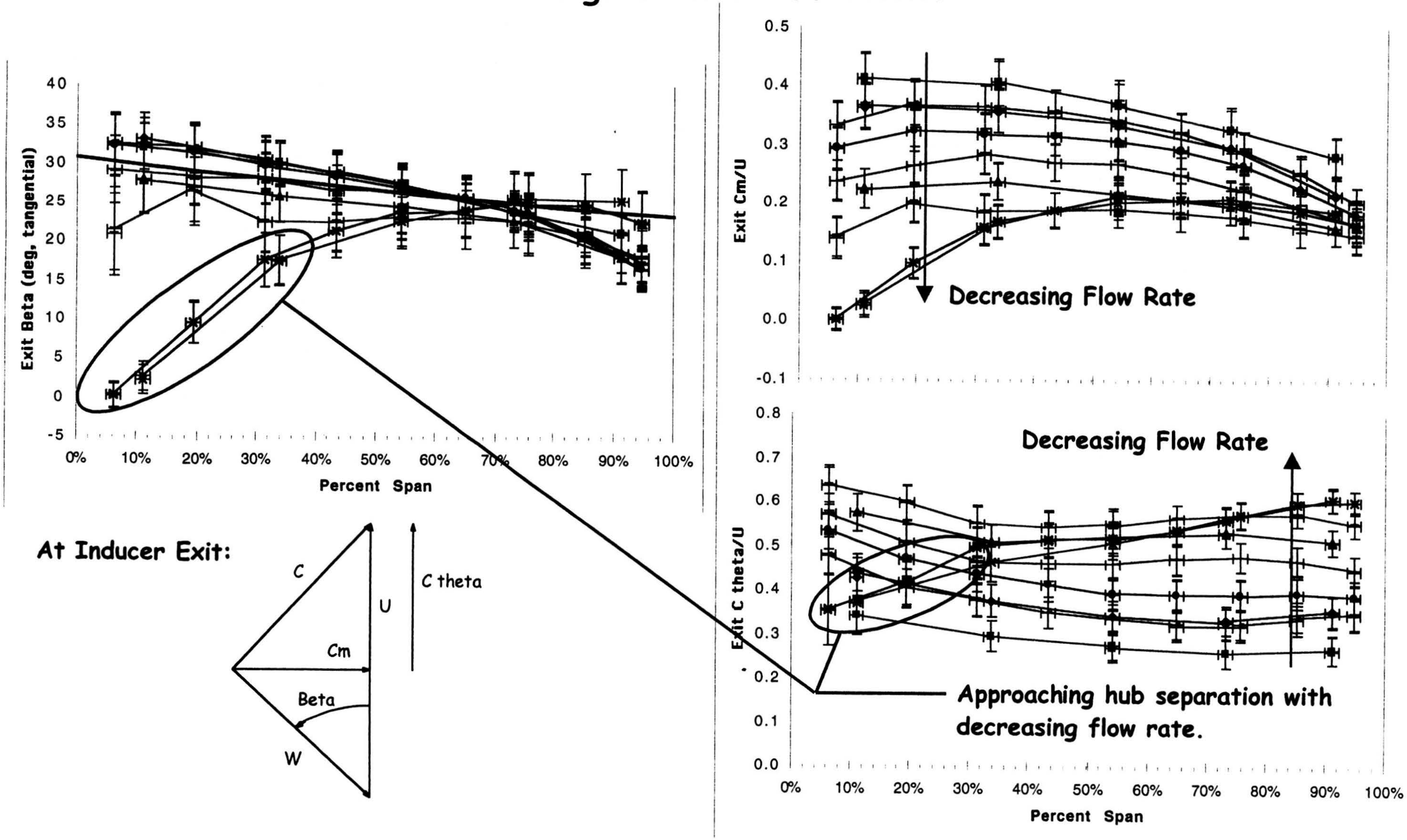
$$Normalized\ Flow\ Coefficient = \frac{\phi}{\phi_{Design\ Point}}$$



Hub separation with strong radial velocity gradient.

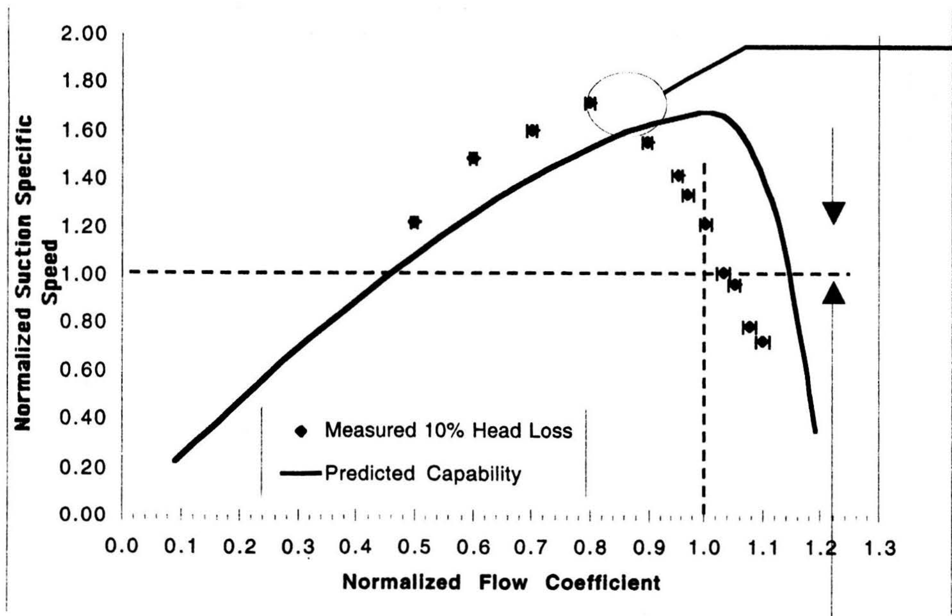
RS-83 Main Lox Inducer

- Small measured deviation with exit flow closely following blade at and near design flow coefficient.

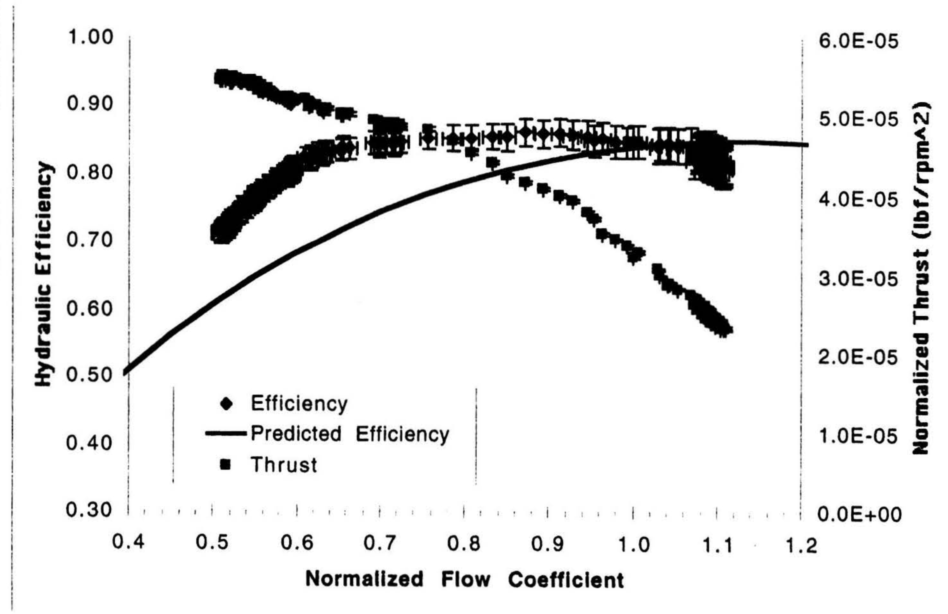


RS-83 Main Lox Inducer

- Suction capability trend consistent with predicted although peak performance shifted to lower flow coefficient.
- Measured efficiency relatively uniform with flow coefficient and equal to predicted at design point.

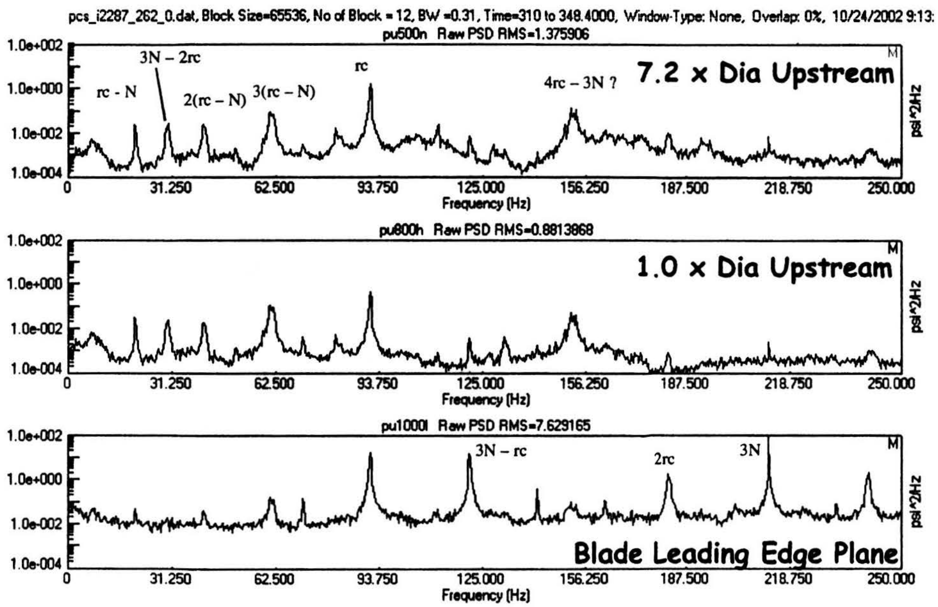


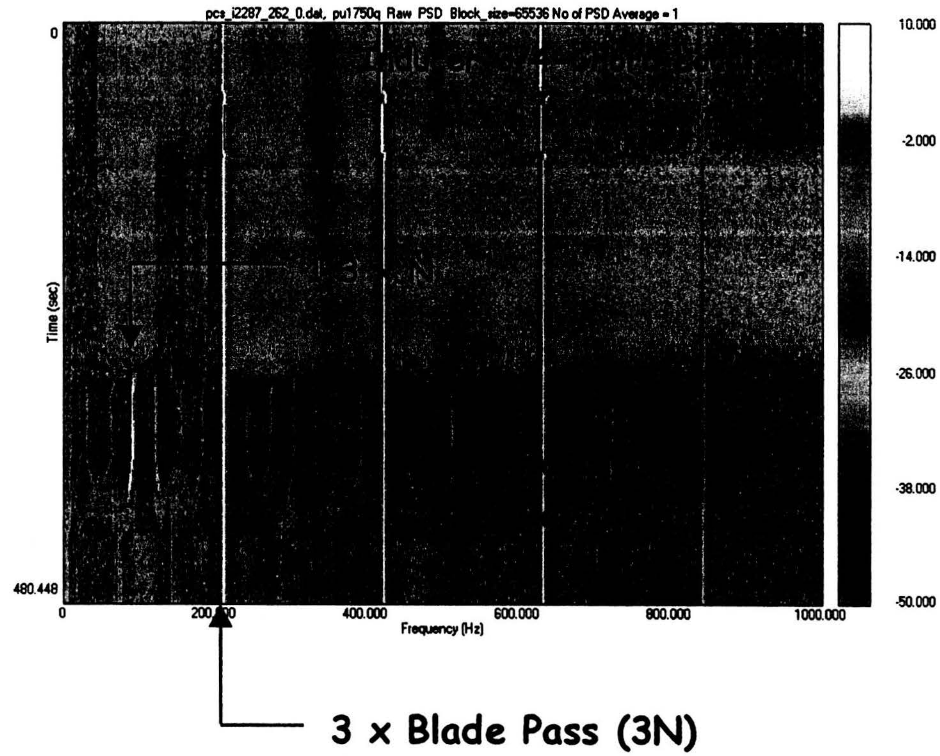
NPSH margin = 23% at design flow coefficient



RS-83 Main Lox Inducer

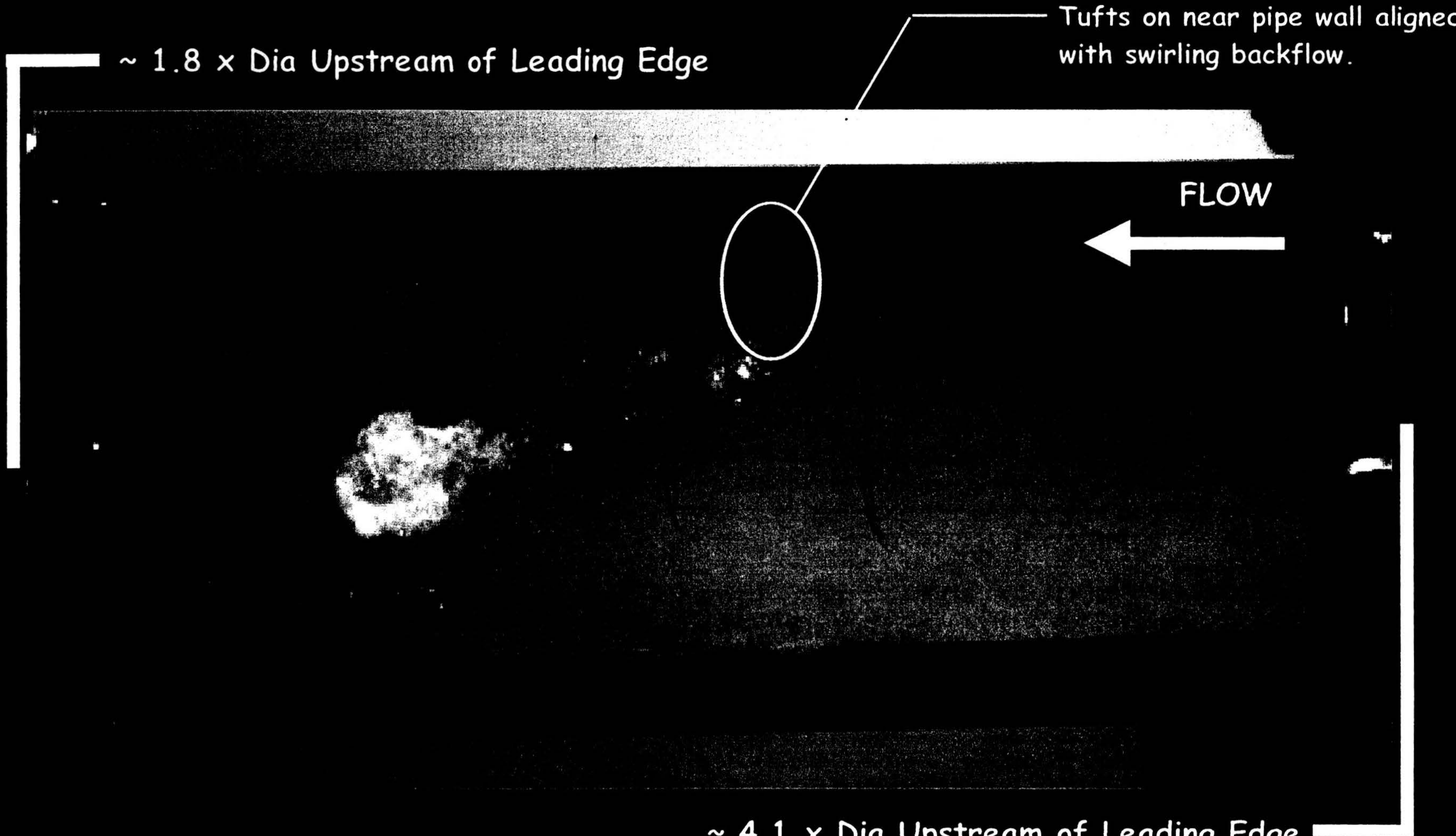
- Single-cell rotating disturbance observed at 70% of design flow moving in direction of inducer rotation (1.3 x N).





RS-83 Main Lox Inducer

- Inlet backflow and swirl captured on high-speed digital video.

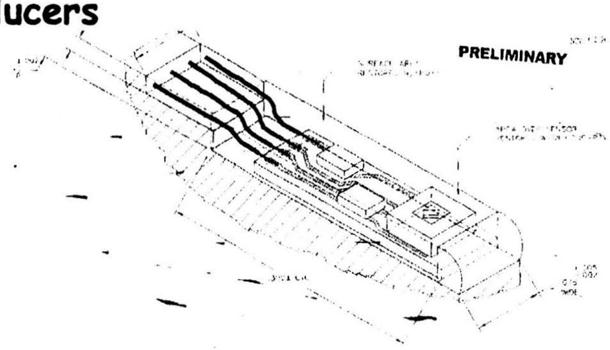


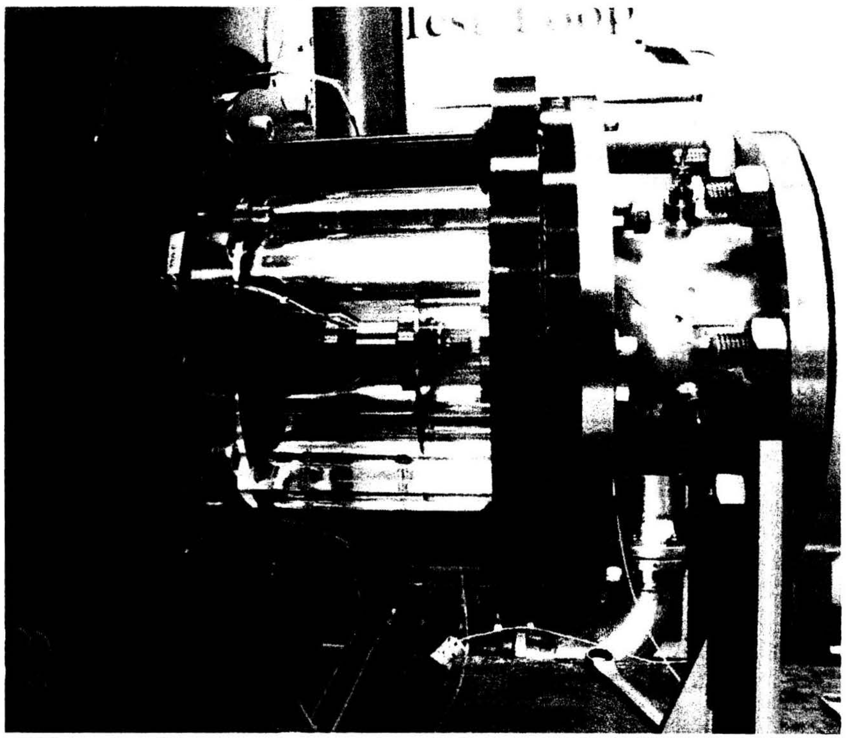
Frame Rate = 7000 fps
Speed = 4200 rpm

Future

- Objective: Directly measure inducer blade loads by miniature pressure transducers embedded in blades.
- Technology demonstrated in air turbine applications.
- Water demonstration partially successful - performance matched reference device but life limited by sealant failure.

Turbine Blades with Embedded Transducers





Water Test Article with Transducers Embedded in Rotating Disk

Future

- Objective: Revive Cal Tech's dynamic pump test facility, replicate data, and establish institutional capability to measure pump dynamics - mass flow gain and cavitation compliance.

Video courtesy of Dr. Christopher Brennen, California Institute of Technology

Test Team Members

- Unsteady Data Analysis: Thomas Zoladz, Andrew Mulder
- Facility Operation: James Aaron, Bo Jones, Doug McBride
- Data Acquisition System Development: Joey Kirkpatrick, Richard Norman, David Goodwin
- Test Article Design: Dwight Goodman, John Forbes, Phyllis Rabun, John Farrow