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High Head Unshrouded Impeller Pump Stage Technology

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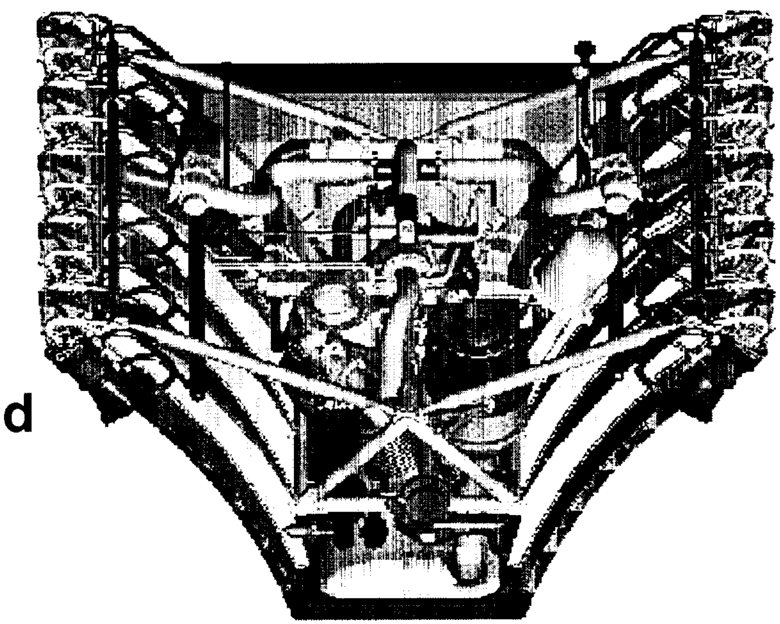

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Introduction

- **Typical pump impellers in rocket turbopumps are shrouded**
- **Shroud is a heavy metal casing which covers the impeller blade passages to help maintain performance and control axial thrust**
  - Shroud adds weight and manufacturing complexity
- **As a pump spins faster, stress due to centrifugal force in the impeller increases**
- **Weight of the shroud increases the stress and limits the speed at which a pump can operate**
  - Shrouded Titanium impeller tip speed limit is 2000 ft/sec
- **Pump impeller without a shroud can operate at higher speeds with lower stress and generate more head**
  - Unshrouded Titanium impeller tip speed limit is 2500 ft/sec
- **A multi stage pump with unshrouded impellers can produce the same amount of head with fewer number of stages**

RLV Design Point

- **NASA's 2nd Generation RLV Goals**
  - Develop safe, affordable and reliable reusable launch vehicles
  - Improve the safety of 2nd generation systems by two orders of magnitude
  - Decrease cost tenfold to approximately $1000 per pound of payload

- **Target RLV YRS-2200 design point**
  - To decrease cost, the RLV will require higher thrust-to-weight (T/W) ratio engines than currently available
  - Key technology that will enable significant improvements in T/W ratio and help NASA reach its goals is the application and use of unshrouded impellers

Background

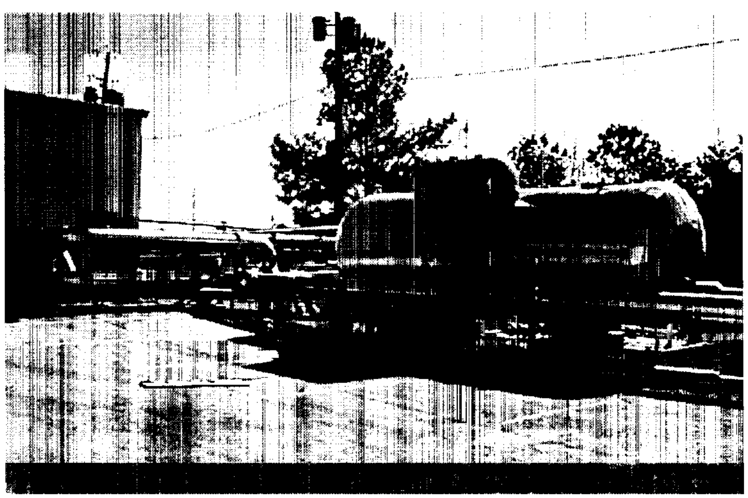
- Turbopump is typically between 25% and 30% of the gross engine weight
- Housing assembly makes up about 80% of the total turbopump weight
- Housing size is driven by the size of the rotor assembly
- Unshrouded impellers allows for higher tip speeds, which increases stage loading resulting in reduction of rotor and housing size and weight
- This project has shown that a space shuttle main engine (SSME) 2-stage high pressure fuel turbopump (HPFTP) alternate turbopump (AT) and a RLV YRS-2200 2-stage HPFTP would reduce turbopump weight between 45% and 50% as compared to the 3-stage designs

Objective

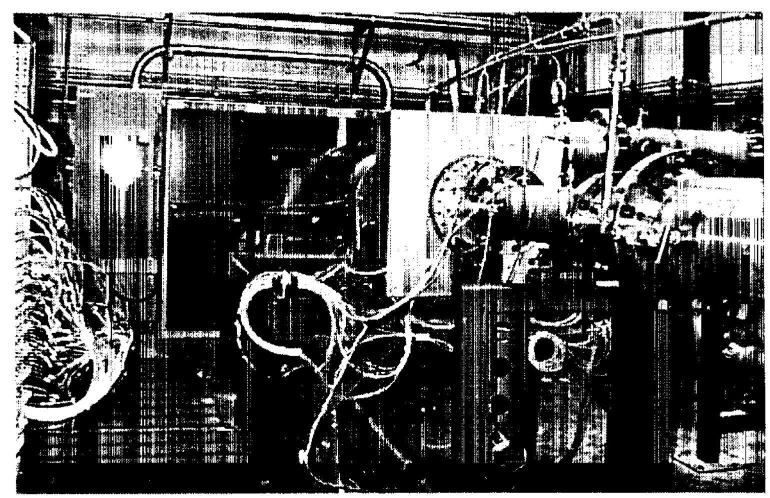
- **Develop an unshrouded impeller design, using the latest analytical techniques and experimental data, which will meet the performance requirements of a 3-stage fuel pump with a 2-stage pump design**
  - Experimentally determine unshrouded impellers sensitivity to performance with tip-clearance variation and compare to analytical predictions
    - SSME HPFTP/AT design point unshrouded impeller
  - Design an unshrouded impeller that will meet the performance requirements of the RLV engine balance with a 2-stage pump
    - Design was based on experimental data and analytical techniques developed in the project
    - Verification test to be completed at a later date - January 2001
  - Produce a conceptual, complete, viable 2-stage design of the RLV fuel turbopump that incorporates the verified unshrouded impeller design

Baseline Impeller Test

- **The performance of the SSME HPFTP/AT design point unshrouded impeller was experimentally verified at three tip-clearances at scaled operating conditions with water as the test fluid**
  - Extend the design database to higher stage loading supporting a reduction in RLV turbopump stage requirements
  - Develop and verify analytical models for use with unshrouded impellers



MSFC Pump Test Equipment Facility



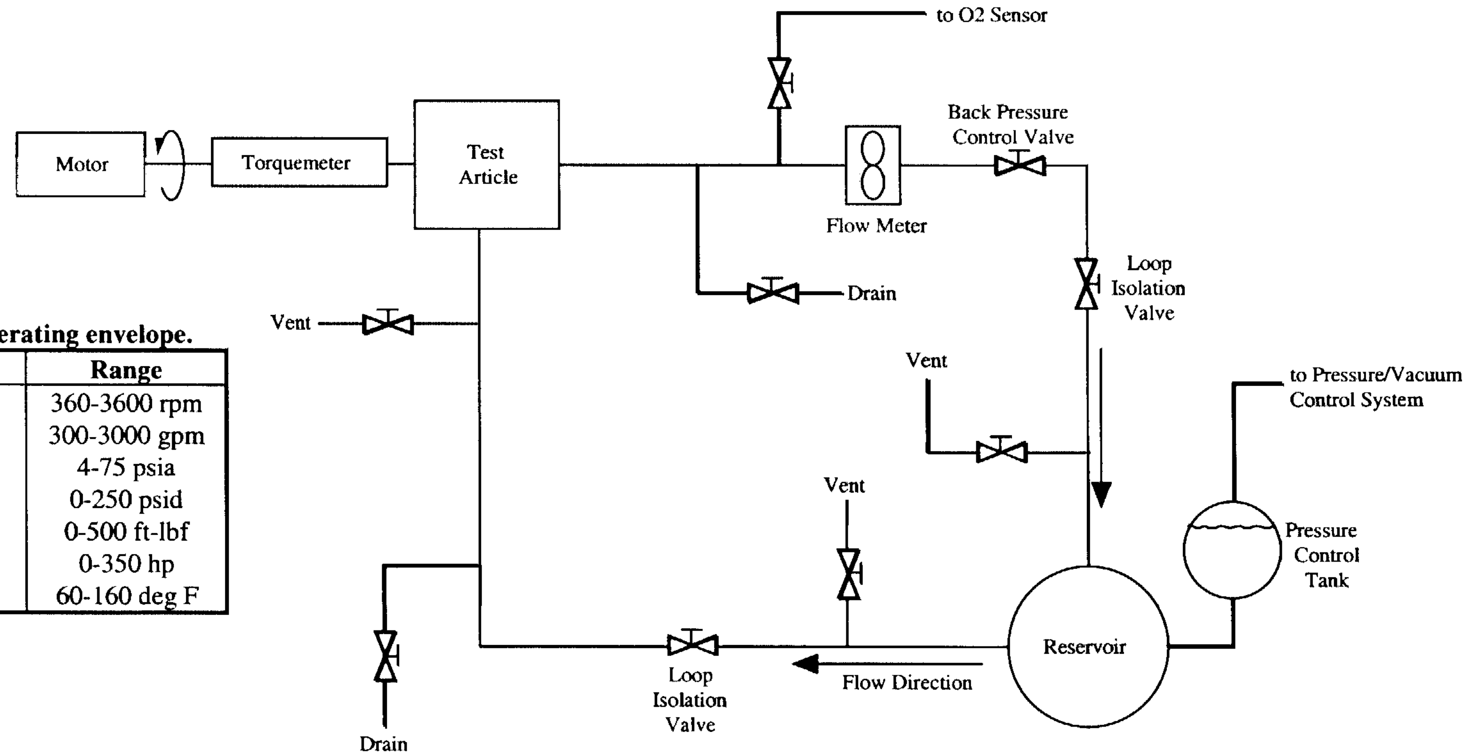
Unshrouded Impeller Test Article

PTE Facility Description

- **MSFC's Pump Test Equipment (PTE) facility. The PTE is a closed-loop water flow facility with 10,000-gallon reservoir, deaeration and pressurization systems, facility flow meter, flow control valve, torquemeter, and 350 horsepower drive motor**

Table 1 - PTE operating envelope.

Parameter	Range
Shaft Speed	360-3600 rpm
Facility Flow Rate	300-3000 gpm
Inlet Total Pressure	4-75 psia
Pump Pressure Rise	0-250 psid
Shaft Torque	0-500 ft-lbf
Drive Line Power	0-350 hp
Water Temperature	60-160 deg F



Pump Test Equipment Facility Schematic

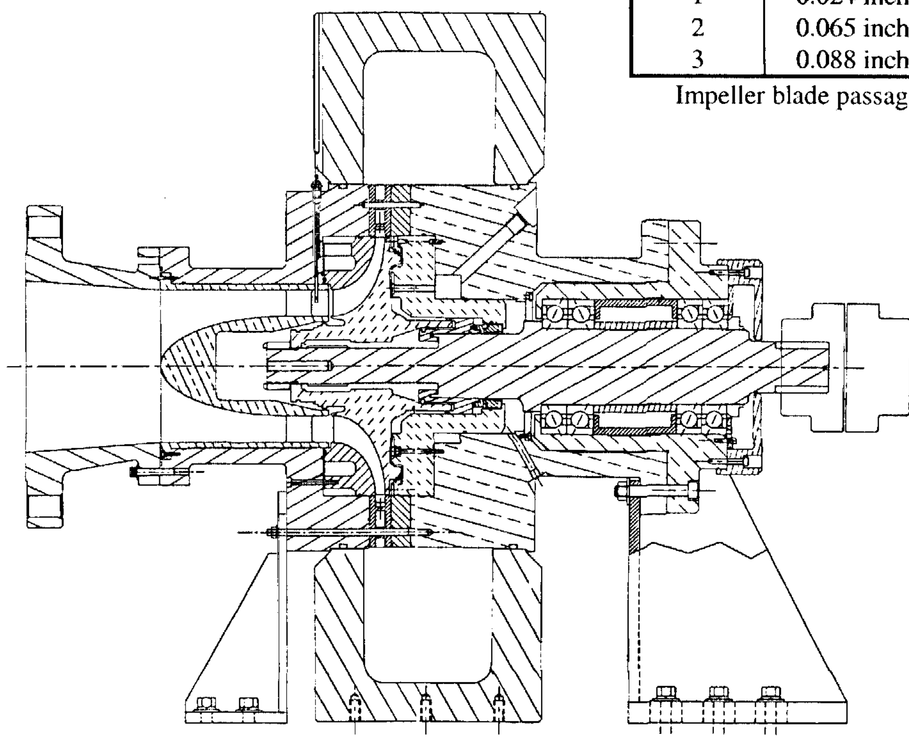
Baseline Test Article Description

- **Modular design of the test article allows for use with a variety of inlet guide vanes, impellers, and diffuser configurations**

Table 1 - Baseline Impeller clearance summary.

Rig Build	Tip-Clearance	Shim ID	Percent b_2
1	0.024 inches	1	5.33%
2	0.065 inches	5	14.4%
3	0.088 inches	N/A	19.6%

Impeller blade passage height – b_2 = 0.45 inches.



Baseline unshrouded impeller test article

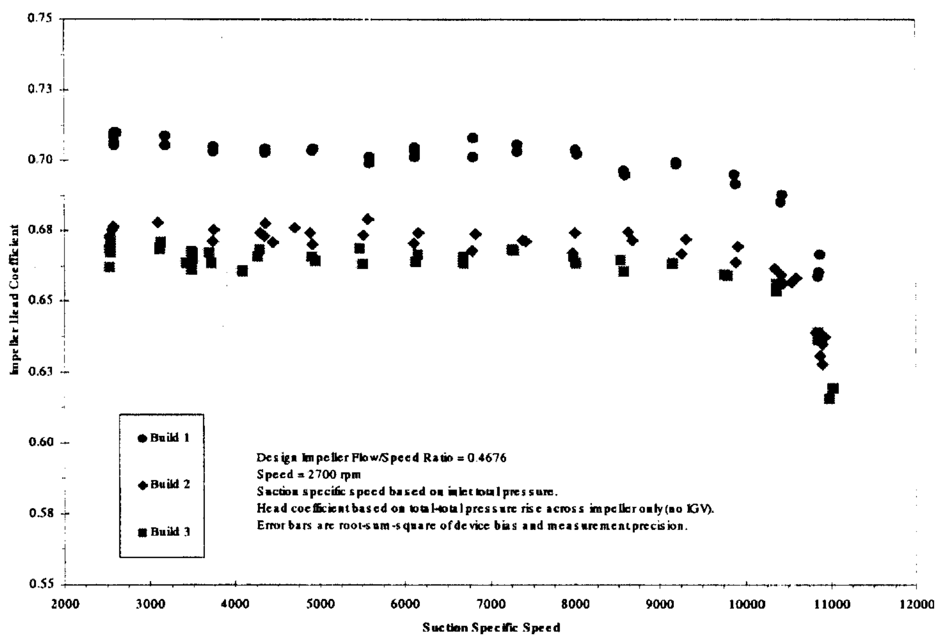
Baseline unshrouded impeller

Test Matrix

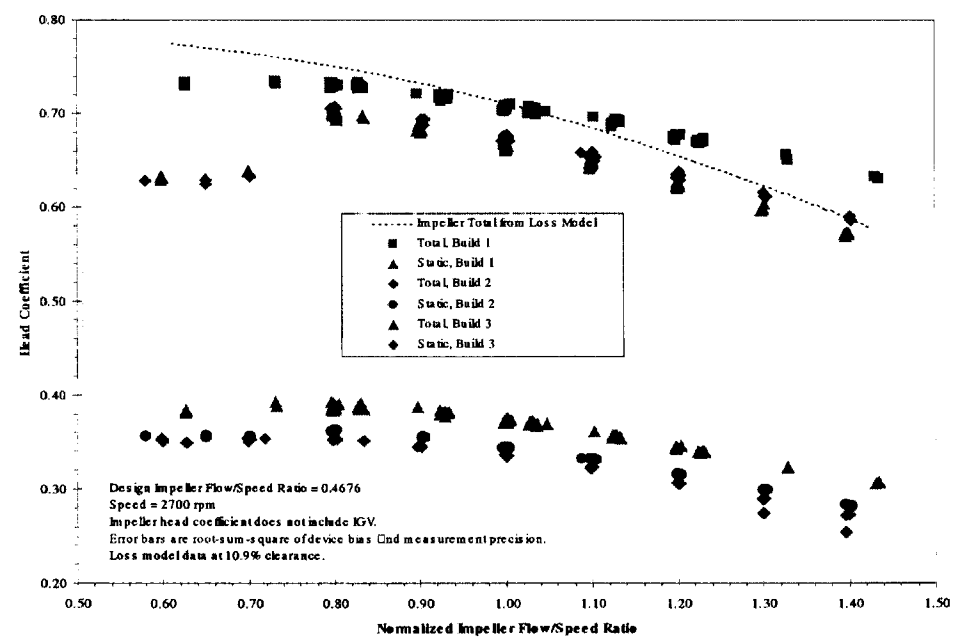
- **Test article performance was evaluated over a range of scaled operating conditions at a constant shaft speed of 2700 rpm**
- **Five test series were conducted to fully document pump performance at each tip-clearance**
  - Head-flow curve at constant suction specific speed
  - Suction performance at design flow coefficient
  - Suction performance at higher flow coefficients
  - Suction performance at lower flow coefficients
  - High-frequency recording of suction and speed ramps
- **Steady-state measurements acquired during testing were used to confirm test conditions, evaluate test article performance, and monitor test article health**
- **Unsteady pressures and accelerations were recorded during inlet pressure and speed ramps at each flow coefficient**

Test Results - Performance

- Test article performance was calculated from measured values and plotted for comparison using a spreadsheet



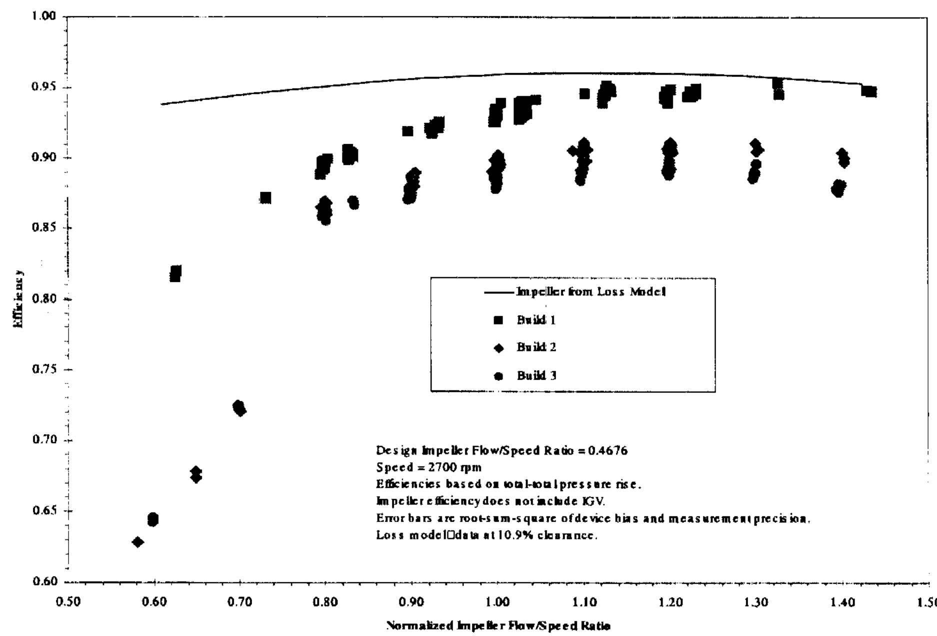
Impeller head coefficient versus suction specific speed at design impeller flow/speed ratio



Impeller head coefficient versus normalized impeller flow/speed ratio

Test Results - Efficiency

- Pump Efficiency measured directly with torquemeter
- Impeller efficiency isolated with total pressure measurements



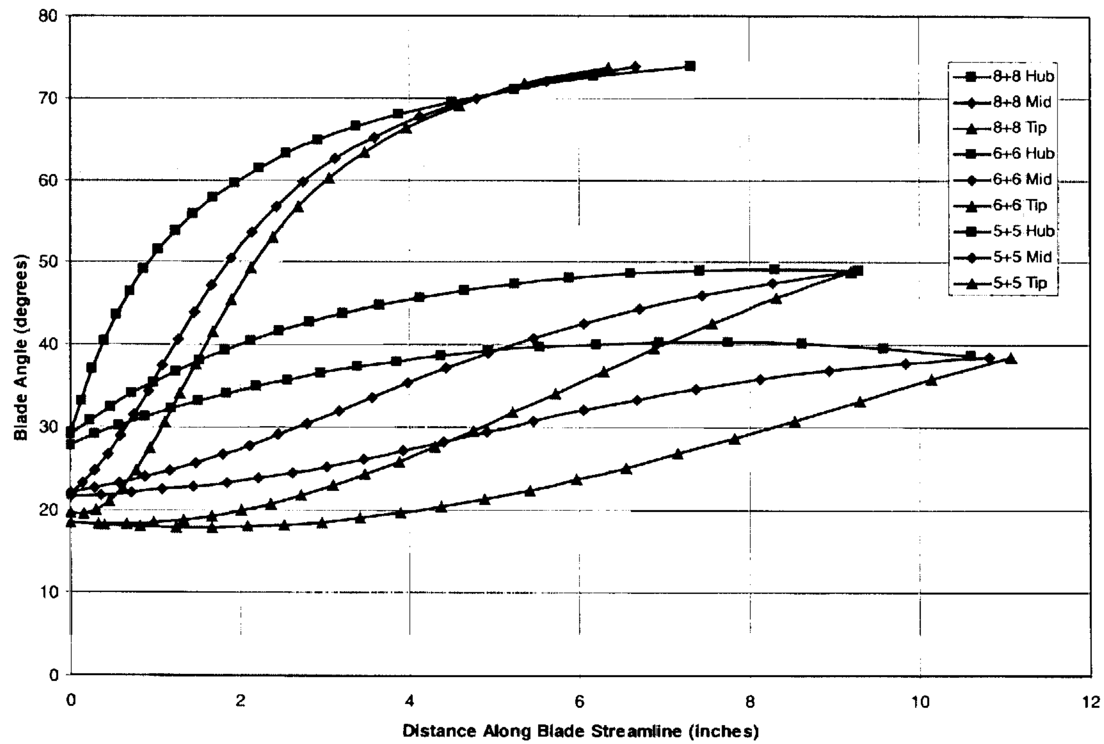
Impeller efficiency versus normalized impeller flow/speed ratio

RLV Impeller Trade Study

- **Primary design parameters of interest are:**
  - Blade solidity
  - Blade number
  - Blade wrap
  - Axial length
  - Diffusion factor
  - Cant angle
  - B2-width
  - Exit blade angle
  - Head coefficient
- **Fixed parameters due to engine balance constraints or need to minimize changes to the tester**
  - Head coefficient
  - Axial length (shroud contour)
  - B2-width
- **With these parameters fixed, blade solidity, blade wrap, diffusion factor, and exit blade angle are all varied with change in blade number**

RLV Impeller Designs

- Blade number was the parameter selected for further study
- Three impeller designs were completed as part of the blade number trade study to evaluate performance sensitivity: 5+5, 6+6, and an 8+8 impeller



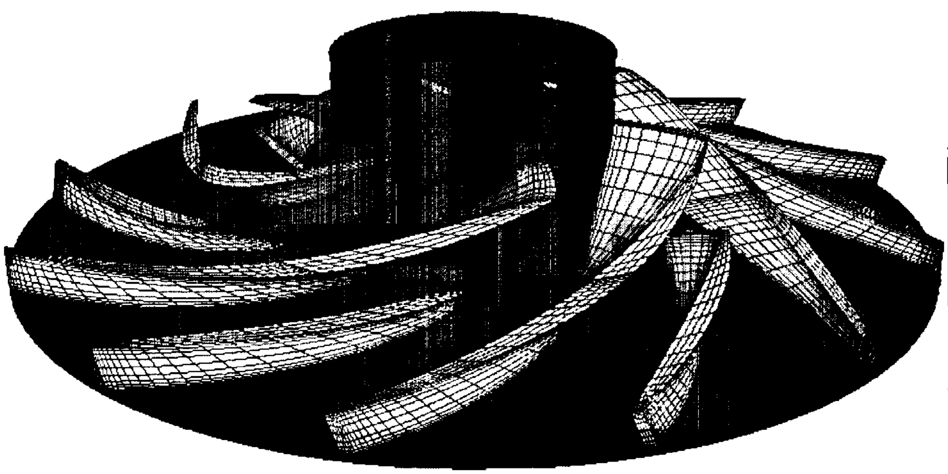
Blade Angle Distribution for 5+5, 6+6, and 8+8 Designs

3-D Flow Models

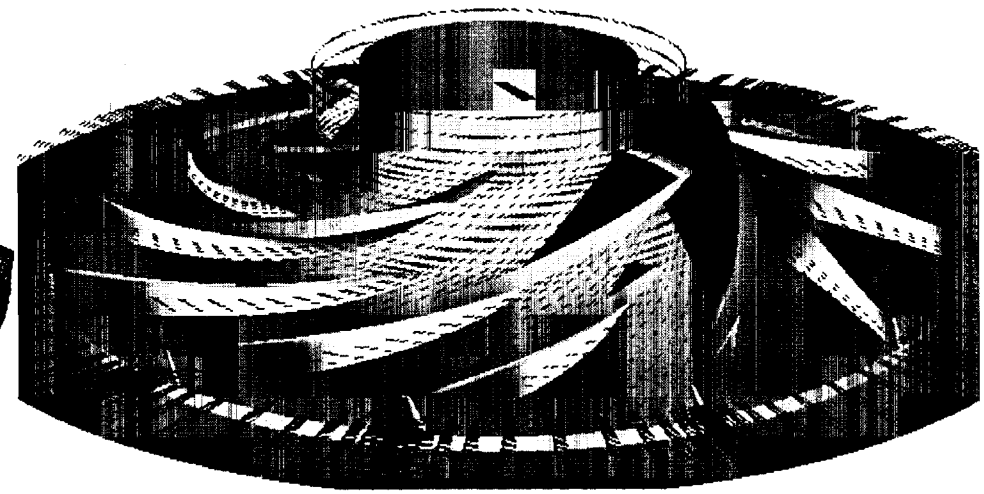
- **Three-dimensional (3-D) computational fluid dynamics (CFD) analysis was used to calculate performance of the three unshrouded impeller designs**
  - The numerical flow grids were generated algebraically from the impeller contour and surface definition
    - Grid generation tool was integrated with the impeller geometry tool to support quick parametric CFD analysis studies
  - Parametric study of all three geometries was performed using CFD analysis
    - Over 60 CFD analyses were completed
    - Each geometry was analyzed at 0%, 6%, 10%, and 20% clearance
    - Each clearance was analyzed at on- and off-design conditions from 80% to 120% flow

CFD Results

- Static pressure along the blade passage flow surface obtained from the CFD models was applied to a finite element model to determine blade stress
- Pressure loading on the shroud surface was used to determine axial load applied to the bearings



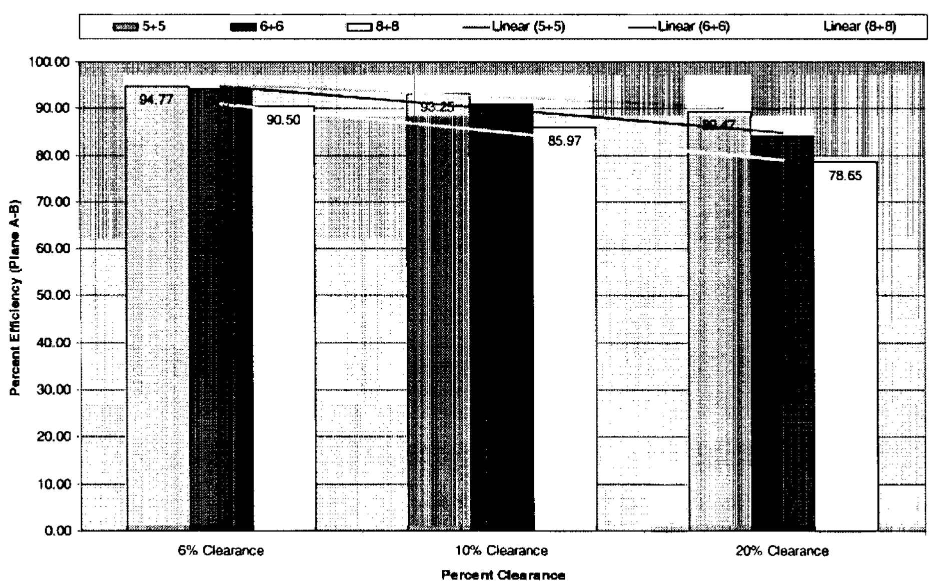
Surface grid for CFD model for 6+6 geometry



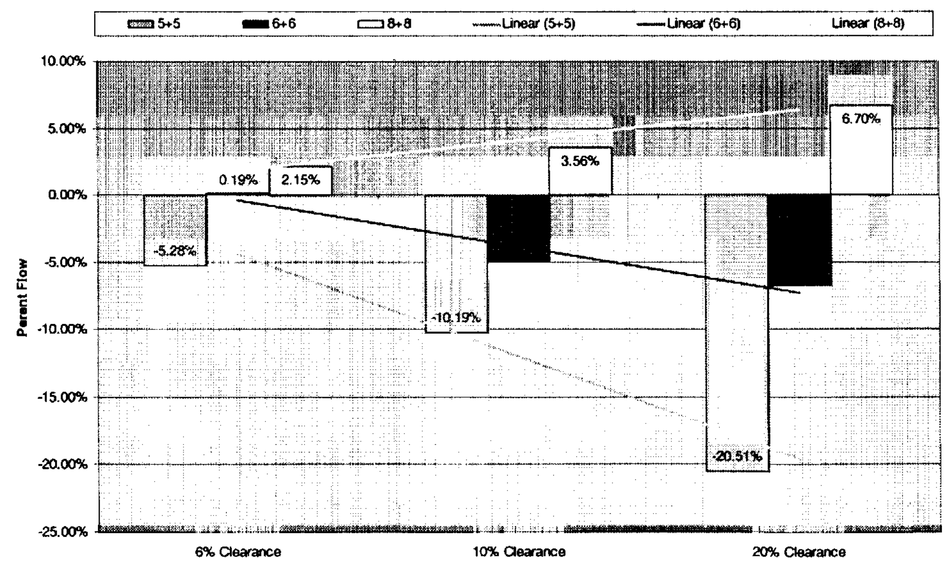
Surface pressure color contours and velocity vectors for 6+6 design

CFD Parametric Studies

- Comprehensive database was compiled and results between cases were compared
- Global performance parameters and local flow uniformity was assessed to determine the best candidate geometry for the 2-stage RLV HPFTP design
- The 6+6 design was selected for the 2-stage unshrouded impeller configuration based on overall performance and flow uniformity



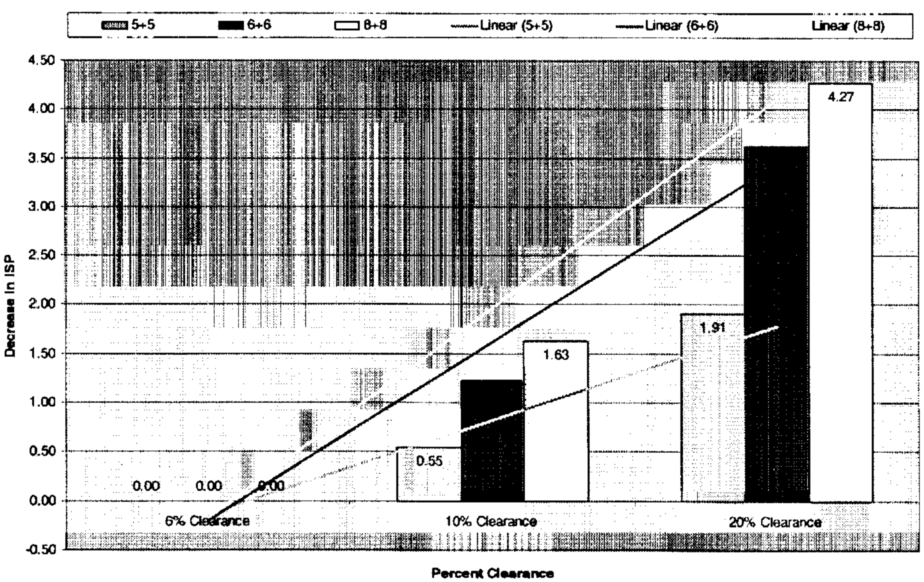
Impeller Efficiency



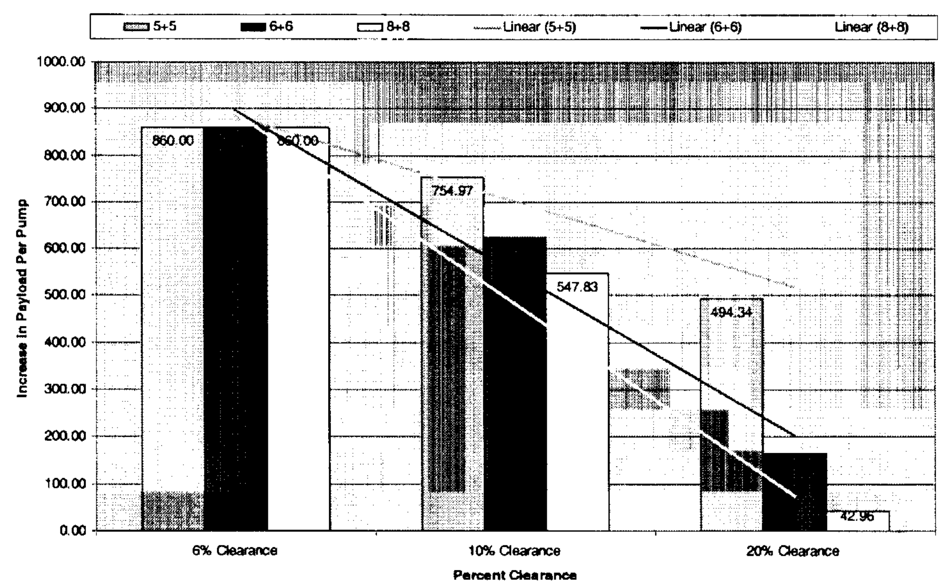
Back flow at blade leading edge

Weight Savings

- Vehicle system trades were performed to determine the overall potential increase in payload to orbit
- The 6+6 unshrouded impeller design at 6% clearance had similar performance to a shrouded design
- At this clearance the increase in payload would be 860 lbs. per engine



Impeller Efficiency



Back flow at blade leading edge

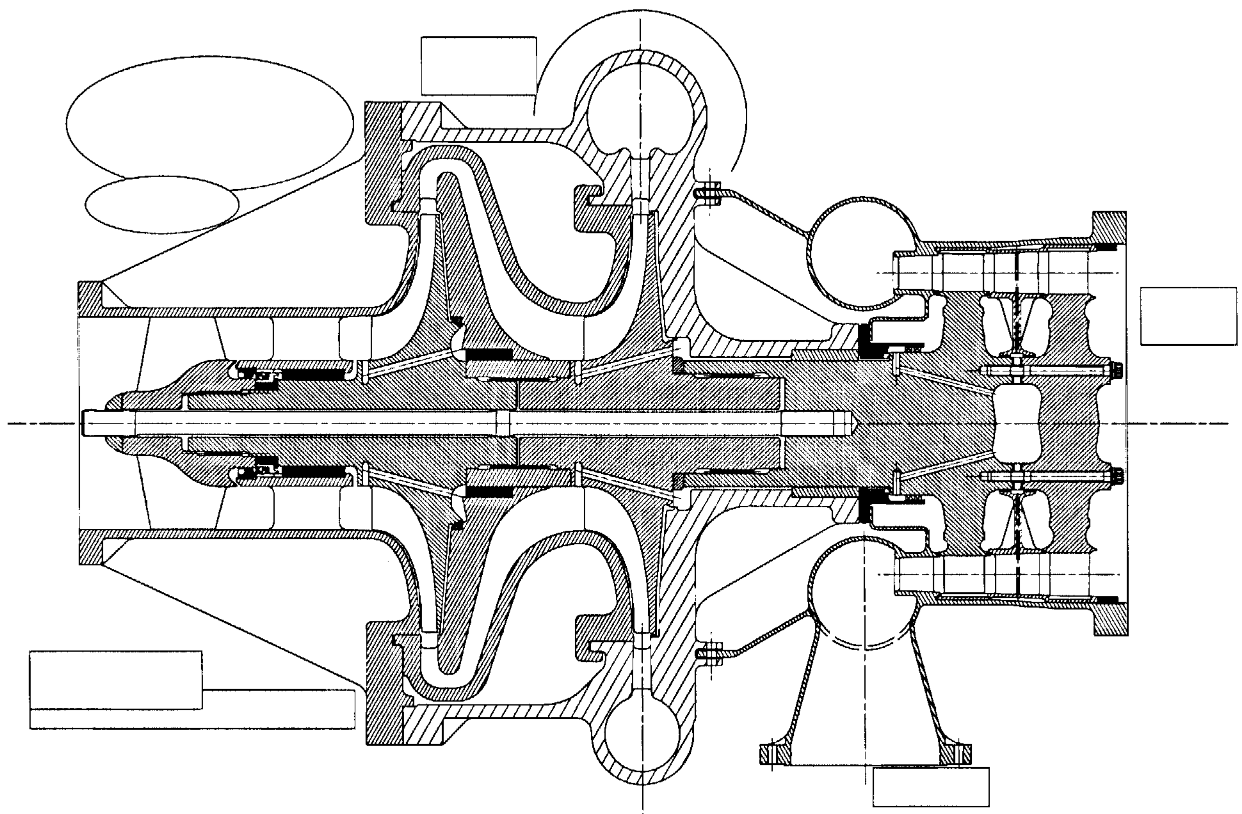
RLV HPFTP Mechanical Layout

- Preliminary 2-stage turbopump mechanical layout was completed based on the RLV engine balance
- Inducer was sized to meet the requirements of the balance
- Hydrostatic bearings were baselined assuming long life goals
- Clutching bearing was integrated to allow for transient start and shutdown loads
- Wear rings and an inter-stage seal were defined to balance axial thrust and provide rotordynamic stability
- Turbine envelope definition was based on an advanced turbine under development in a parallel NRA8-21 project
- Axial length provides spacing between turbine and pump to accommodate turbine temperatures
- Preliminary design also included assessment of axial thrust, rotordynamics, weight, and impeller stress to ensure a viable concept to advance to an operational turbopump

Conclusions

- Objective to develop an unshrouded impeller design, which meets the performance requirements of a 3-stage fuel pump with a 2-stage pump design, has been accomplished
- Performance of the baseline unshrouded impeller has been experimentally verified
- Unshrouded impeller trade study and final 6+6 unshrouded impeller configuration has been presented
- Structurally viable, 6+6-impeller design concept has been produced
- Based on results presented in this study, at a nominal 10% tip-clearance, the 6+6 impeller design would increase payload to orbit by almost 625 lbs. per engine
- The RLV vehicle requires 7 engines, therefore, application of high head unshrouded technology would increase payload capability by as much as 4,375 lbs. per vehicle

Concept



RLV HPFTP unshrouded concept