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Subsystem & Component Development Department
Space Transportation Directorate
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Unshrouded Impeller Technology Task Status

TD Fluids Workshop, April 4-5, 2001

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Agenda

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- Background
- Objectives and Approach
- Unshrouded Team Members
- Baseline Experiment
- Advanced Design
- Concept
- Advanced Experiment
- Resources
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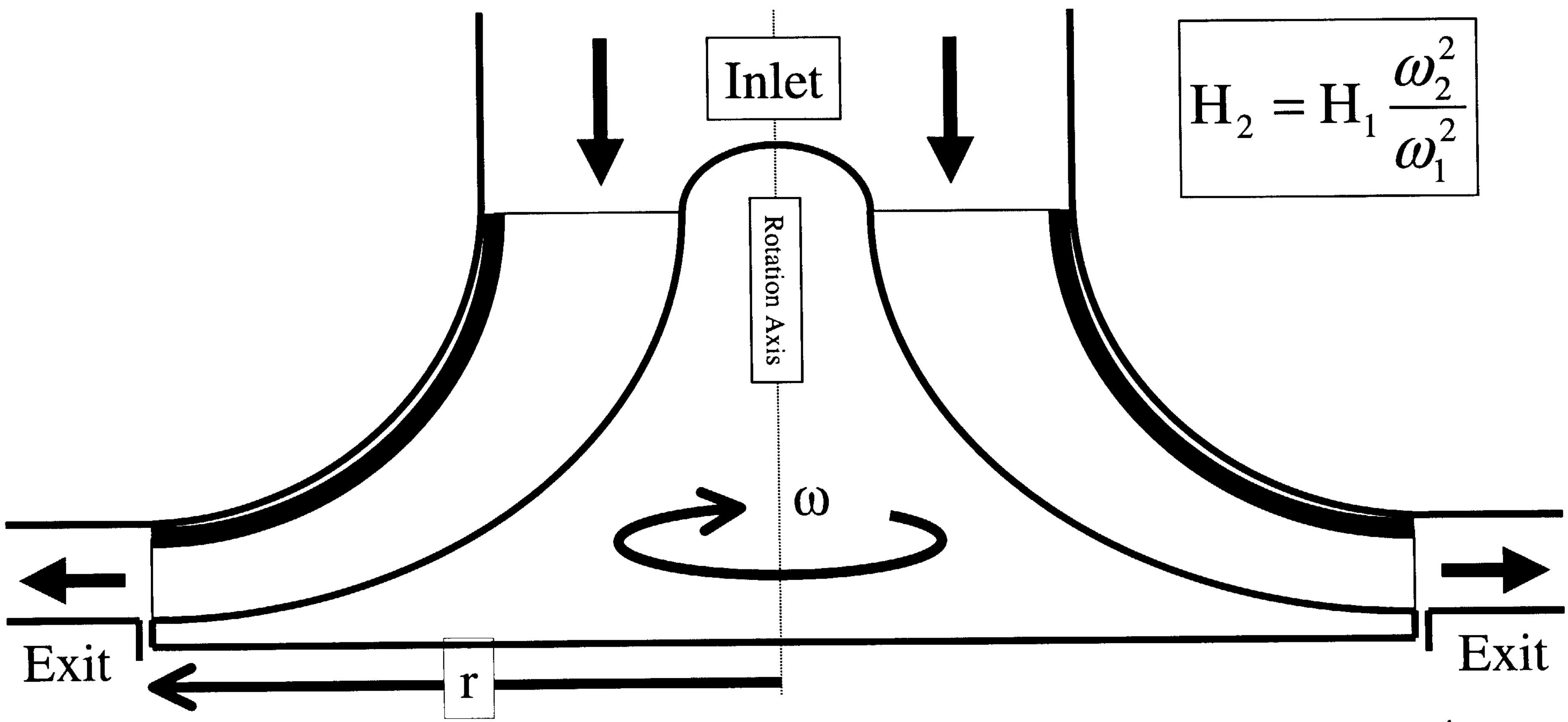
Introduction

- **NASA's 2nd Generation RLV Program goals are to develop safe, affordable and reliable Reusable Launch Vehicles (RLV's)**
  - Improve safety of 2nd Generation systems by two orders of magnitude (equivalent to a crew risk of 1 in 10,000 missions)
  - Decrease cost tenfold to approximately $1000 per pound payload
- **To decrease cost, an RLV will require higher thrust-to-weight (T/W) ratio engines than currently available.**
- **One 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**
- **A team of engineers at NASA/MSFC are developing unshrouded impeller technologies that will increase payload and decrease cost of future reusable launch vehicles**
- **This technology is available for transfer to commercial pump designers and rocket engine developers**

Background - Typical Turbopump

- A turbopump develops required head by spinning very fast
- The faster the pump rotates, the more head is generated
- A shroud is a heavy metal casing which covers blade passages
- Shrouds help maintain performance and control axial thrust

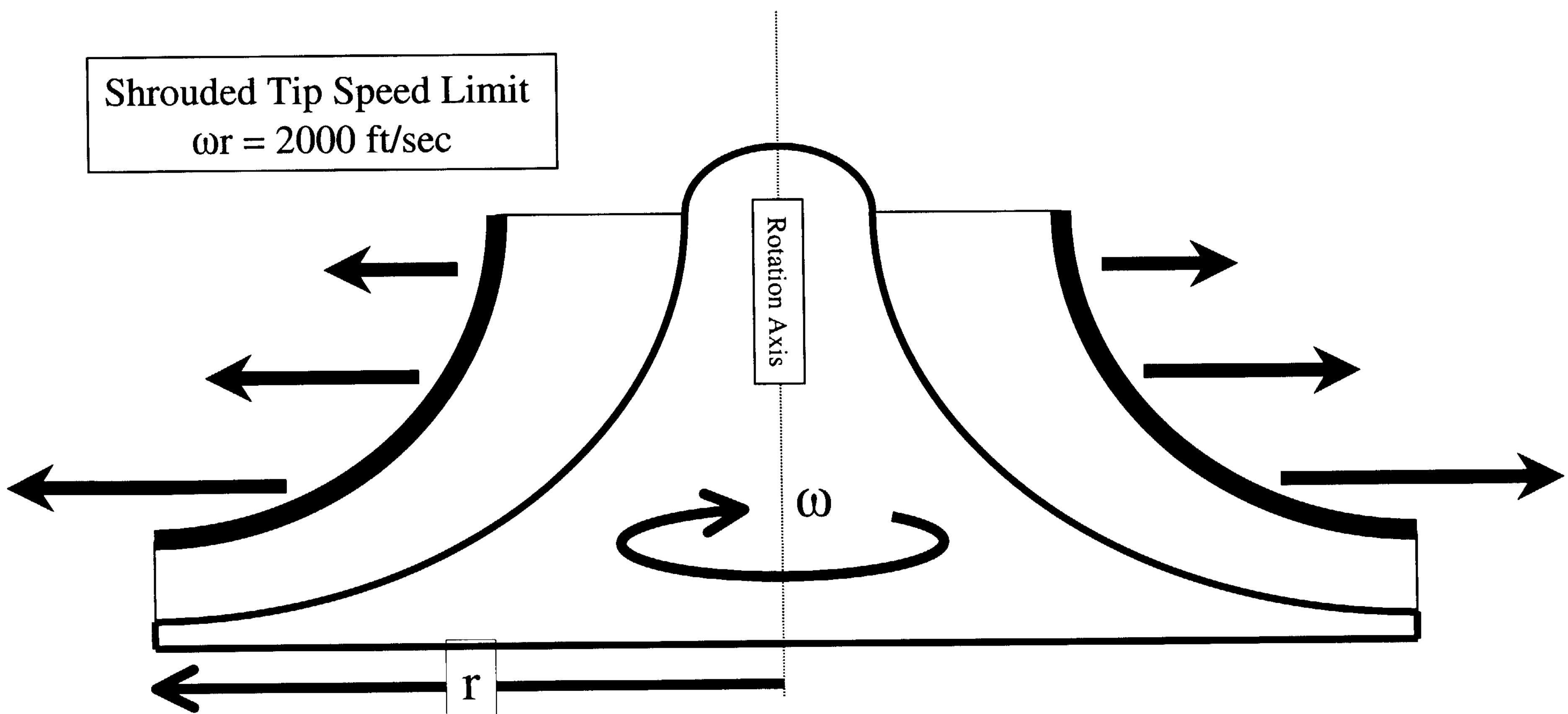


$$H_2 = H_1 \frac{\omega_2^2}{\omega_1^2}$$

Background - Shrouded Tip Speed Limit

- As a pump spins faster, stresses due to centrifugal force increase
- The weight of the shroud increases the stress on the blades
- This stress limits the speed at which a pump can operate

Shrouded Tip Speed Limit
$\omega r = 2000$ ft/sec

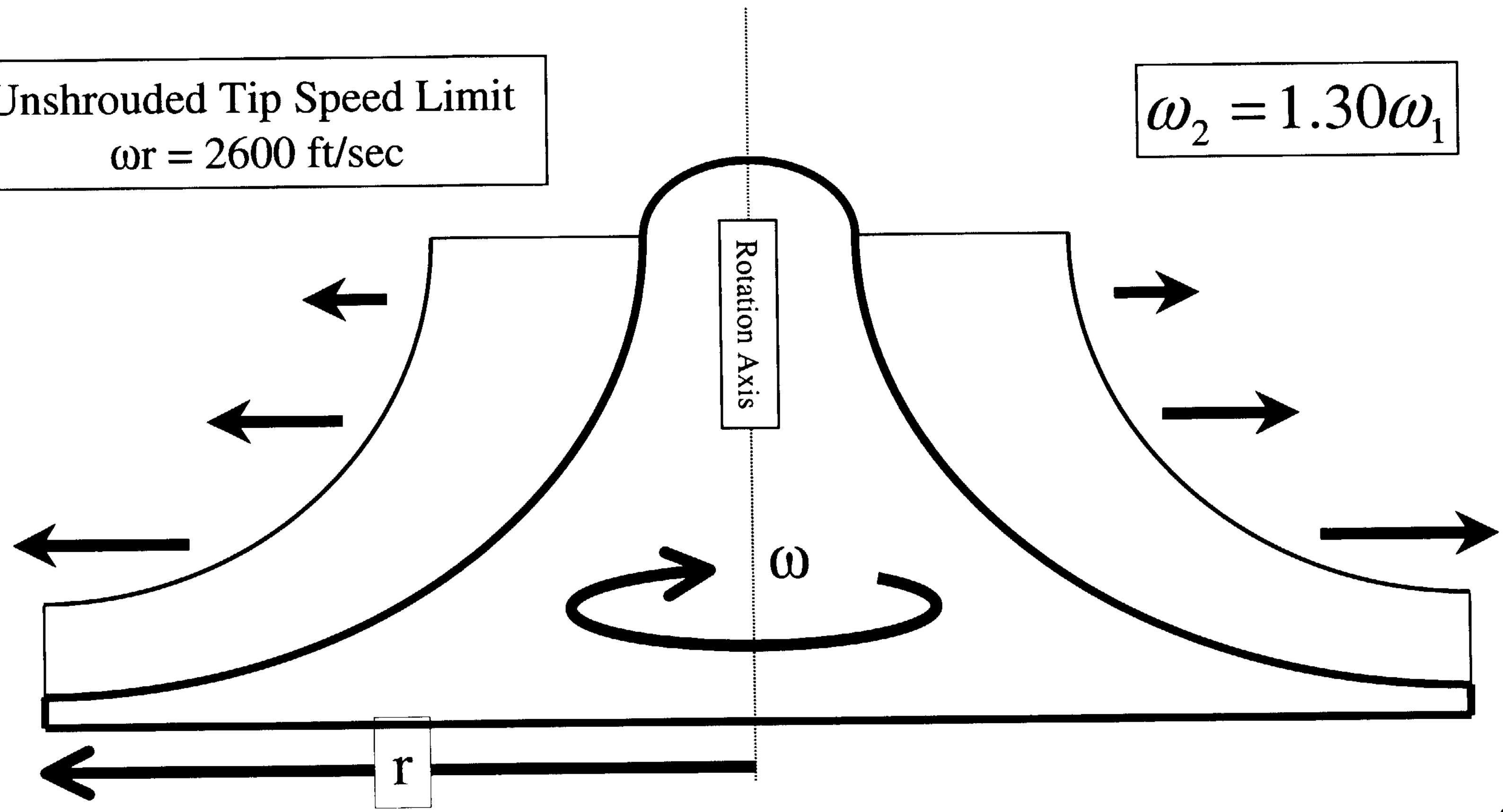


Background - Unshrouded Tip Speed Limit

- A pump impeller without a shroud has less centrifugal force
- Unshrouded Impellers operate at higher speeds with lower stress
- Higher speeds allow Unshrouded impellers to generate more head

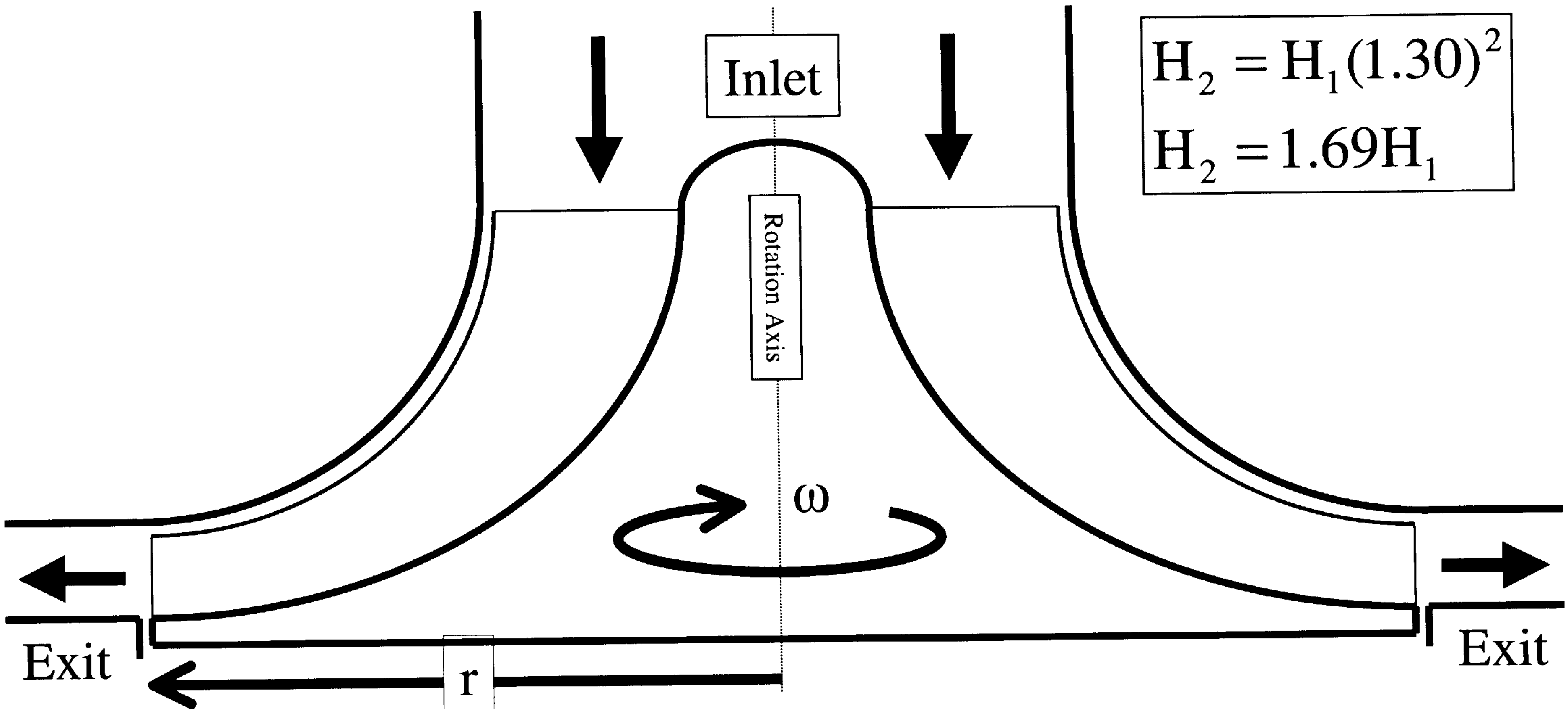
Unshrouded Tip Speed Limit
$\omega r = 2600$ ft/sec

$\omega_2 = 1.30\omega_1$



Background - Unshrouded Issues

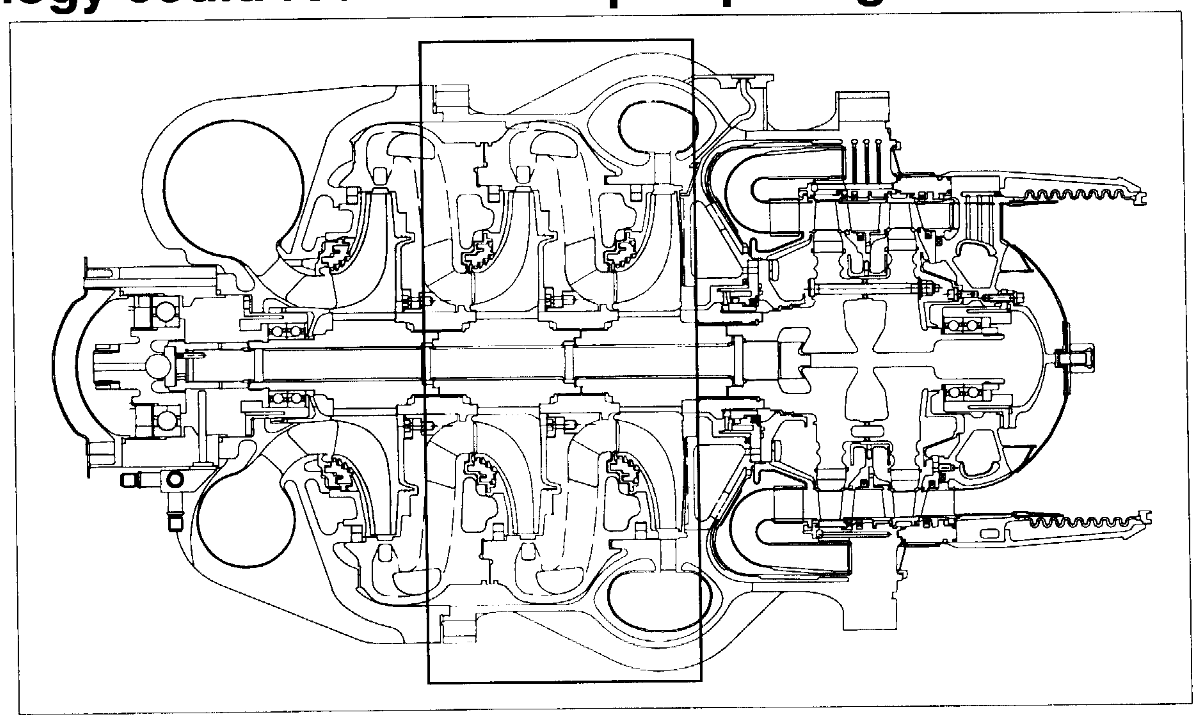
- Tip clearance effects performance of unshrouded impeller
- Lacks shroud surface for axial thrust control
- Rotordynamic coefficients not quantified
- Other turbopump constraints may limit tip speed



$$H_2 = H_1(1.30)^2$$
$$H_2 = 1.69H_1$$

Background - Reducing Pump Stages

- A turbopump is between 25% and 30% of the gross engine weight
- The housing assembly is about 80% of the total turbopump weight
- Housing size is driven by the size of the rotor assembly
- Use of unshrouded impellers allows for increased stage loading
- Results in reduction of pump stages from 3- to 2-stages
- This technology could reduce turbopump weight between 45% - 50%



Objectives and Approach

- **Objective:**
  - Develop an unshrouded impeller design that will meet the performance requirements of a 3-stage fuel pump with a 2-stage pump design
- **Approach:**
  - Experimentally develop a database, using a baseline unshrouded impeller, of tip clearance sensitivity to performance
  - Design an advanced unshrouded impeller that will meet the performance requirements of the RLV engine balance with a 2-stage pump
  - Produce a conceptual design of a RLV 2-stage fuel turbopump incorporating the advanced unshrouded impeller
  - Experimentally verify the unshrouded impeller design in water flow testing

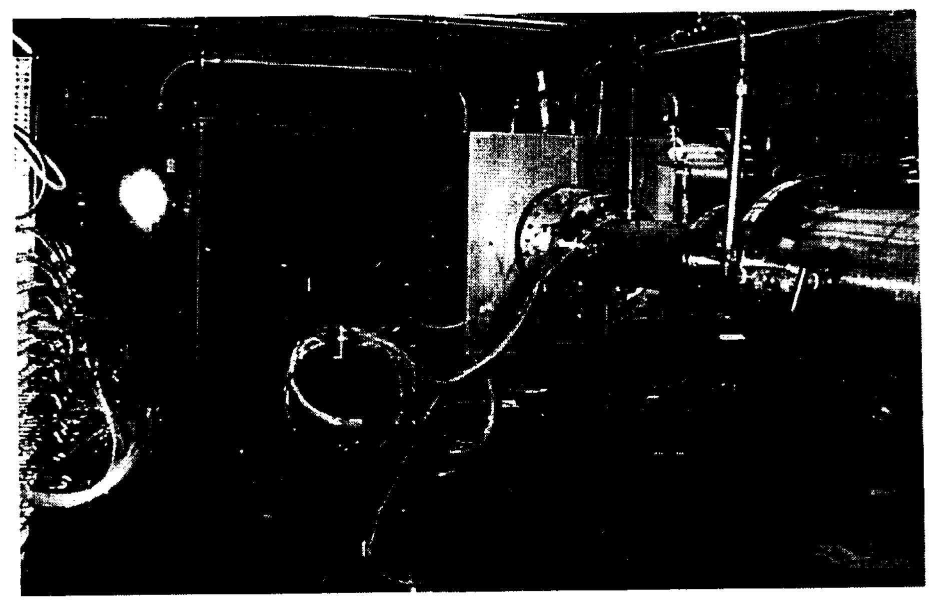
Unshrouded Team Members

- **Task Lead**
  - NASA/MSFC/TD64
- **MSFC Support**
  - TD63 - Test Engineer, Data Reduction, Steady and Unsteady
  - TD64 - Impeller Design, Analysis, and Management
  - TD74 - Facility Engineering, Facility Operations, Instrumentation, Controls, Data Acquisition, and Safety
- **Contractor Support**
  - Pratt & Whitney - IGV, Baseline Impeller, and Diffuser Design
  - Boeing, Rocketdyne - Advanced Impeller Design, Analysis, and Tool Development
  - $A^2 I^2$ (Micro Craft Inc.) - Rig Mechanical Design and Fabrication
- **Documentation**
  - Maintained on MSFC's Online Project Management System (OPMS)
  - http://voyager1.msfc.nasa.gov/
  - Select - NRA8-21 Unshrouded Impeller Technology Wing

Baseline Experiment - Impeller Test

- **The performance of the baseline unshrouded impeller was experimentally determined at three tip-clearances with scaled operating conditions using water as the test fluid**
  - Develop a design database to higher stage loading supporting a reduction in RLV turbopump stage requirements
  - Verify analytical models for use with unshrouded impellers

MSFC Pump Test Equipment Facility



Unshrouded Impeller Test Article

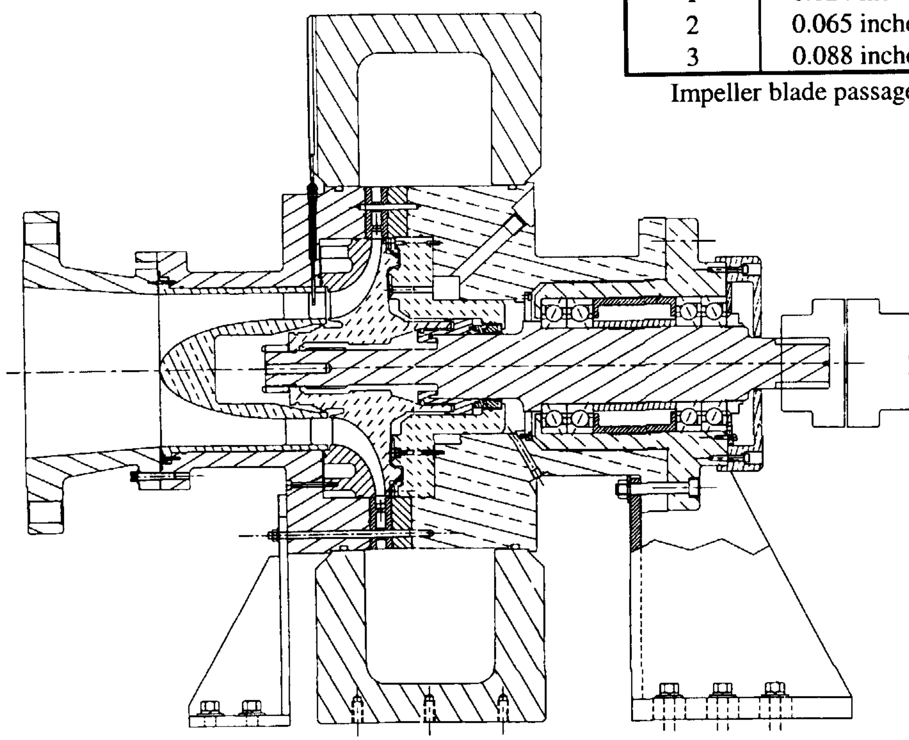
Baseline Experiment - Test Article Description

- **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.

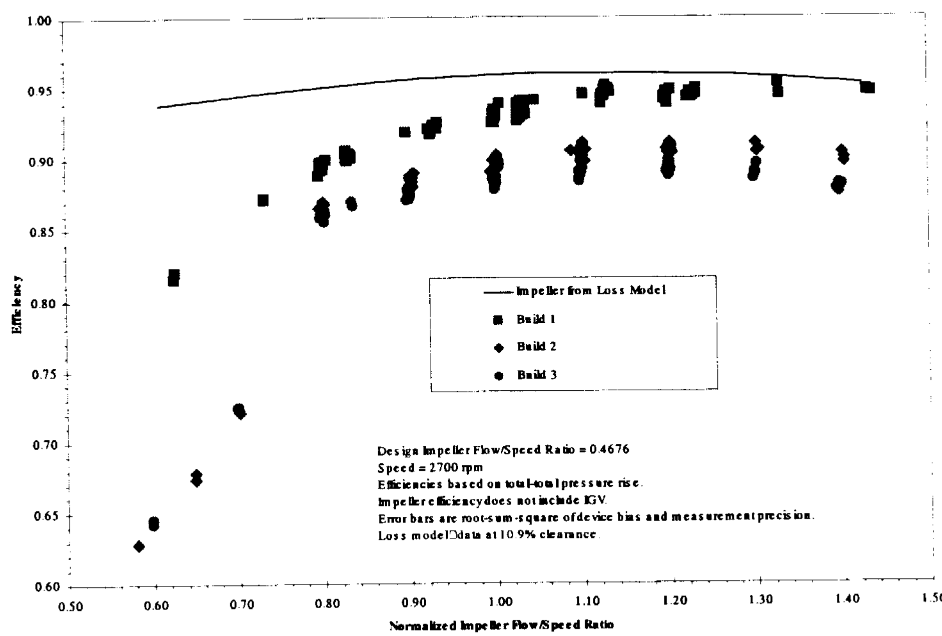


Baseline unshrouded impeller test article

Baseline unshrouded impeller

Baseline Experiment - Efficiency Test Results

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



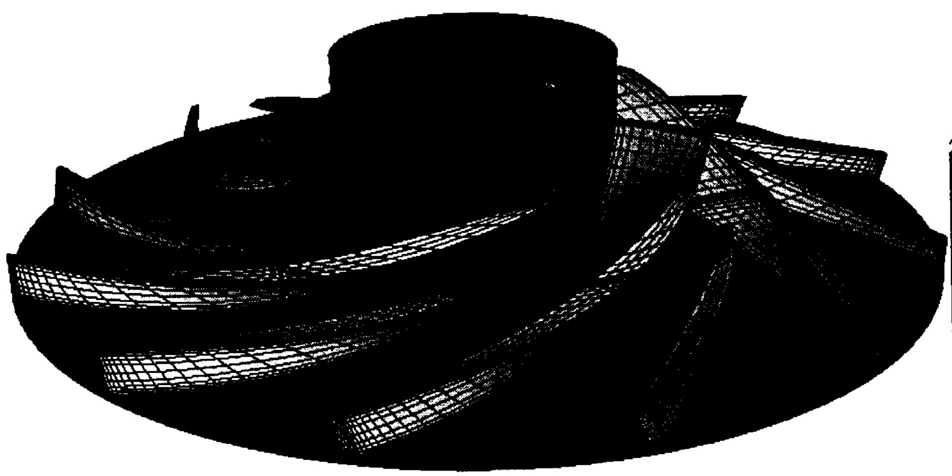
Impeller efficiency versus normalized impeller flow/speed ratio

Advanced Design - 3-D Flow Models

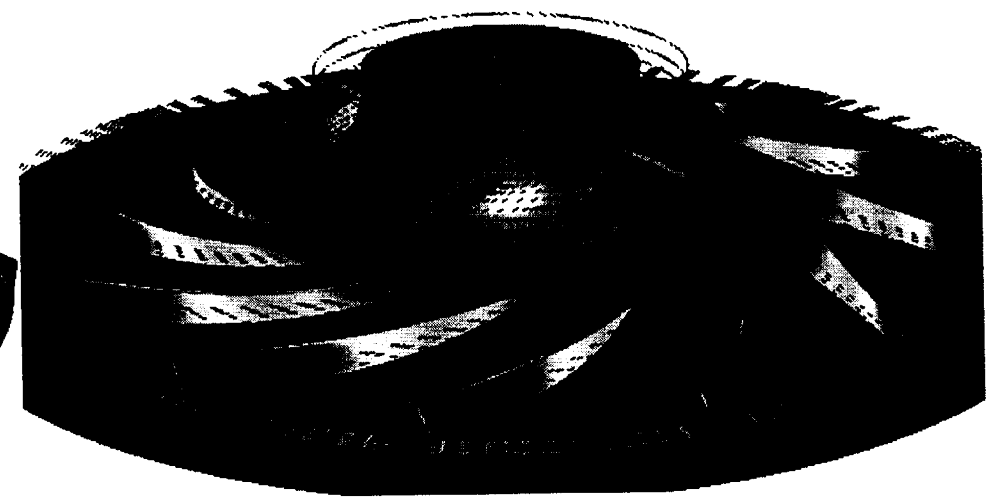
- **RLV Impeller Trade Study was performed**
- **Three impeller geometries were selected for further analysis**
  - Blade solidity, blade wrap, diffusion factor, and exit blade angle are all varied with change in blade number
- **Three-dimensional (3-D) computational fluid dynamics (CFD) analysis was used to calculate performance of three 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

Advanced Design - 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



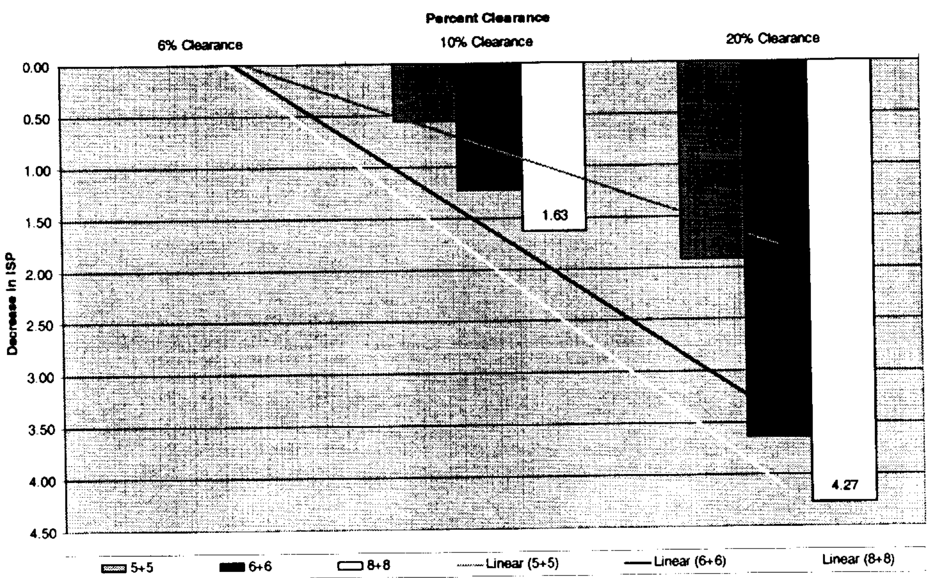
Surface grid for CFD model for 6+6 geometry



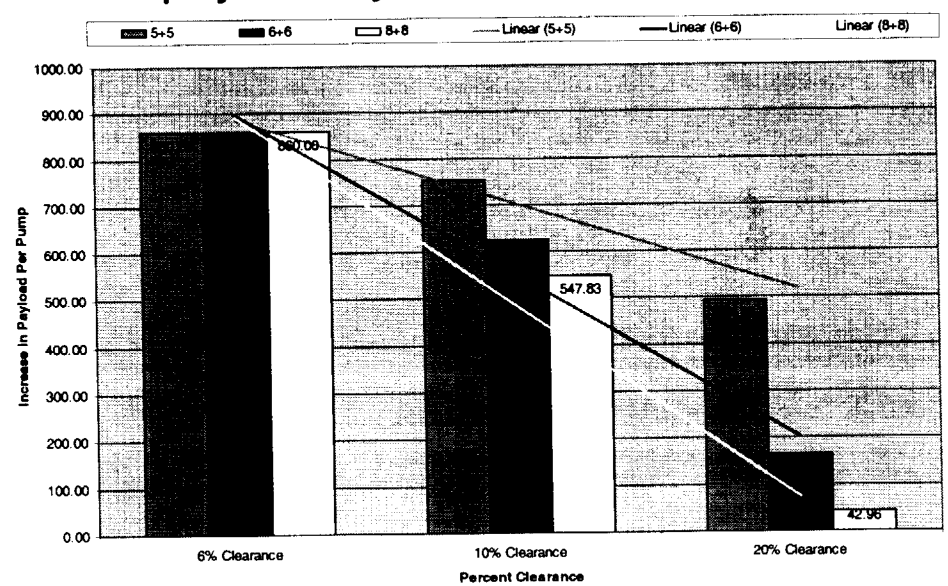
Surface pressure color contours and velocity vectors for 6+6 design

Advanced Design - Weight Savings

- **Analytical database was compiled using CFD analysis results**
  - At 6% clearance the increase in payload would be 860 lbs. per engine
    - 3-stage RLV estimate 1870 lbs. versus 2-stage CAD weight estimate 1010 lbs.
  - Impeller performance related to payload by RKDN's engine Systems Group
    - Where: $\eta_{pump} = 0.87\ \eta_{impeller}$, $Isp = 0.36\ \eta_{pump}$ (seconds), and $Payload_{net} = 220\ Isp$ (pounds)
  - At operational 10% clearance payload increase would be 625 lbs. per engine
    - 625 lbs. = 860 lbs. - (220 lbs.)(0.36)(0.87) $\eta_{impeller}$
  - Venture Star with 7 engines could increase payload by 4,375 lbs. per vehicle



Engine Specific Impulse Decrease - Isp



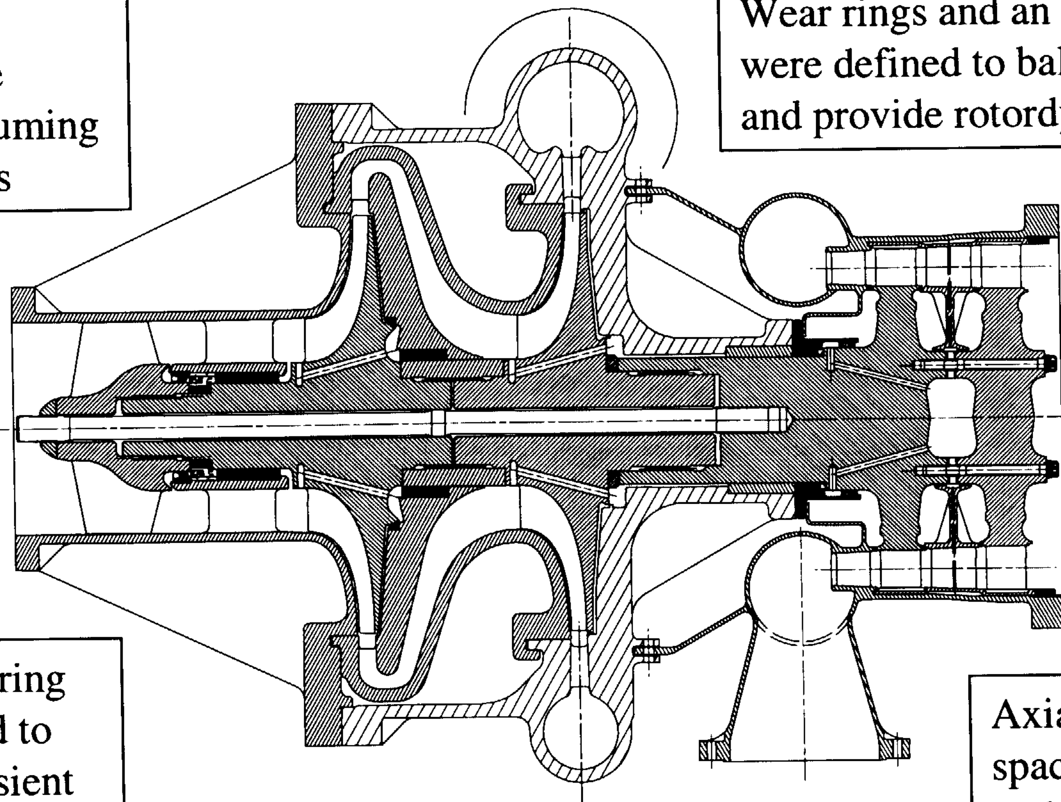
Increase in Payload per Engine

Concept - Unshrouded Turbopump

Hydrostatic bearings were baselined assuming long life goals

Wear rings and an inter-stage seal were defined to balance axial thrust and provide rotordynamic stability

Inducer was sized to meet the requirements of the balance



Turbine definition based on turbine optimization task

Clutching bearing was integrated to allow for transient start and shutdown loads

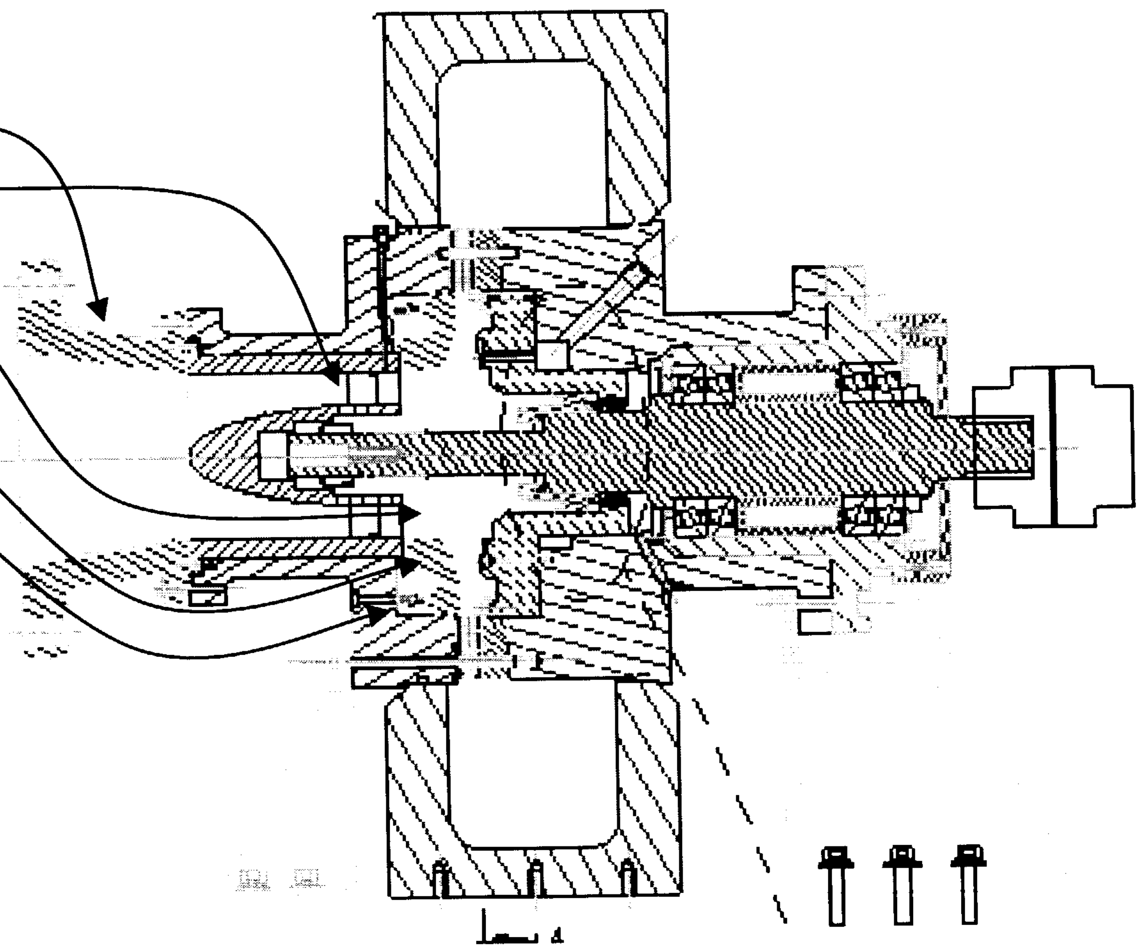
Axial length provides spacing between turbine and pump to accommodate turbine temperatures

RLV HPFTP unshrouded concept

Concept design also included assessment of axial thrust, rotordynamics, weight, and impeller stress to ensure a viable concept to advance to an operational turbopump

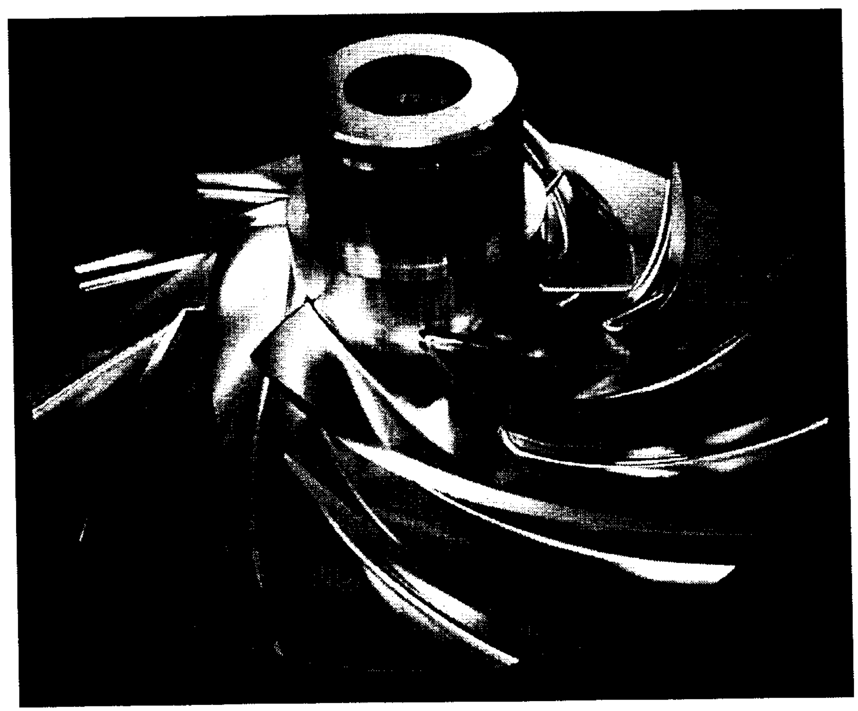
Advanced Experiment - Test Article Description

- **Modular Design Allows for Use With a Variety of Inlet, Impeller, and Diffuser Configurations**
- **Advanced Modifications**
  - Inlet Adapter
  - Inlet Guide Vane Assembly
  - 6+6 Impeller
  - Front Shroud
  - Shims



Advanced Experiment - Impeller Test Status

- Modifications to unshrouded impeller test article completed
- Test article installed in PTE Facility
- Test Readiness Review (TRR) completed
- Bearing wear-in and test article Tare test completed
- Testing to began in March and will be completed in May 2001



Task Summary

- Unshrouded Impeller Task to be completed in July 2001
- Viable Turbopump Concept Completed and ready for more detailed design and analysis
- Recommend Concept to proceed to next level of design as candidate for turbopump demonstrator
- MSFC accepts role of providing service to develop high risk hardware and transfer technology to rocket engine industry
- Industries request for technology during NRA8-30 process shows their desire to leverage MSFC's capability
- Cooperative tasks with GRC and ARC have also been generated because of this task