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RI/RD 93-195

PUMP CFD CODE VALIDATION TESTS - FINAL REPORT

15 December 1993

NAS8-38864

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16. Abstract

Pump CFD code validation tests were accomplished by obtaining non-intrusive flow characteristic data at key locations in generic current liquid rocket engine turbopump configurations. Data were obtained with a laser two-focus (L2F) velocimeter at scaled design flow. Three components were surveyed: a 1970's-designed impeller, a 1990's-designed impeller, and a four-bladed unshrouded inducer. Two-dimensional velocities were measured upstream and downstream of the two impellers. Three-dimensional velocities were measured upstream, downstream, and within the blade row of the unshrouded inducer.

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FORWARD

Computer advancements and improvements in numerical algorithms, and physical modeling make using Computational Fluid Dynamics (CFD) codes a feasible and cost-effective approach to pump design. Complex three-dimensional geometry and flow fields necessitate an accurate and substantial data base to validate the CFD codes.

A test program to obtain benchmark quality data for typical rocket engine pump geometry was successfully completed in Rocketdyne's Engineering Development Laboratory (EDL) Pump Test Facility (PTF). A two-component laser two-focus velocimeter was used to obtain flow field data at the inlet and discharge of two impellers: the Space Shuttle Main Engine (SSME) high pressure fuel turbopump (HPFTP) impeller and the Pump Consortium baseline impeller. Unshrouded inducer flow field data were obtained with a three-component laser two-focus velocimeter.

All laser velocimeter data acquired at scaled design flow for the three test articles were electronically transmitted to NASA-MSFC in an agree upon plot3d format.

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TABLE OF CONTENTS

Forward	i
Page Revision Log	ii
Table of Contents	iii
List of Illustrations	iv
List of Tables	v
Introduction	1
Test Article	2
Test Facility	6
Test Instrumentation	7
Test Program	9
Results	16
Conclusion	22
Bibliography	23

LIST OF ILLUSTRATIONS

Illustration Number	Illustration Title	Page
1	SSME HPFTP Impeller Tester Configuration	4
2	Consortium Baseline Impeller and ADP Inducer Tester Configuration	5
3	Schematic of Test Facility	6
4	Location of SSME HPFTP Impeller Discharge Laser Velocimeter Survey	10
5	Location of Consortium Baseline Impeller Discharge Laser Velociemeter Survey	12
6	Location of Inducer Laser Velocimeter Survey	13
7	Secondary Flow Direction	16
8	SSME HPFTP Impeller Discharge - Nondimensional Absolute Velocity	17
9	Consortium Baseline Impeller Discharge - Nondimensional Absolute Velocity	18
10	Inducer Radial Velocity Component	19
11	Nondimensional Absolute Axial Velocity Component	20
12	Nondimensional Absolute Tangential Velocity Component	21

LIST OF TABLES

Table Number	Table Title	Page
1	Design Details of SSME HPFTP Impeller	2
2	Design Details of Consortium Baseline Impeller	2
3	Design Details of ADP Unshrouded Inducer	3
4	Test Instrumentation	7
5	SSME HPFTP Impeller Inlet Laser Survey Radial Locations	9
6	SSME HPFTP Impeller Discharge Laser Survey Axial Stations	10
7	Consortium Baseline Impeller Inlet Laser Survey Radial Locations	11
8	Consortium Baseline Impeller Discharge Laser Survey Axial Locations	12
9	ADP Inducer Inlet Pipe Laser Survey Radial Locations	13
10	Inducer Laser Survey Locations	14

INTRODUCTION

In 1990 the National Aeronautics and Space Administration (NASA) established the Consortium for CFD (Computational Fluid Dynamics) Application in Propulsion Technology at the George C. Marshall Space Flight Center (MSFC) [1]. Among the tasks for the Pump Stage Team of the Consortium was coordinating and focusing MSFC sponsored activities aimed at the advancement, application, and demonstration of CFD technology for pump design.

Development of Computational Fluid Dynamics computer codes for complex turbomachinery affords three-dimensional (3-D) flow field calculations. Accurate data bases are required to validate the CFD codes to enable evaluation of existing turbulence models. However, existing data for pump CFD code validation is limited.

Traditional flow field survey information, pressure sensors and directional probes, are intrusive and typically have an accuracy which yields results with uncertainties greater than 0.5 percent of transducer range: thus not yielding benchmark quality data. Laser velocimetry is non-intrusive and yields accurate flow velocity ($\pm$0.5 percent of measured value) and angle data ($\pm$0.5 degrees). More importantly, pressure sensors and directional probes only yield circumferentially-average information, whereas laser velocimeter provides information at specific blade-to-blade circumferential location.

Under contract to NASA-MSFC (NAS8-38864) a test program described herein was undertaken. The test program had the specific objective to obtain benchmark quality data, flow velocity and angle, at key locations in a generic pump at design flow rate. A total of three pump components were surveyed with the laser velocimeter: a 1970's-designed impeller (SSME HPFTP), a 1990's-designed impeller (Pump Consortium baseline), and a four-bladed unshrouded inducer. The fluid medium for the laser velocimeter surveys was ambient water.

The test program comprised three test series, one for each of three test articles. A summary test report was issued at the conclusion of each test series and fully describe the test articles and results [2], [3], and [4]. Test articles, tester configurations, laser velocimeter survey locations, and results are sufficiently dissimilar to warrant referencing individual reports rather than incorporating all three into one report.

Standard nondimensionalizing, by relevant tip diameter and tip speed, was performed to enable general application of the data for CFD code benchmarking.

TEST ARTICLE

The test articles represent a range of turbopump component design: a 1970's design impeller, a 1990's design impeller and a 1990's design inducer. The 1970's-designed shrouded impeller was a trimmed Space Shuttle Main Engine (SSME) High Pressure Fuel Turbopump (HPFTP) first stage impeller. Table 1 gives specific impeller design details.

Table 1. Design Details of SSME HPFTP Impeller

PARAMETER	VALUE
Number of Impeller Full Blades	6
Number of Impeller First (Short) Partials	6
Number of Impeller Second (Long) Partials	12
Nondimensional Inlet Eye Diameter	0.5743
Shaft Speed, rpm	6322
Impeller Tip Speed, m/s	92.4867
Nondimensional Impeller Shroud Wear Ring Radial Clearance	0.000136
Impeller Inlet Design Flow Coefficient*	0.256
Nondimensional Inducer Tip Radial Clearance	0.000636
Nondimensional Impeller B2 Width	0.053864
Nondimensional Impeller Shroud Thickness at Discharge	0.013091
Nondimensional Impeller Hub Thickness at Discharge	0.018773
* Based on tester inlet flow and impeller eye speed, does not take recirculation flow into account	

The 1990's-designed shrouded impeller was designated the Pump Consortium Baseline impeller. Table 2 gives specific impeller design details.

Table 2. Design Details of Consortium Baseline Impeller

PARAMETER	VALUE
Number of Impeller Full Blades	6
Number of Impeller Partial Blades	6
Nondimensional Inlet Eye Diameter	0.6633
Shaft Speed, rpm	6322
Impeller Tip Speed, m/s	76.0493
Nondimensional Impeller Shroud Wear Ring Radial Clearance	-0.000166
Impeller Inlet Design Flow Coefficient*	0.144
Nondimensional Inducer Tip Radial Clearance	0.000967
Nondimensional Impeller B2 Width	0.078699
Nondimensional Impeller Shroud Thickness at Discharge	0.01393
Nondimensional Impeller Hub Thickness at Discharge	0.01739
* Based on tester inlet flow and impeller eye speed. Does not take recirculation flow into account.	

The unshrouded inducer was previously designed for application under the Advanced Development Program (ADP). Table 3 gives specific inducer design details.

Table 3. Design Details of ADP Unshrouded Inducer

PARAMETER	VALUE
Number of Inducer Blades	4
Inducer Tip diameter, cm	15.24
Nondimensional Inducer Discharge Tip Diameter	1.00
Nondimensional Inducer Inlet Hub Diameter	0.30
Nondimensional Inducer Discharge Hub Diameter	0.65
Shaft Speed, rpm	6322
Inducer Tip Speed, m/s	50.4473
Nondimensional Inlet Pipe Radius	0.510075
Nondimensional Inducer Tip Radial Clearance	0.00167
Inducer Inlet Design Flow Coefficient*	0.0912
* Based on tester inlet flow and inducer tip speed. Does not take recirculation flow into account.	

Two distinct tester configurations were used: one for the SSME HPFTP impeller, Figure 1, and one for both the Consortium baseline impeller and the ADP inducer surveys, Figure 2. In the SSME HPFTP impeller test configuration a six-blade unshrouded inducer, originally designed to match the SSME HPFTP impeller early in the program, was used. The current SSME HPFTP does not include an inducer nor was the inducer surveyed during this test program and therefore will not be described herein. Both tester configurations incorporated an axial inlet, an unshrouded inducer upstream of the impeller, a shrouded impeller, and a crossover diffuser discharge. The inducers in both testers were decoupled from the impellers via an atypical axial length between the inducer and impeller. This allowed representative flow into the impellers i.e. swirl and inducer blade wakes, without complicating the impeller inlet flow sufficiently that the CFD codes are not reasonably expected to be able to model the physical flow. Impeller shroud leakage flow was minimized in both tester configurations via tight impeller labyrinth seal radial clearances. Minimizing leakage eliminates the need to model the leakage flow with the CFD codes. In both test configurations the diffuser was located further downstream than typical. In the case of the trimmed SSME HPFTP impeller the trimming operation of the impeller outer diameter resulted in an increase in radial clearance between the impeller discharge and the diffuser inlet. The same crossover diffuser discharge, from an SSME HPFTP, was used for both test configurations. The Consortium baseline impeller outer diameter was 17.8 percent less than the SSME HPFTP impeller. The interaction effects between the impeller and diffuser were not examined in this project and so the atypical radial clearance between the impeller and diffuser was not deemed significant for the purposes of this test program. The crossover discharge was used to minimize any asymmetric discharge effects in the tester.

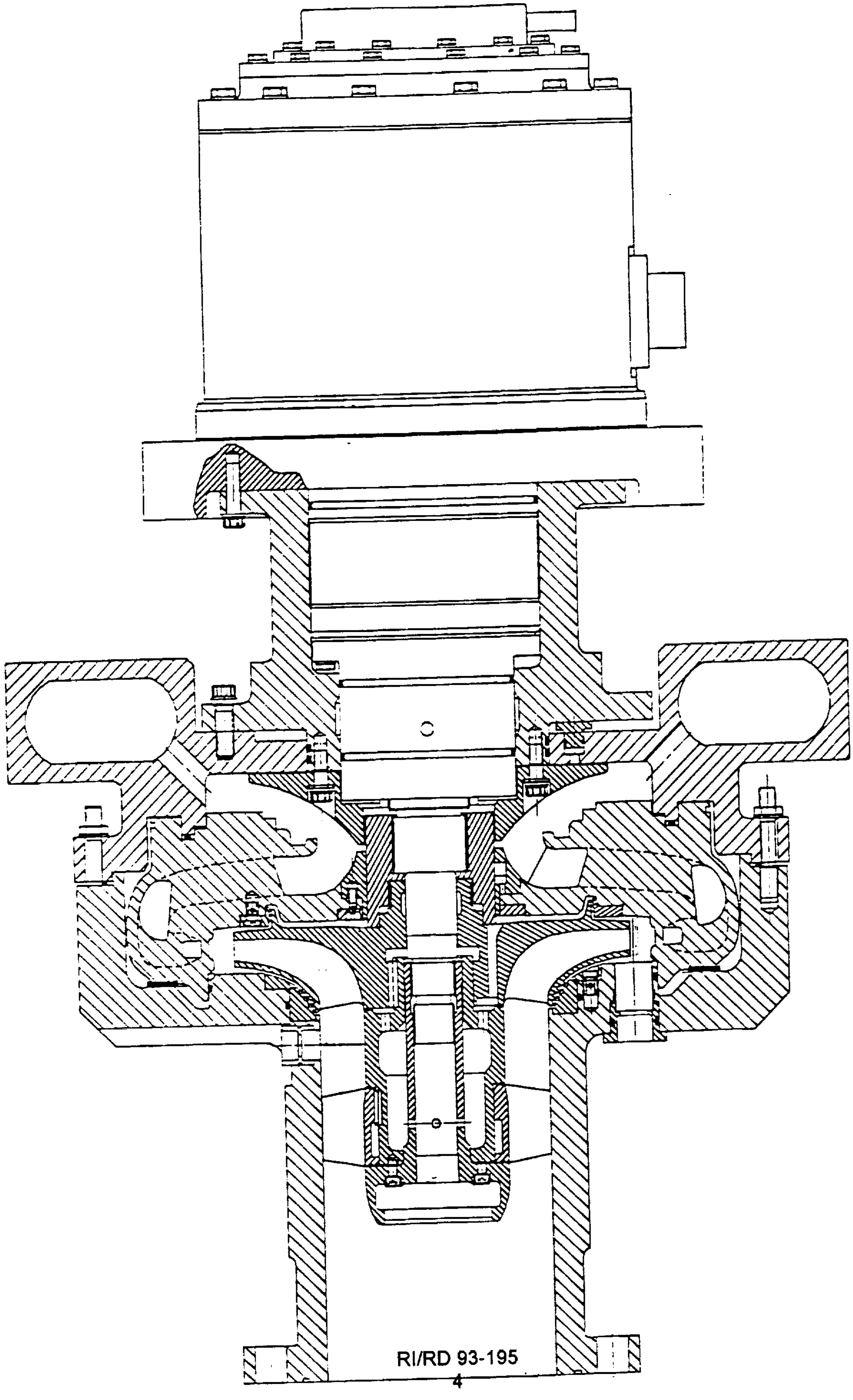

Figure 1. SSME HPFTP Impeller Tester Configuration

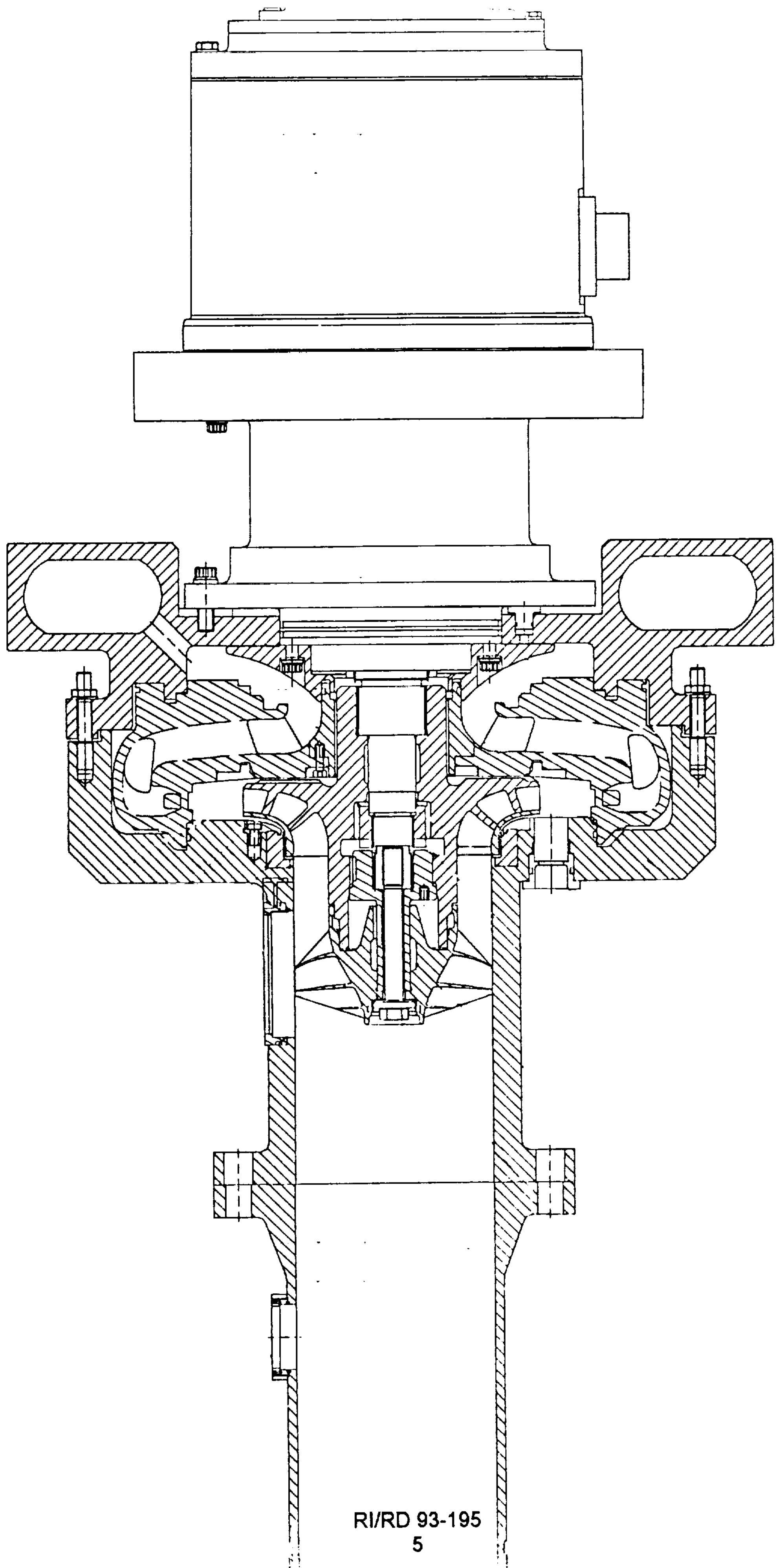

Figure 2. Consortium Baseline Impeller and ADP Inducer Tester Configuration

TEST FACILITY

The three test series of the test program were conducted in the Engineering Development Laboratory (EDL) Pump Test Facility (PTF) located at Rocketdyne's main facility in Canoga Park, California. A schematic of the flow loop is presented in Figure 3. The test article was driven by a 1200 rpm, reversible, synchronous electric motor rated at 2984 kilowatts. The motor is coupled to a 2984 kilowatt gearbox capable of producing speed of 6322, 8013, and 10029 revolutions per minute. The pump CFD code validation configuration was tested at 6322 rpm on the North powerhead (pump position No. 1).

Water was supplied to the closed flow loop from a 28.769 cubic meter stainless steel tank. The tank is rated at 1.0342 MPa with a vacuum capability of 0.0962 MPa. A heat exchanger, located adjacent to the tank, maintained a uniform fluid inlet temperature. The flow rate to the tester was regulated by a throttle valve downstream of the pump. After passing through the throttle valve and into the tank, the flow passed through a series of baffles in the tank and was recirculated through the facility.

The tester inlet ducting consisted of 20.32 cm schedule 10 and 15.24 cm schedule 40 piping. A reducer located approximately 10 inlet line diameters upstream of the inducer mated the 20.32 cm line to the 15.24 cm line. Victaulic coupled joints were used in a 15.24 cm inlet line section. All Victaulic coupled joints were heavily greased to assure an airtight system.

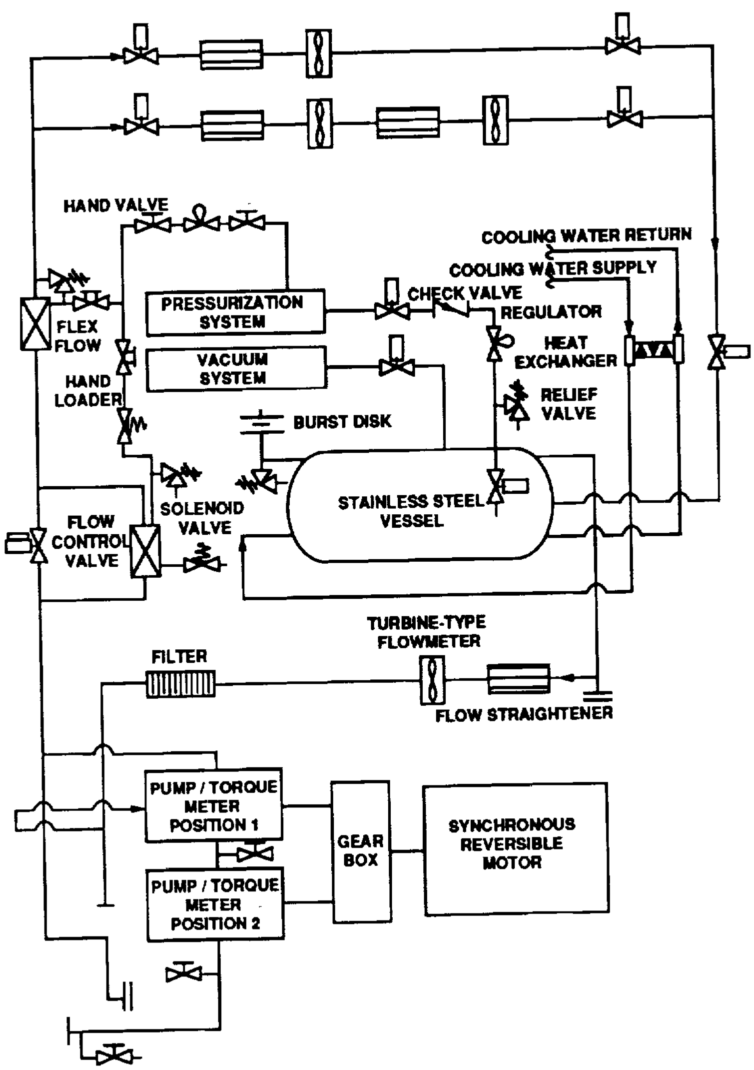

Figure 3. Schematic of Tester Facility

TEST INSTRUMENTATION

All three test series used similar instrumentation which is presented in Table 4. Two four-tap static piezometer rings were used to measure the inlet static pressure. Pressure PZ0 was located approximately 13.5 inlet pipe diameters upstream of the inducer. Pressure PZ1 was located approximately 8.7 inlet pipe diameters upstream of the inducer. Water temperature was measured in the inlet line with a platinum wire filament temperature detector to allow calculation of the fluid density and vapor pressure.

Table 4. Test Instrumentation

PARAMETER	RANGE	UNITS
Inlet Static Piezometer PZ0	0-0.6895	MPa, abs
Inlet Static Piezometer PZ1	0-0.6895	MPa, abs
Inlet Line Flowmeter	0-15.14	m^3/sec
Tester Shaft Speed	0-6322	rpm
Tester Torque	0-2260	N-m
Inlet Fluid Temperature	4.44-54.44	degrees C
Impeller Shroud Seal Upstream Static Pr. P4	0-6.8948	MPa
Tester Discharge Static Piezometer PZ2	0-6.8948	MPa
Pump Differential Pressure PD1-PZ0	0-6.8948	MPa
Impeller Inlet Static Pressure P1	0-2.4132	MPa
Impeller Inlet Static Pressure P2	0-2.4312	MPa
Impeller Inlet Static Pressure P3	0-2.4312	MPa
Impeller Discharge Static Pr. Plane 1 PD1	0-6.8948	MPa
Impeller Discharge Static Pr. Plane 2 PD2	0-6.8948	MPa
Impeller Discharge Static Pr. Plane 2 PD4	0-6.8948	MPa
Impeller Discharge Static Pr. Plane 2 PD5	0-6.8948	MPa
Impeller Discharge Static Pr. Plane 3 PD3	0-6.8948	MPa

Three inducer discharge (impeller inlet) static pressure measurements (P1, P2, and P3) were aligned in one axial plane but distributed around the circumference (90 degrees apart) to identify any circumferential pressure variations of impeller inlet flow. This identification is important because the laser survey occurs at one particular circumferential location and is assumed to represent all symmetric sections.

Similarly, identification of circumferential variations at the impeller discharge was accommodated by three static pressure taps located around the tester circumference in a radial plane located downstream of the impeller. One static pressure tap was included at each of two radial plane above and below the previously discussed plane. A differential static pressure measurement between the lowest radial impeller discharge survey plane and the tester inlet provided redundancy. All pressure measurements were obtained with Taber full bridge strain gage transducers with an accuracy of ± 0.5 percent of full range.

Tester fluid flow rate was measured with one 20.32 cm turbine-type flowmeter in the inlet line with measurement redundancy provided by one 20.32 cm turbine-type flowmeter in the discharge line. The inlet line flowmeter was used to control tester flow. Flowmeter accuracy is ± 0.1 percent of full range. A Lebow torquemeter with grease-packed bearings was installed between the gearbox and the mounting pedestal.

Two three-axis accelerometer blocks were used, one mounted on to the Universal Adapter and one mounted on to the tester inlet housing. Gearbox, torquemeter, and lube oil temperatures, lube oil pressures and additional facility temperatures and pressures were installed and monitored. The accelerometer data were recorded on FM tape to yield resolution up to 5000 Hz.

All data were recorded with a Pump Test Facility Digital Data Acquisition System (PDAS). The data were sent using BLAST software, to an IBM PS/2 model 50Z computing system. All engineering calculations were performed in single precision on the Apollo computing system using a data reduction program written specifically for the Pump Test Facility.

Measurements were made in U.S. Customary System (USCS) units and have been converted to Le Système International d'Unités (SI) in Table 3. SI units will be used exclusively in this report. All calculations were performed with USCS units and converted to SI units in the final data processing step.

The two impeller flow fields were surveyed with a Polytec fiber-optic based two component laser two-focus velocimeter (model L2F-O-5000). A Polytec fiber-optic based three-component laser two-focus velocimeter (model L2F-O-6000) was used to obtain velocity and flow angle data. Accuracy of the velocity measurements is ±0.5 percent of measured velocity and ±0.5 degrees in flow angle. Both static and dynamic phase angle measurements between the inducer timing mark, referenced to a known location on the test article and the shaft once-per-revolution glitch used for laser synchronization, were performed. The static phase angle measurement was performed with no rotation in air and the dynamic phase angle measurement was performed at test speed and flow in water. Checks for all test series showed excellent agreement between the static and dynamic phase checks. Because the dynamic phase check reflected actual test conditions it was used for laser synchronization.

TEST PROGRAM

The test programs were performed to maximize flow field characterization by strategically locating the laser survey positions. This laser survey location criteria resulted in the SSME HPFTP impeller inlet and discharge survey locations as indicated in Table 5 and Table 6, respectively. The impeller inlet survey was performed at ten radial locations in one axial plane to provide boundary conditions to CFD codes. The impeller inlet annulus at the hub is designated as 0 percent and at the tester inner wall is 100 percent.

Table 5. SSME HPFTP Impeller Inlet Laser Survey Radial Locations

NONDIMENSIONAL RADIUS	% IMPELLER INLET ANNULUS HEIGHT
0.18871	10
0.19437	15
0.20567	25
0.21698	35
0.22828	45
0.23959	55
0.25089	65
0.26220	75
0.27351	85
0.28481	95

SSME HPFTP Impeller inlet surveys were performed over 60 circumferential degrees corresponding to one impeller full blade passage. The 60 degree segment was partitioned into 16 electronic data windows yielding distinct flow zone of 5.625 degrees (60/16) of angular sweep. A slot machined into the inducer/impeller adapter was used as a timing mark. The impeller inlet timing mark centerline was located from an axial projection of the full blade leading edge tip. Data at the impeller inlet were ensemble averaged, i.e., for a particular electronic window, data were collected in each of the six blade passages, thereby yielding flow angles and velocities from all six blade passages.

The purpose of the impeller discharge surveys is to provide data for CFD code benchmarking. For this reason, locations that provide a complete flow field description are required. The SSME HPFTP impeller discharge surveys were performed at multiple axial locations along three radial planes. The nondimensional radial locations of the axial surveys were: 0.5064, 0.5183, and 0.5303. In Table 6 the laser survey nondimensional axial positions have been referenced from the impeller discharge tip shroud, 0.0 percent of impeller B_2 width. A negative value occurs when the axial location of the survey point is forward (toward the tester inlet) of the impeller discharge tip shroud. A value greater than 100.0 percent is indicative of a laser survey position at an axial distance toward the tester aft end, in excess of the impeller B_2 width.

Encompassed in a 60 degree segment between two adjacent full blades at the SSME HPFTP impeller discharge are: two short partial blades and one long partial blade. Circumferential partitioning over two adjacent 30 degree segments provided better circumferential flow definition between adjacent blades. With sixteen windows, data are segregated into distinct flow zones of 1.875 degrees (30 degrees/16 windows) of angular sweep. A slot was machined into the impeller shroud for use as a timing mark. The impeller discharge timing mark centerline was located from an axial projection midway between the impeller suction and pressure surfaces at the impeller tip, 0 percent impeller B_2 width.

The center of the timing mark was used to commence circumferential laser velocimeter surveys at all axial survey locations. Adjacent 30 degree segments were not similar and ensemble averaging of the impeller discharge data was not performed.

Table 6. SSME HPFTP Impeller Discharge Laser Survey Axial Stations

LASER SURVEY POINT DESIGNATION	NONDIMENSIONAL AXIAL LOCATION FROM REFERENCE	% IMPELLER B_2 WIDTH
Nondimensional Radius = 0.5064		
18	0.09465	-50.9283
17	0.10572	-30.3713
14	0.12285	1.4295
13	0.12419	3.9156
7	0.13177	17.9899
6	0.14069	34.5502
12	0.14515	42.8354
5	0.14961	51.1089
4	0.15853	67.6692
11	0.16299	75.9494
3	0.16745	84.2363
10	0.17504	98.3122
Nondimensional Radius = 0.5183		
7	0.13177	17.9899
6	0.14092	34.5502
5	0.14961	51.1089
4	0.15853	67.6692
3	0.16745	84.2363
Nondimensional Radius = 0.5303		
22	0.09652	-47.4641
9	0.10019	-40.6498
21	0.10816	-25.8473
8	0.11613	-11.0447
7	0.13177	17.9899
6	0.14092	34.5502
5	0.14961	51.1089
4	0.15853	67.6692
3	0.16745	84.2363
2	0.18614	118.9198
20	0.19022	126.5097
19	0.19431	134.0979
1	0.1984	141.6878

Figure 4 presents the SSME HPFTP impeller discharge laser survey locations.

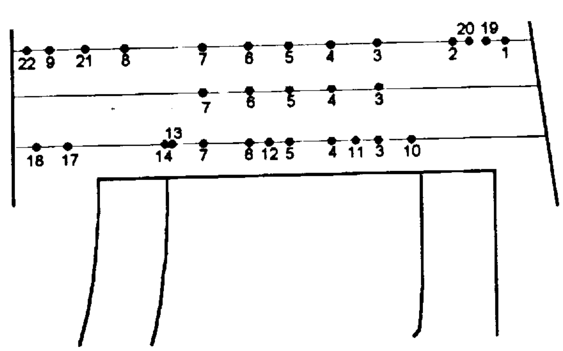

Figure 4. Location of SSME HPFTP Impeller Discharge Laser Velocimeter Survey

The laser velocimeter surveys at the impeller inlet of the Consortium baseline impeller corresponded to the same annulus height percentages as for the SSME HPFTP impeller. These are indicated in Table 7. Laser surveys were performed over two adjacent 90 degree arc segments. Each survey commenced with the impeller inlet timing mark defined with its centerline located from an axial projection of the full blade leading edge tip. Each segment was partitioned into sixteen circumferential electronic data windows (90/16) yielding data over 5.625 arc degrees. Adjacent 90 degree arcs were surveyed because it was not known a priori if the four inducer blades or if the six impeller blades would be dominant in the flow field. Because adjacent 90 degree arc segments were dissimilar, data were not ensemble averaged.

Table 7. Consortium Baseline Impeller Inlet Laser Survey Radial Locations

NONDIMENSIONAL RADIUS	% IMPELLER INLET ANNULUS HEIGHT
0.22731	10
0.23317	15
0.24489	25
0.25660	35
0.26832	45
0.28004	55
0.29176	65
0.30348	75
0.31520	85
0.32692	95

The impeller discharge surveys were performed at multiple axial locations, Table 8, along two radial planes. The nondimensional radial locations of the axial surveys were: 0.5138 and 0.5597. Encompassed in a 60 degree segment between two adjacent full blades at the impeller discharge is one partial blade. Circumferential partitioning over two adjacent 30 degree segments provided better circumferential flow definition between adjacent blades. With sixteen windows, data are segregated into distinct flow zones of 1.875 degrees (30 degrees/16 window) of angular sweep. A slot was machined into the impeller shroud for use as a timing mark. The impeller discharge timing mark centerline was located from an axial projection midway between the impeller suction and pressure surfaces at the impeller tip, 0 percent impeller B_2 width.

The center of the timing mark was used to commence circumferential laser velocimeter surveys at all axial survey locations. Adjacent 30 degree segments were not similar and ensemble averaging of the impeller discharge data was not performed. Figure 5 presents the Consortium baseline impeller discharge laser survey locations.

The three-component inducer laser survey mapping provided flow field velocity and flow angle at one axial laser survey upstream of the inducer inlet and six axial surveys: upstream of, downstream of, and within the blade row. This provided detailed characterization of the inducer flow field. The inducer inlet pipe survey was performed in one axial plane at nine radial spaced positions across the inlet pipe. Table 9 lists the nondimensional radial positions, referenced from the shaft centerline. Zero percent is the pipe centerline and 100 percent is the pipe inner wall. The radial points were chosen to provide good flow definition near the boundary and to check for symmetry across the pipe. Since a check for flow symmetry was performed, the same pipe radius position was surveyed on either side of the pipe centerline. The surveys are distinguished by an indication of 9 o'clock or 3 o'clock referring to the clock position of the survey looking into the inducer eye.

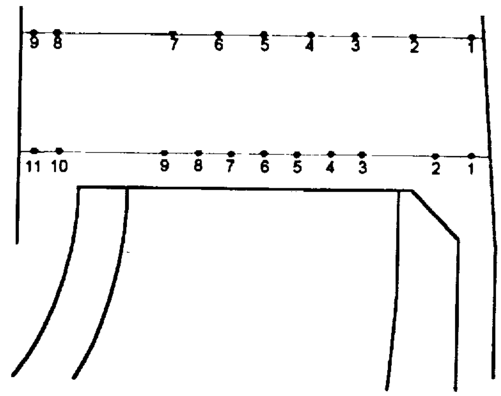

Figure 5. Location of Consortium Baseline Impeller Discharge Laser Velocimeter Survey

Table 8. Consortium Baseline Impeller Discharge Laser Survey Axial Locations

LASER SURVEY POINT DESIGNATION	NONDIMENSIONAL AXIAL LOCATION FROM REFERENCE	% IMPELLER B_2 WIDTH
Nondimensional Radius = 0.5138		
11	0.15427	-32.6
10	0.16013	-25.1
9	0.18976	12.5
8	0.19960	25.0
7	0.20944	37.5
6	0.21927	50.0
5	0.22911	62.5
4	0.23895	75.0
3	0.24878	87.5
2	0.26391	106.7
1	0.27903	125.9
Nondimensional Radius = 0.5597		
9	0.15427	-32.6
8	0.16013	-25.1
7	0.19304	16.7
6	0.20616	33.3
5	0.21927	50.0
4	0.23239	66.7
3	0.24551	83.3
2	0.26094	102.9
1	0.27638	122.6

Circumferential laser surveys were performed over sixty degrees, corresponding to an inducer blade passage, was performed to allow any upstream inducer effects to be exhibited.

Table 9. ADP Inducer Inlet Pipe Laser Survey Radial Locations

NONDIMENSIONAL RADIUS	% PIPE RADIUS	CLOCK POSITION
0.4973	97.50	9
0.4846	95.00	9
0.4591	90.00	9
0.4081	80.00	9
0.3060	60.00	9
0.1526	29.93	9
0.0008	0.15	3
0.1542	30.23	3
0.3076	60.30	3

The inducer laser surveys were performed at multiple radial locations along six axial planes. The nondimensional axial locations of the surveys were: -0.0083, 0.1222, 0.1793, 0.2364, 0.2925, and 0.4644. The first plane was located just upstream of the inducer blade row near the inducer blade leading edge hub, the second plane corresponded to the inducer leading edge tip, the third and fourth planes were totally within the blade row, the fifth plane corresponded to the inducer suction surface trailing edge tip, and the sixth plane was located downstream of the inducer blade row near the inducer blade trailing edge hub. Table 10 lists the nondimensional radial positions, referenced from the inducer centerline. The positions, chosen to maximize flow definition in the inducer hub and tip region, are also identified in terms of the percentage of the annulus height. With this designation, 0 percent is the inducer hub and 100 percent is the tester inner wall.

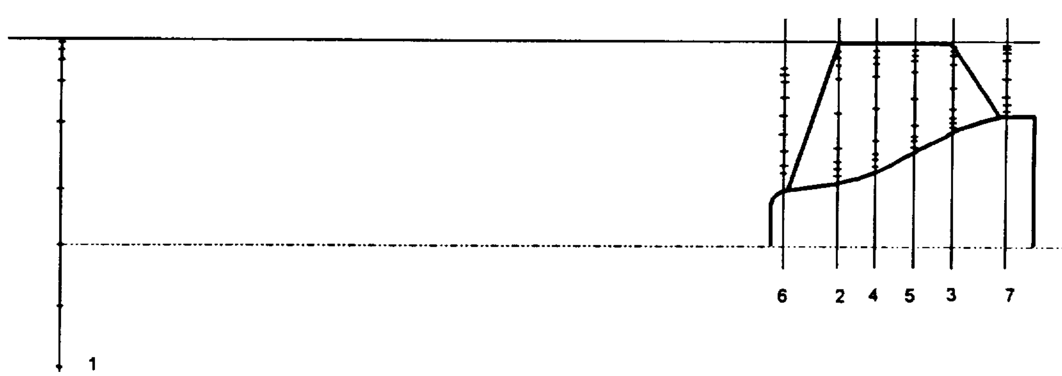

Figure 6. Location of Inducer Laser Velocimeter Survey

Table 10. Inducer Laser Survey Locations

LASER SURVEY POINT DESIGNATION	NONDIMENSIONAL RADIAL LOCATION FROM REFERENCE	% ANNULUS HEIGHT
Plane 2 - Nondimensional Axial Plane = 0.1222		
9	0.22855	10
8	0.26042	15
7	0.34008	25
6	0.37993	50
5	0.39985	62.5
4	0.41976	75
3	0.45161	85
2	0.46755	90
1	0.48348	95
Plane 3 - Nondimensional Axial Plane = 0.2925		
9	0.29045	7.5
8	0.29613	10
7	0.30745	15
6	0.33012	25
5	0.38678	50
4	0.44343	75
3	0.46612	85
2	0.47743	90
1	0.48877	95
Plane 4 - Nondimensional Axial Plane = 0.1790		
9	0.23127	7.5
8	0.23853	10
7	0.25305	15
6	0.28210	25
5	0.35473	50
4	0.42737	75
3	0.45642	85
2	0.47095	90
1	0.48547	95
Plane 5 - Nondimensional Axial Plane = 0.2358		
9	0.26112	7.5
8	0.26755	10
7	0.28047	15
6	0.30628	25
5	0.37082	50
4	0.43533	75
3	0.46115	85
2	0.47405	90
1	0.48697	95
Plane 6 - Nondimensional Axial Plane = -0.0083		
9	0.18460	10
8	0.19335	12.5
7	0.20207	15
6	0.23700	25

Table 10. Continued

LASER SURVEY POINT DESIGNATION	NONDIMENSIONAL RADIAL LOCATION FROM REFERENCE	% ANNULUS HEIGHT
Plane 6 - Nondimensional Axial Plane = -0.0083		
5	0.32432	50
4	0.36798	62.5
3	0.41167	75
2	0.42912	80
1	0.44658	85
Plane 7 - Nondimensional Axial Plane = 0.4644		
9	0.33793	7.5
8	0.34232	10
7	0.35110	15
6	0.36863	25
5	0.41262	50
4	0.45657	75
3	0.47413	85
2	0.48292	90
1	0.49172	95

RESULTS

The following nomenclature is used:

Absolute velocity, C
Absolute tangential velocity, C_u
Absolute axial velocity, C_a
Absolute radial velocity, C_r
Relative Velocity, W
Flow angle in plane normal to laser heads, $Alpha_2$
Flow angle in plane along line-of-sight of to laser heads, $Alpha_3$

Over the course of a test series multiple test days were required to complete the laser survey. Statistical data were reviewed at the conclusion of each test series, excellent test condition repeatability was demonstrated. Thus, data acquired throughout a test series were done so at essentially the same flow conditions.

Static pressures located circumferentially around the impeller inlet, for both the SSME HPFTP trimmed impeller and the Consortium baseline impeller, revealed no significant circumferential variations. All variations were within transducer accuracy. At the discharge of both the SSME HPFTP trimmed impeller and the Consortium baseline impeller the circumferential static pressure variation was slightly asymmetric.

Flow continuity matches for impellers and inducer were performed by calculating an integrated flow rate based on the laser velocimeter velocities and the flow area and then comparing the value to the flow rate measured with the flowmeters. It is appropriate to perform this check when sufficient data across the region of interest is available and it fully describes the flow. Flow continuity matches at the inlet to the two impellers and at the inducer pipe and inducer discharge yielded continuity matches in agreement with previous test programs. As anticipated the deviation between calculated and measured flow rate at the discharge of both impellers was typically greater than at the impeller inlet. This is attributed to a fairly course mesh for the data points and indicates that the flow field was not fully described by the data obtained. A flow continuity check of the inducer interblade measurements is not appropriate because blade shadowing precluded obtaining laser measurements over the entire through-flow area.

For a set of data to be used for CFD code benchmarking, not only must the data be accurate and non-intrusive, but the locations of the data must be well established. Laser survey locations were verified by physical measurements and laser speckle pattern data whenever possible. Because of rotor thrust, the rotating assemblies shifted axially from the static position to the dynamic position. This axial movement was detected and measured with a photonic sensor at the rear of the tester directed at the shaft. All reported data locations reflect the actual location of the survey during the test.

Impeller discharge laser velocimeter laser surveys clearly exhibited impeller wake decay and secondary flow into the impeller shroud and hub cavities. Figure 7 shows the secondary flow exhibited in the Consortium baseline impeller discharge survey. The SSME HPFTP impeller discharge revealed similar second flow patterns. Flow mixing was exhibited as the radial planes surveyed moved further away from the impeller discharge. As mixing occurred the flow velocity tending to became more uniform and the wake effects less distinct. Figure 8 presents flow mixing as exhibited in the nondimensional absolute velocity of the SSME HPFTP impeller discharge. Figure 9 presents a similar plot for the Consortium baseline impeller.

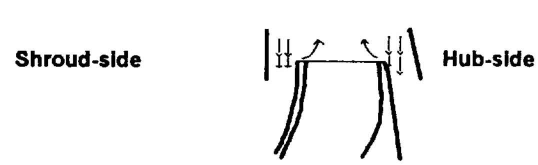

Figure 7. Secondary Flow Direction

PUMP CFD CODE VALIDATION TESTS

SSME HPFTP Impeller Discharge Laser Survey

Nondimensional Radial Planes 0.5064, 0.5183, 0.5303, Impeller Inlet Flow Coefficient = 0.256

Nondimensional Absolute Velocity C

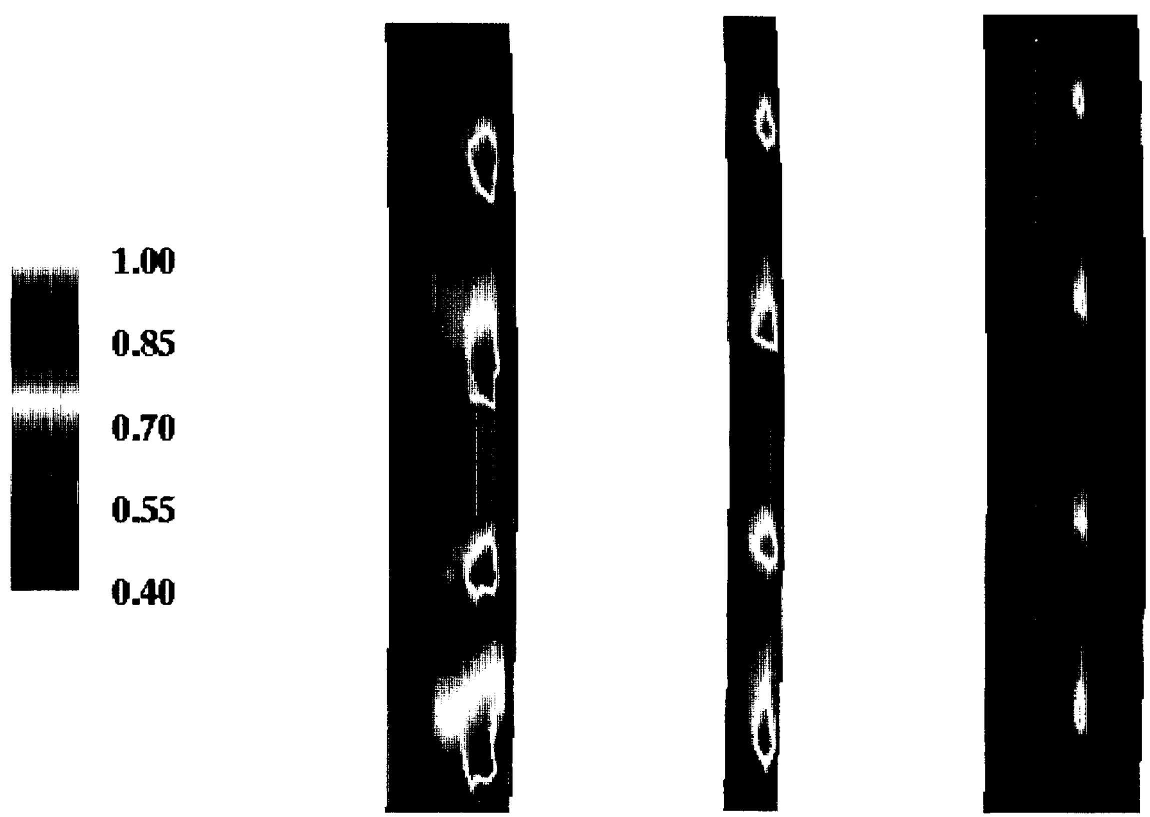

Figure 8.

PUMP CFD CODE VALIDATION TESTS

Consortium Baseline Impeller Discharge Laser Survey

Nondimensional Radial Planes 0.5138, 0.5597, Impeller Inlet Flow Coefficient = 0.144

Nondimensional Absolute Velocity $\bar{C}$

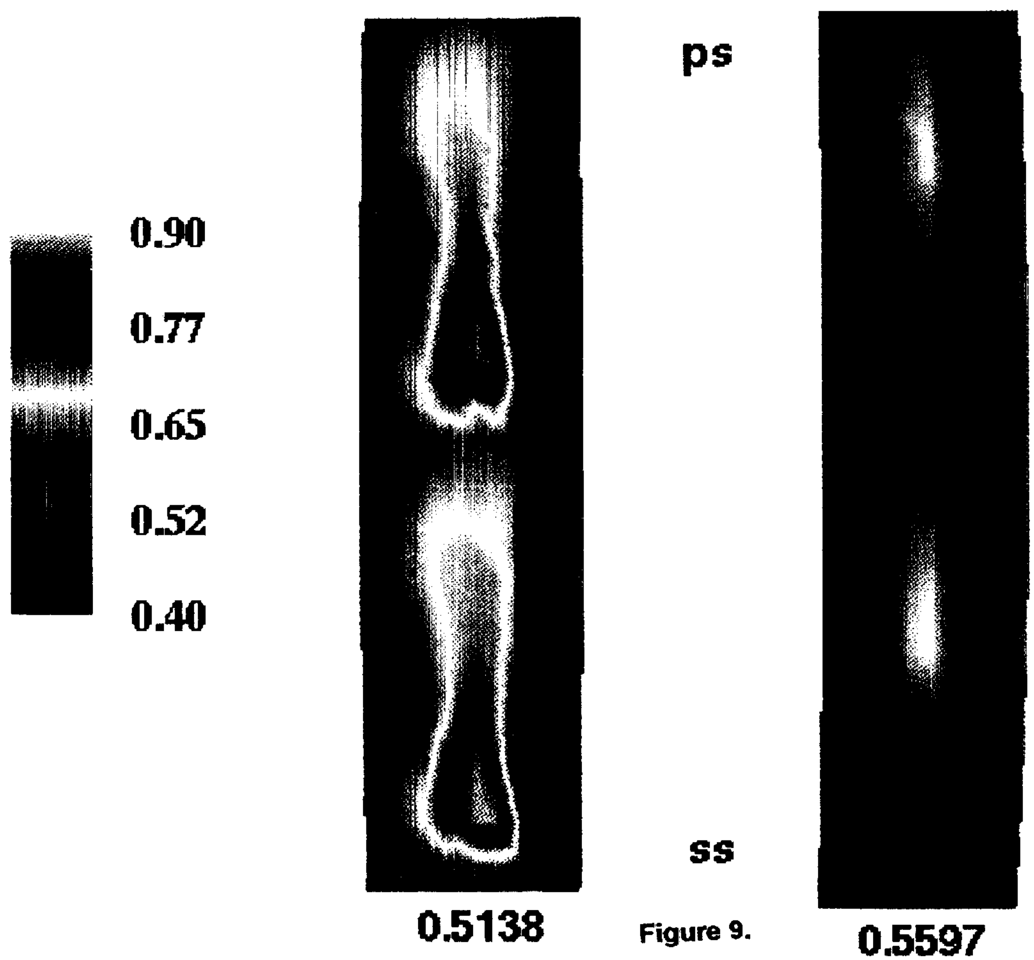

Figure 9.

The inducer surveys added valuable three-component velocity information. Previous laser two-focus surveys data were used with the assumption that one velocity component, namely, the radial component of velocity, was negligible. The three-component laser velocimeter provided three velocity components and is therefore more accurate for pump CFD code validation. While the radial components of velocity was found to be small in comparison to the axial velocity, the inducer laser surveys clearly exhibited secondary flows. Figure 10 presents a qualitative description of the radial velocity component at the inducer leading edge.

Figure 10. Inducer Radial Velocity Component

Performing laser velocimeter surveys for the inducer upstream of the impeller affords a more complete understanding of the flow as it progresses through the pump. Figures 11 and 12 present the circumferential average axial and tangential velocity components in the inducer inlet pipe, at the inducer inlet, at the inducer discharge, and at the impeller inlet. To be consistent, the velocity and location information were nondimensionalized by the relevant inducer parameter.

All laser velocimeter data acquired at scaled design flow for the three test articles were electronically transmitted to NASA-MSFC in an agree upon plot3d format. Measurement of the SSME HPFTP impeller discharge width, B_2, revealed that it was 2.6 percent larger than the model geometry. Data locations obtained which corresponds to locations within the impeller B_2 width were adjusted to maintain the same impeller B_2 width percent location. Outside of the impeller B_2 width, where housing walls and cavity effects are dominant, the data locations were not adjusted.

Listed below is the data file naming convention.

|_1_|_2_|_3_|_4_|_5_|_6_|_7_|_8_|.*extension*

Where alphanumeric characters 1 through 4, inclusive, indicate the test article.

SSME	SSME HPFTP Impeller
SMED	SSME HPFTP Impeller
PCON	Consortium Baseline Impeller
ADP	ADP Inducer

Alphanumeric character 5 indicates the location of the laser survey.;

Alphanumeric characters 6 through 8, inclusive, indicate the ratio of target test flow to test article scaled design flow.

And the extention indicates the plot3d file contents.

gridnd	nondimensional grid X, Y, Z
absnd	nondimensional absolute velocity Cx, Cy, Cz
lasnd	nondimensional laser velocity Ca, Cr, Cu
relnd	nondimensional relative velocity Wx, Wy, Wz

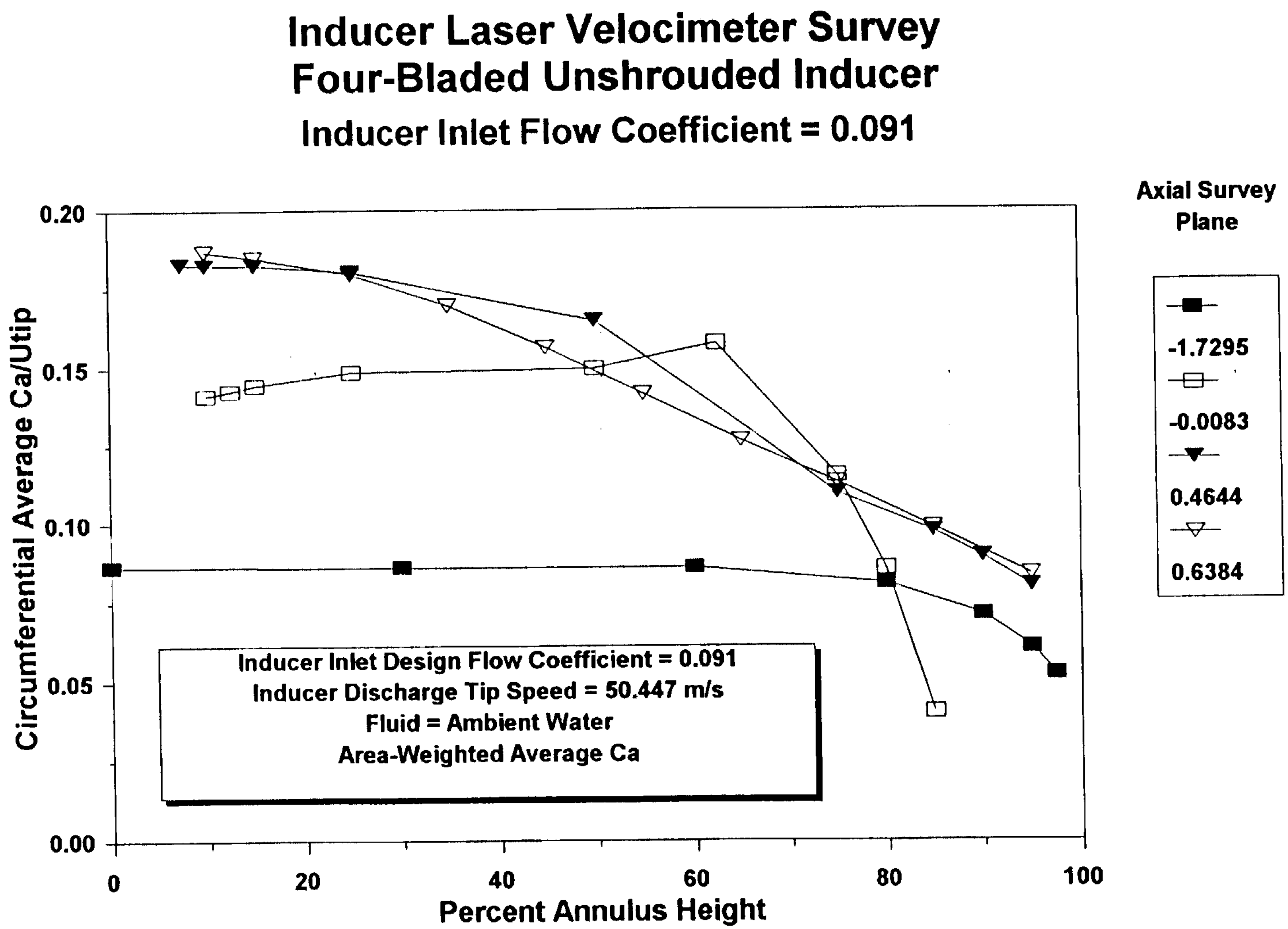

Figure 11. Nondimensional Absolute Axial Velocity Component

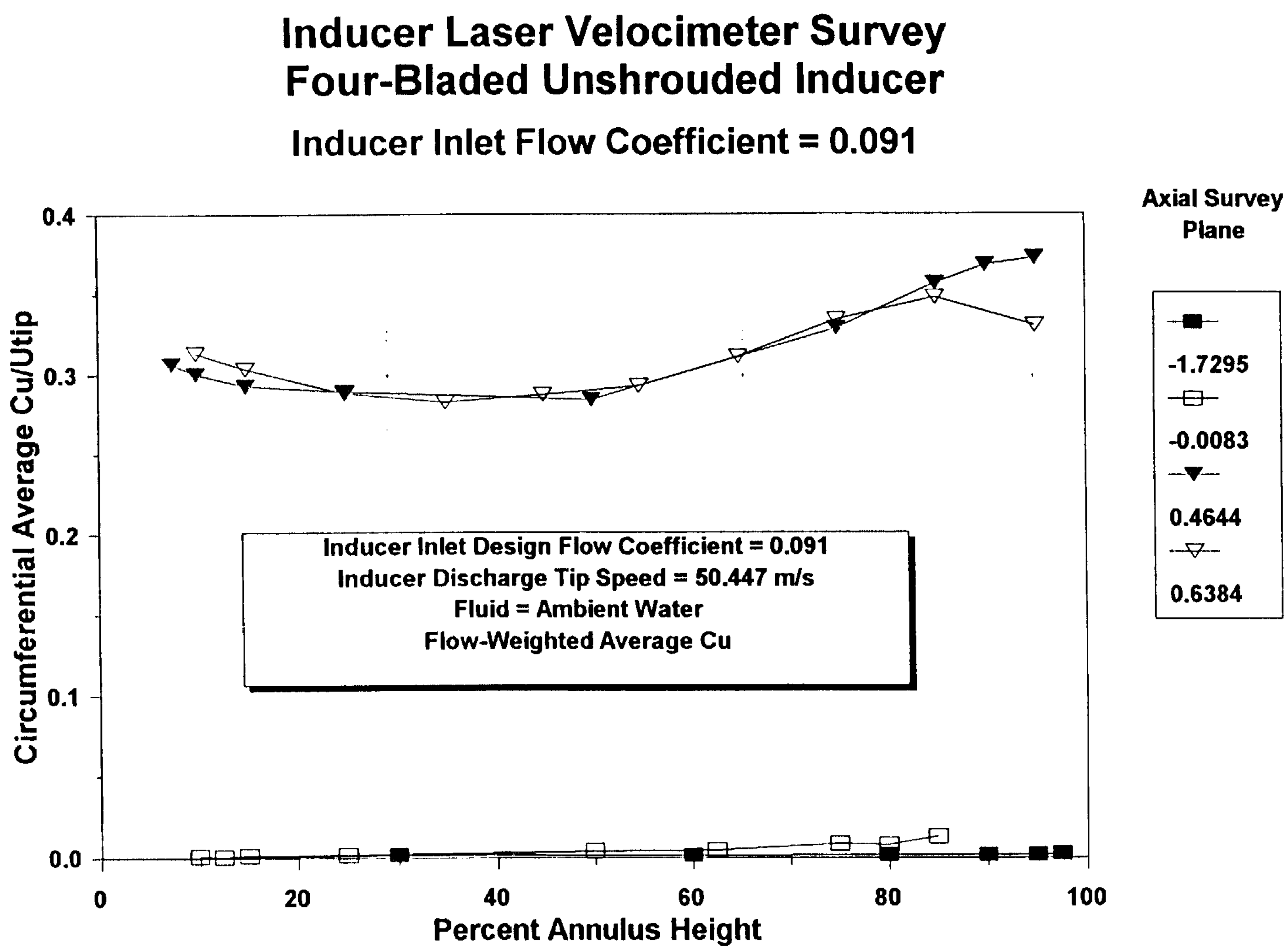

Figure 12. Nondimensional Absolute Tangential Velocity Component

CONCLUSION

A test program to obtain benchmark quality data for typical rocket engine pump geometry was successfully completed in Rocketdyne's Engineering Development Laboratory (EDL) Pump Test Facility (PTF). Data were obtained non-intrusively at the inlet and discharge of two different impellers with a two-component laser tow-focus velocimeter, and throughout an inducer with a three-component laser two-focus velocimeter, static pressures were included at key locations to provide boundary conditions for CFD code validation.

The impeller laser velocimeter surveys clearly identified the significant flow field characteristics. The higher head coefficient Consortium baseline impeller also had a shroud-to-hub tangential velocity which was more conventional for downstream components. Both impeller discharge surveys reflected the secondary flows. This information is essential to benchmarking CFD codes and can be used in future pump designs. A series of impeller laser velocimeter surveys, of impellers designed with CFD optimization with extreme parameter values, will identify the limits or weaknesses of the CFD. A complete impeller blade passage laser velocimeter, performed with a pexiglass shroud and index matching fluid will enhance the CFD code benchmarking significantly.

The three-component inducer surveys provided information for CFD code benchmarking and because of the completeness of the mapping through the information may also be used to alter the inducer design. A similar survey throughout a shrouded inducer could be used for benchmarking CFD codes for shrouded inducers.

The quality and quantity of inducer flow laser data obtained in the three test series described both Rocketdyne and the turbomachinery/fluids technical communities with essential data for pump CFD code validation, improving existing analytical tools, and increasing fluid flow understanding. The data obtained adds significantly to the limited available data base. Non-intrusive, accurate, blade-to-blade data provides detailed fluid characteristics which can significantly improve state-of-the-art pump design optimization.

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