White Paper

<u>FINAL REPORT</u>

AN EVALUATION

OF THE HYDRODYNAMICS MECHANISMS WHICH DRIVE THE PERFORMANCE OF THE WESTFALL STATIC MIXER

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ABSTRACT

The performance of the Westfall Manufacturing Co. static mixer has been evaluated using experimental techniques. At issue was the hydrodynamics mechanism by which the device effectively mixes an additive to the primary fluid stream. A six inch diameter mixer was installed in the Naval Undersea Warfare Center Flow-Loop test facility and the velocity field downstream of the mixer was monitored using Laser Doppler Velocimetry. Multiple two-dimensional profiles of the streamwise and vertical velocity component were measured using this system. The mean and standard deviation of the velocities were computed and are presented at stations up to 8 diameters downstream of the mixer. Two accelerated jets surrounded by very high velocity gradients and intense turbulent mixing dominate the flow. There is no evidence of stable streamwise vortices.

This paper fulfills the contractual obligations to Westfall Manufacturing under purchase order 607619383-5 dated June 16, 1998.

1.0 INTRODUCTION/BACKGROUND

        Westfall manufacturing has developed an innovative static mixer design which is intended to serve as a low-cost, small, highly efficient alternative to other static mixers currently on the market. The mixer is shown as a drawing in figure 1 and as an image in figure 2.
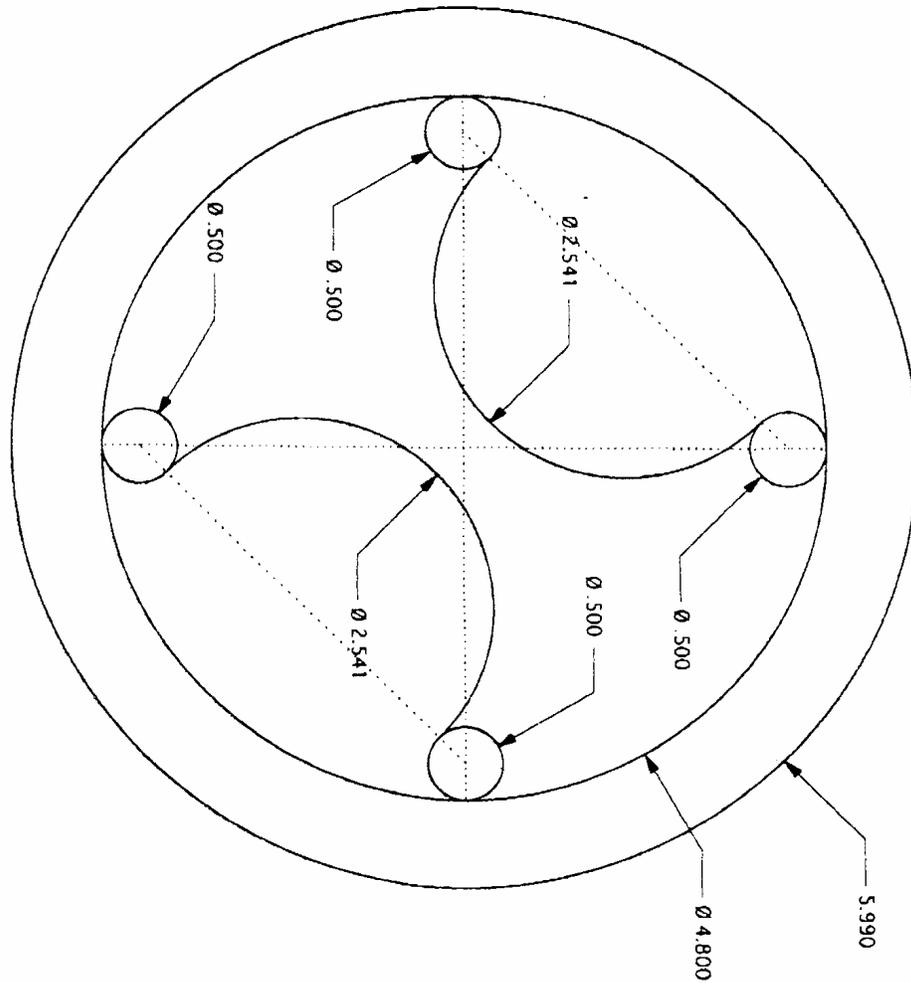

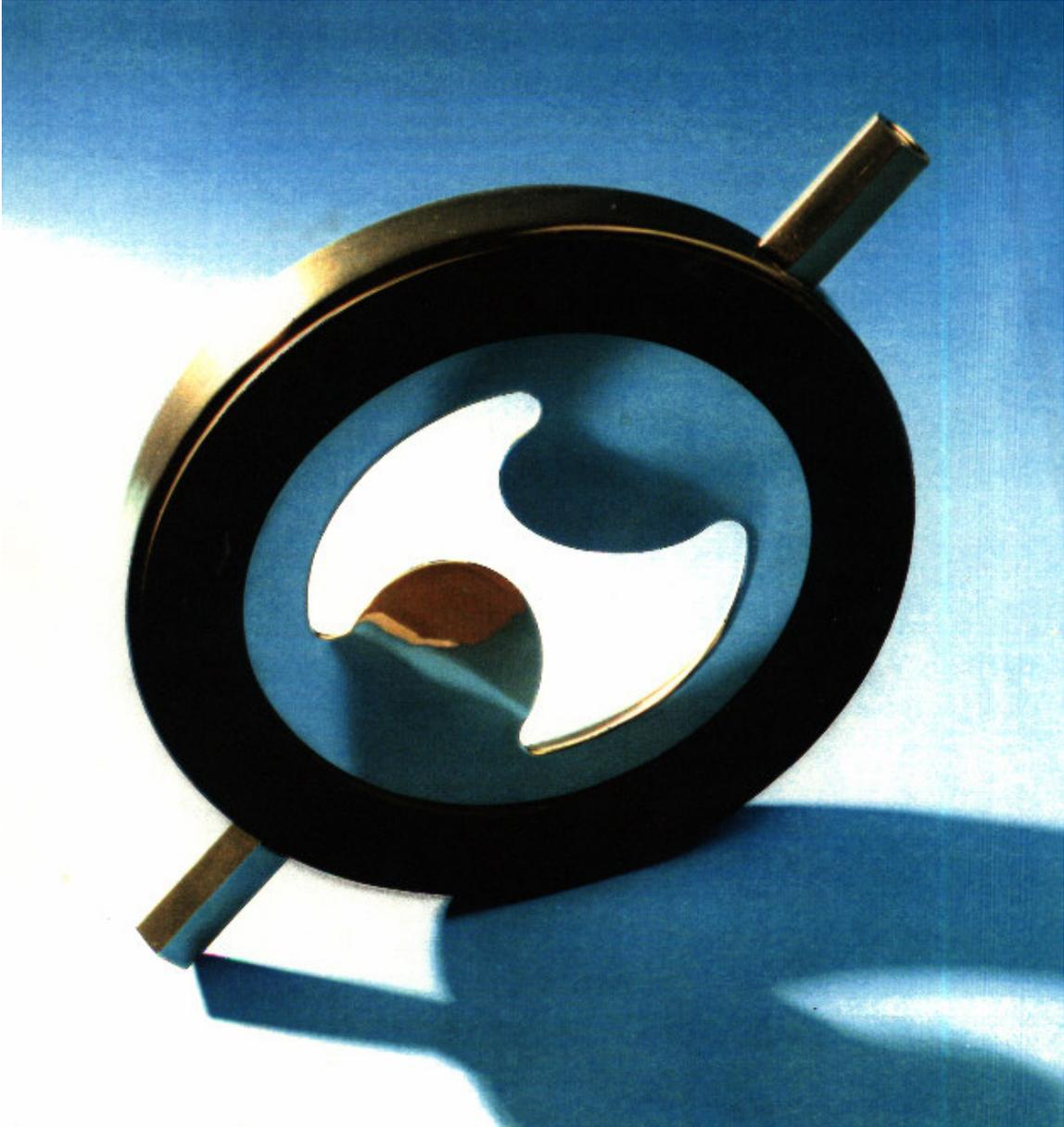***Figure 1. Mechanical Drawing of the Westfall Mixer***

Figure 2. Photograph of the Westfall Mixer

NUWC was contracted to carryout a series of tests to clearly identify the hydrodynamics mechanism which controls the mixer performance. This document contains a description of the experimental and numerical approach taken to document the mixer hydrodynamics.

2.0   TEST APPROACH

A combined experimental and numerical approach was taken for this study. Westfall Manufacturing funded the experimental portion (described in this document) while the computational portion was funded using NUWC internal funds (a summary

document has not been released). All testing was conducted in the NUWC Transient Flow-Loop Facility (figure 3) at the Naval Undersea Warfare Center Division Newport, RI, building 1246. This facility is a 12,000-gallon recirculating flow-loop capable of providing steady state and transient flows at pressures up to 50 psi and freestream velocities up to 50 ft/s in a 6 inch diameter pipe. The flow velocity is controlled by varying the speed of the 300 hp drive pump or by throttling a large ball valve.
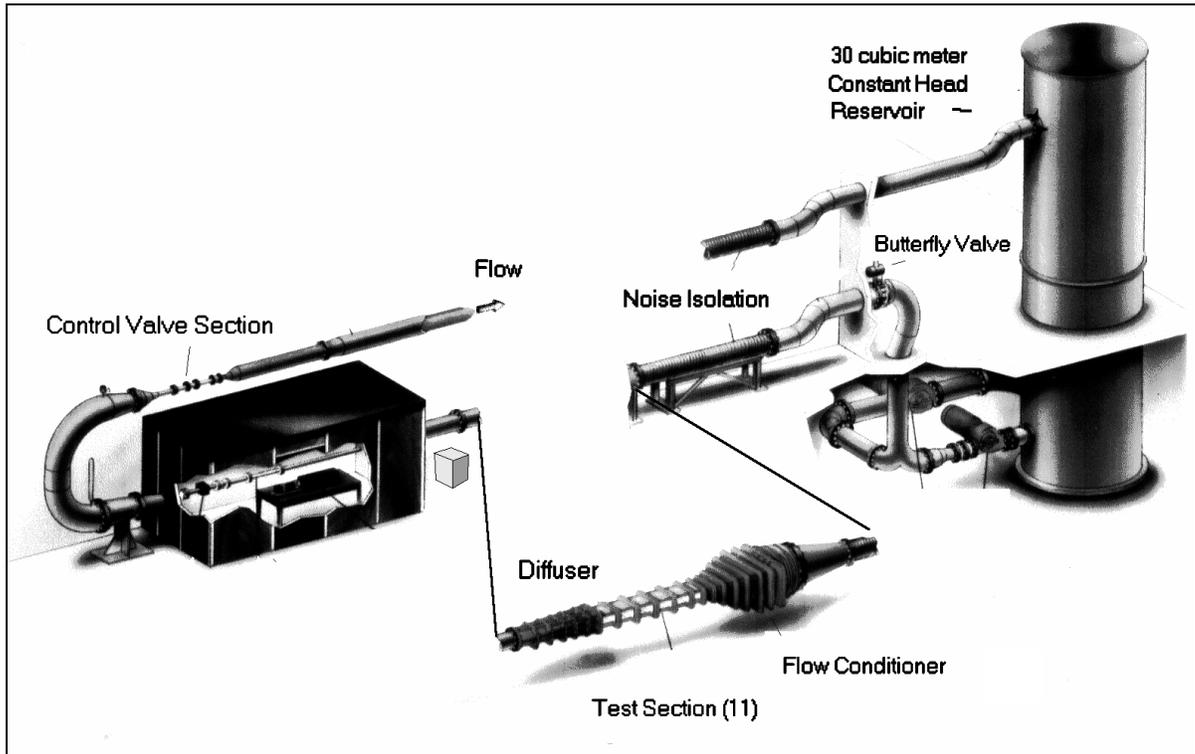
. Figure 3. Transient Flow-Loop Facility

In its normal configuration, the flow-loop has a rectangular test with internal dimensions 9 x 18 x 93 inches followed by 60 feet of 16 inch diameter pipe and a return elbow. The mixer test section was inserted in the lower leg of the flow-loop downstream of the primary test section (noted in Figure 3) by replacing a section of the 16inch diameter pipe which passed through the control room shown in Figure 3. The mixer test section consisted of a reducer, a length of 6 inch PVC pipe, the mixer, a section of Acrylic pipe, an acrylic box surrounding the pipe, and an expansion section. The tank was filled with water to create a single nominally constant index of volume through which laser measurements inside of the pipe could easily be taken. Figures 4 and 5 are drawings provided by Westfall Manufacturing of the test set-up. Figures 6 through 9 show images of the test arrangement. Westfall Manufacturing provided all the necessary integration hardware for testing while NUWC provided all instrumentation.
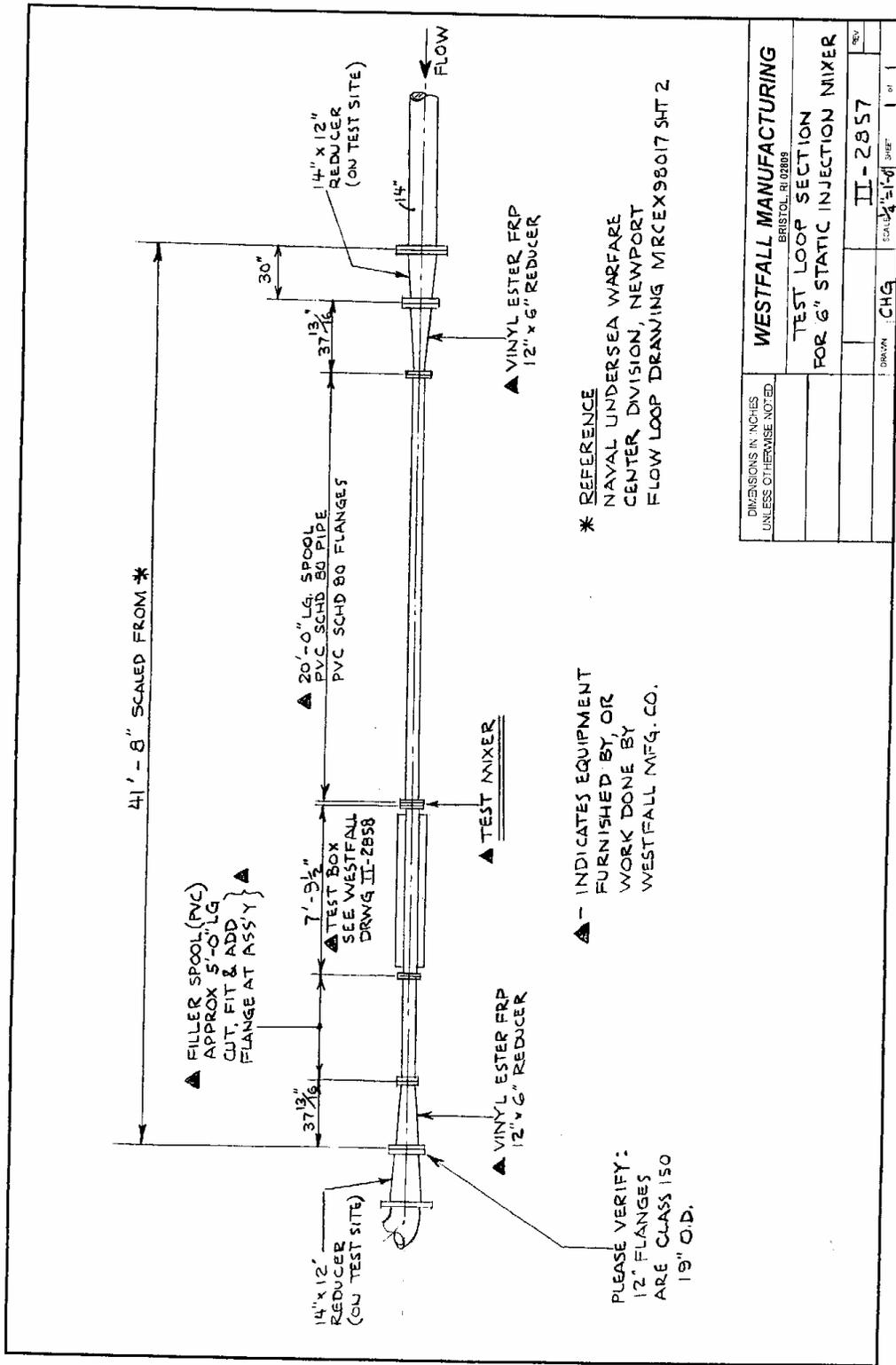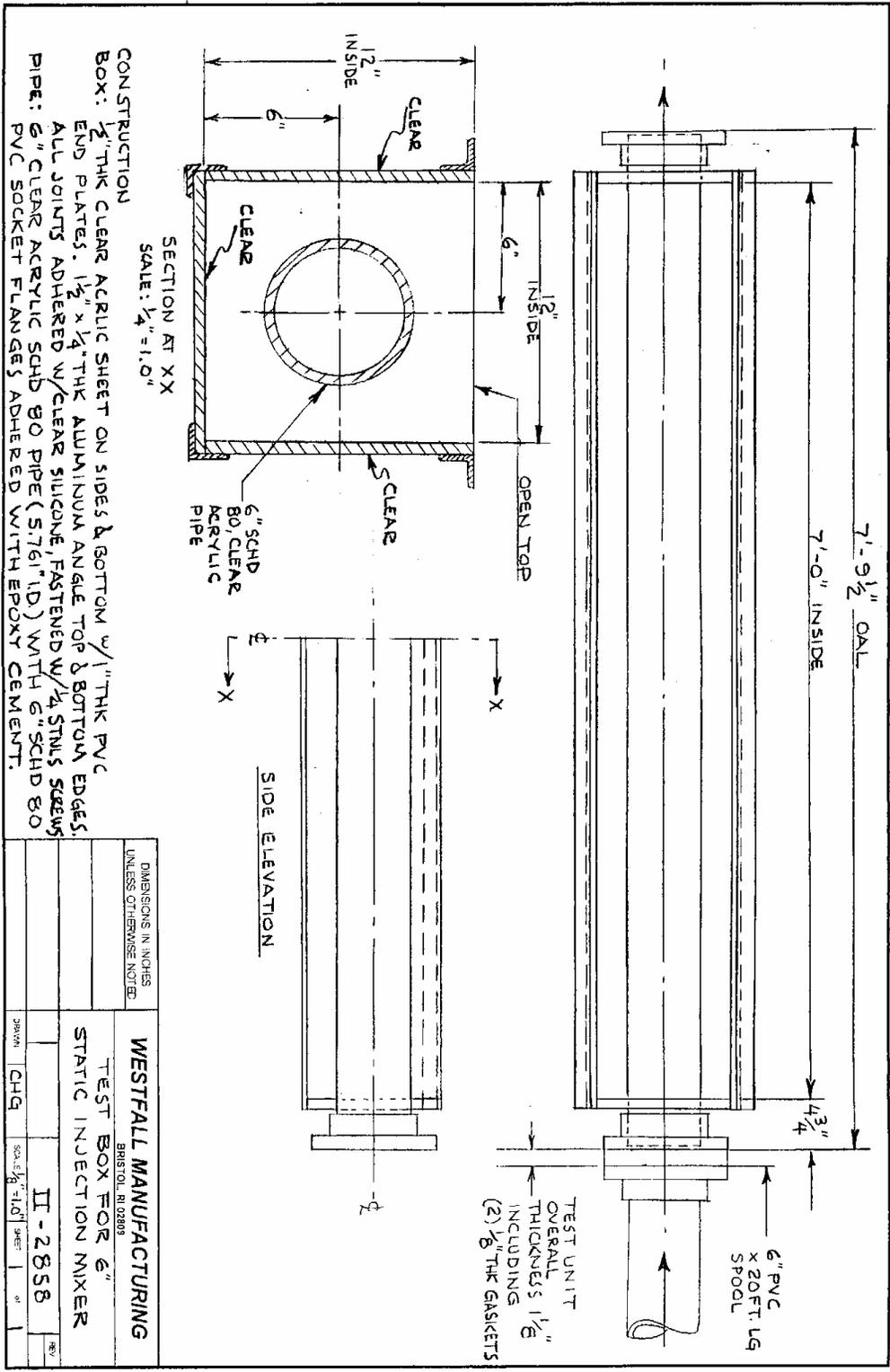
Figure 4. Drawing of the test set-up

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Figure 5. Drawing of the acrylic box for mixer tests
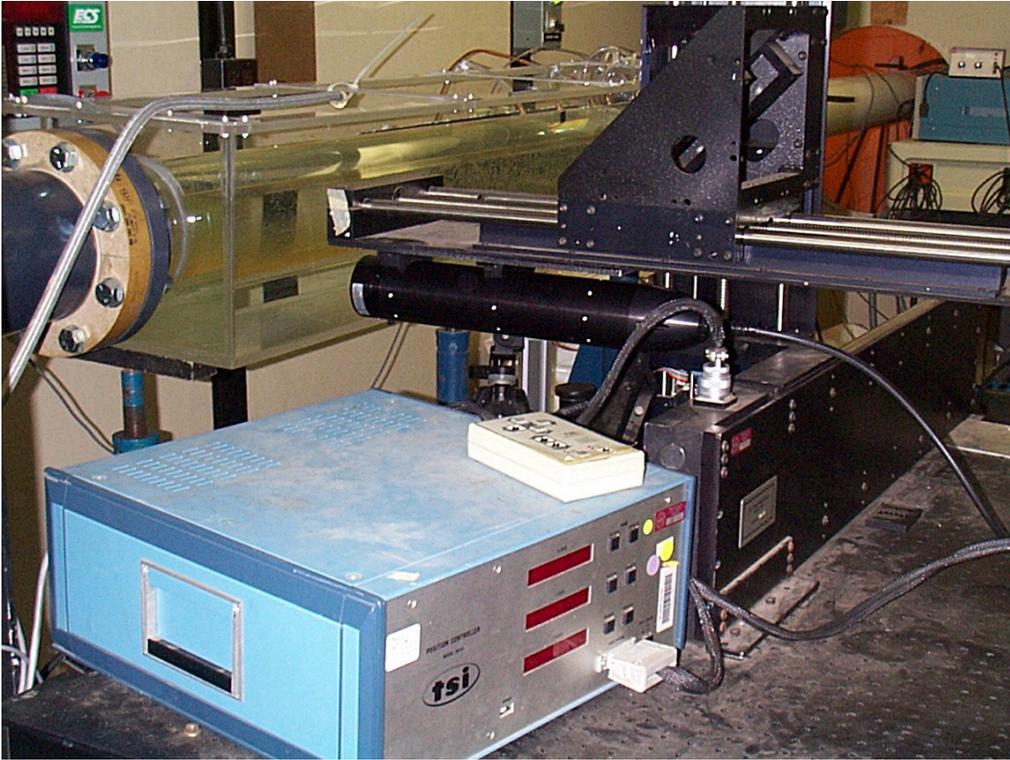
Figure 6. Image of the mixer test section, traverse system, and LDV system
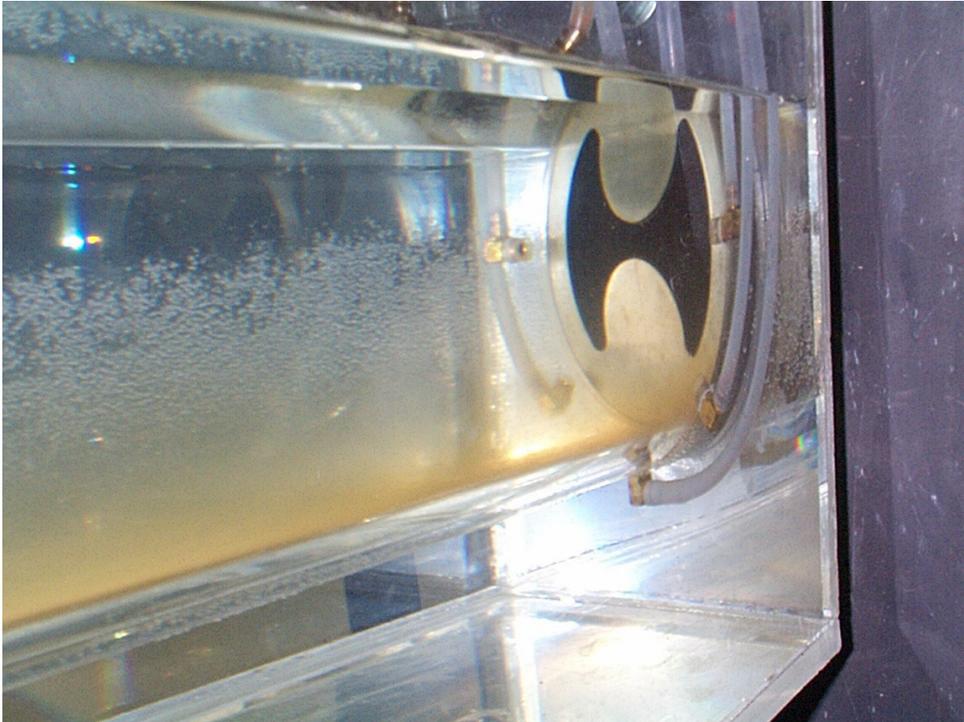

Figure 7. Image of the Westfall Mixer in the flow-loop.
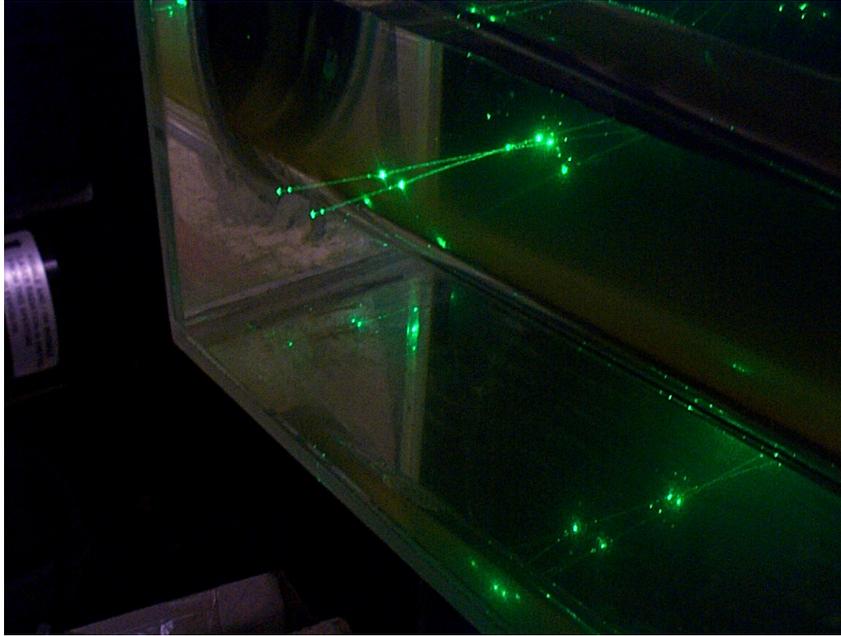
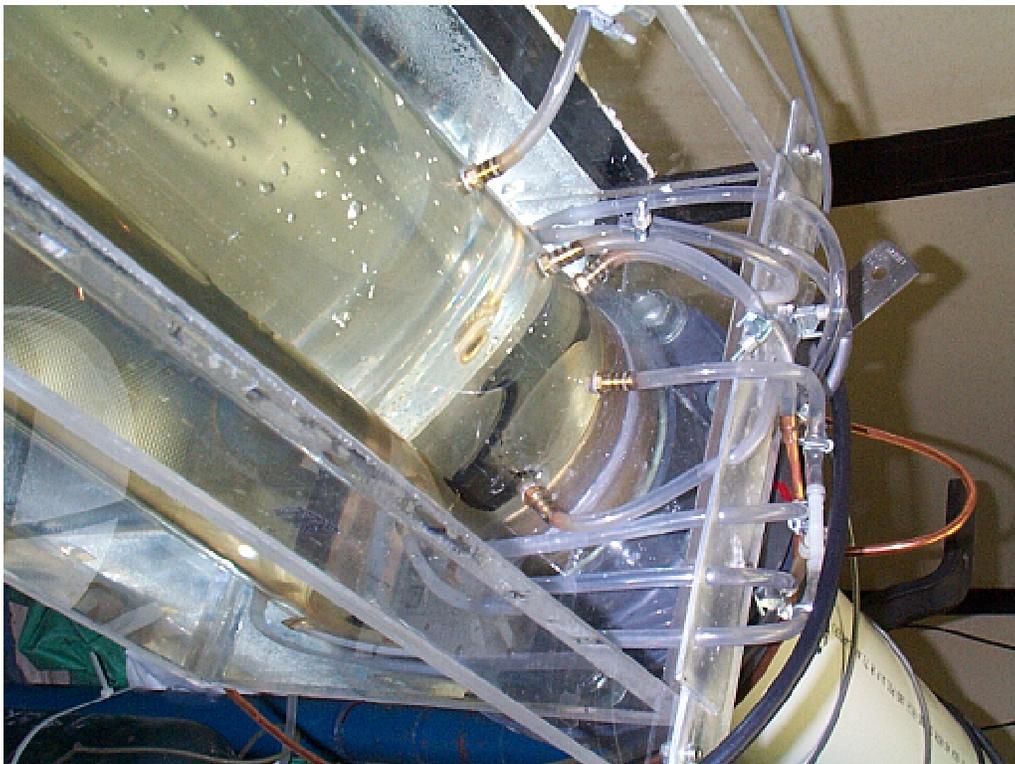*Figure 8. Image of the NUWC laser system in operation*

Figure 9. Alternate view of the mixer test set-up

Two measurement systems were used to monitor the mixer operation. A Validyne differential pressure transducer with a 20psid range was used to monitor the pressure loss across the device and a Laser Doppler Velocimetry System was used to monitor the flow-field down stream of the mixer.

Pressure taps were included in the mixer assembly to monitor the pressure loss across the device. An upstream tap was place 1 diameter upstream of the mixer and a downstream tap was place ½ diameter downstream of the mixer. One quarter inch nylon pressure lines were plumbed between the pressure taps and the Validyne pressure transducer. The voltage output of the transducer was monitored with a Texas Science Instruments integrating voltmeter. One hundred second integration times were used to determine the mean transducer output.

The pressure transducer was calibrated using the following procedure. The pressure line to the downstream side of the mixer was disconnected from the facility, exposing it to air pressure. The facility flow valve downstream of the test section was closed and a reference pressure gauge was installed in the facility at the location of the mixer. The facility pump was operated from rest up to a speed that generated pressures exceeding the anticipated maximum dynamic head during mixer operation. At each operating speed, the transducer output and the reference pressure output were recorded. Figure 10 shows the comparison of the reference gage output and the transducer voltage output. The calibration curve-fit is shown in the figure.
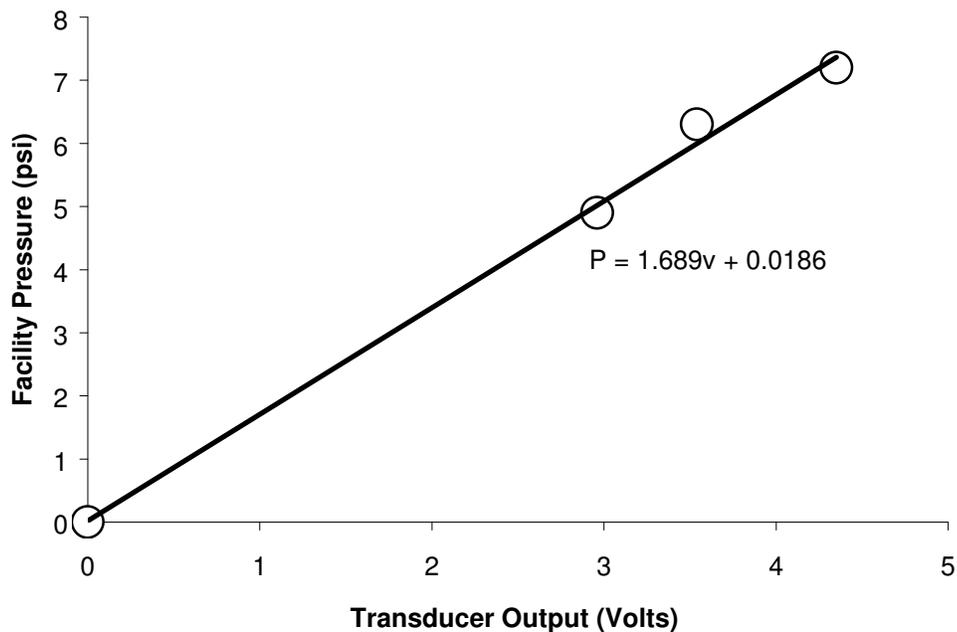

$P = 1.689v + 0.0186$

Figure 10. Pressure calibration results

The flow field measurements were taken using a single-component TSI Laser Doppler Velocimetry system. The test arrangement was configured to facilitate measurements in the acrylic pipe. An acrylic box was placed around the pipe and the volume between the pipe and the box was filled with water. The effect was to create a single mass with constant index of refraction, thus permitting light rays to travel undeflected from the outer window surface through the acrylic box, the water between the walls and the pipe, the pipe, and the water in the pipe without significantly deflecting. This configuration enabled relatively unrestricted motion of the LDV measurement volume within the pipe section.

Velocity profile measurements were taken at nine stations downstream of the mixer. At each station, mean and standard deviation streamwise and vertical velocity measurements were conducted. These measurements were taken on a grid spanning one quarter of the pipe. The measurements proceeded as follows:

1) The LDV probe was placed at a prescribed station downstream of the static mixer using the automatic traverse table.

2) The LDV measurement volume (point of beam intersection) was positioned in the core of the mixer wake, at a prescribed vertical position with respect to the centerline of the pipe.

3) The measurement volume was progressively traversed horizontally closer and closer to the pipe walls until the data rate (frequency at which particles pass through the measurement volume) dropped excessively.

4) The automatic traverse system was then used to cause the measurement volume to travel in small increments back across the pipe toward the pipe centerline.

5) At each point during the traverse, approximately 32,000 data points or 200 seconds of data (whichever was reached first) were taken and recorded to disk for processing.

6) Steps 4 and 5 were repeated until an entire horizontal profile was acquired.

7) Steps 2 through 6 were repeated until an adequate number of horizontal profiles were taken.

8) Steps 1 through 7 were repeated until all streamwise stations were sampled.

9) The probe head was rotated to measure the vertical component of velocity and steps 1 through 8 were repeated for a subset (six) of the streamwise stations.

Once the measurements were completed, the unprocessed LDV data was converted to velocities and statistics were determined from those values. The time history data was not recorded due to computer space limitations, consequently only the velocity statistics are available for review.

3.0 TEST RESULTS

The pressure loss measurements are provided in Figure 11. The loss coefficient is based on the mean flow velocity and pressure drop as indicated in Equation 1. The resulting computed loss coefficient for the mixer (average for all measurements) was determined to be 13.6. This value is identical to the value reported by Alden Research Laboratory (13.6), Inc. in 1997. The exact agreement is considered to be coincidental. Measurement accuracy was approximately 5%.
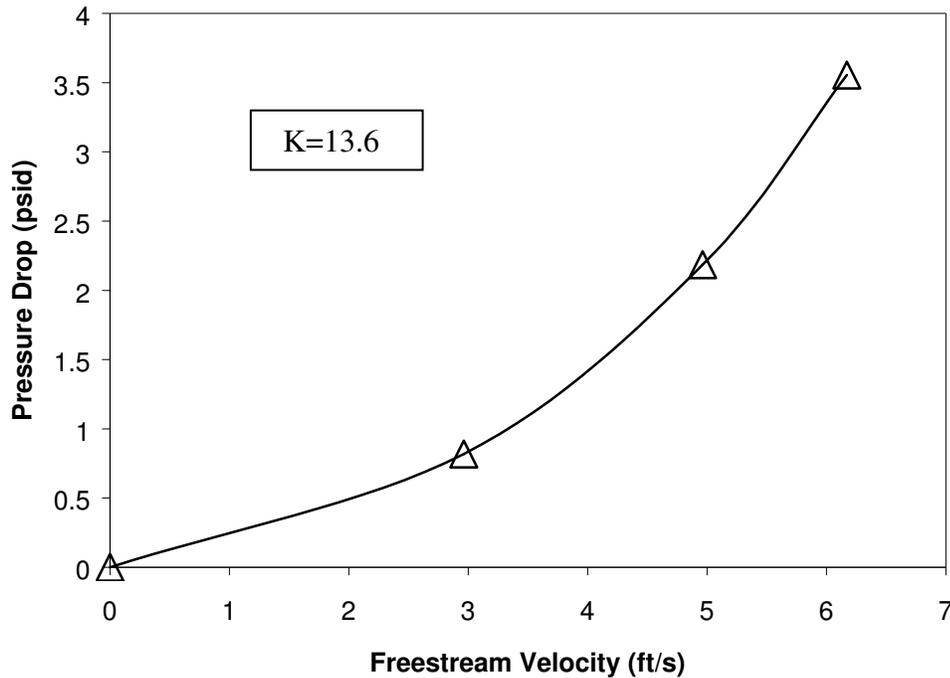

Figure 11. Mixer Pressure Loss Results

The distributions of the streamwise and vertical velocity component statistics (mean and deviation) are summarized in figures 12 through 30. Table 1 summarizes the test grid. Mean vertical velocities were measured but are not presented as the values were all very small (less than 1 ft/s max) as compared to the fluctuations and are not considered informative.

TABLE 1

TEST GRID INFORMATION

X/D station	Components	Horizontal profile locations y/D
0.10	U,V	0.0656
		0
0.33	U,V	-0.0656
		-0.1312
0.50	U,V	-0.1968
		-0.2624
0.67	U,V	-0.328
		-0.3936
1.0	U,V	-0.4592
1.33	U,V	
		0.24272
		0.14432
2.0	U	0.04592
		-0.05248
2.7	U	-0.15088
		-0.24928
3.3	U	-0.31488
		-0.38048
10.0	U	-0.41328

Figure 12. Streamwise velocity contours at x/D=0.1
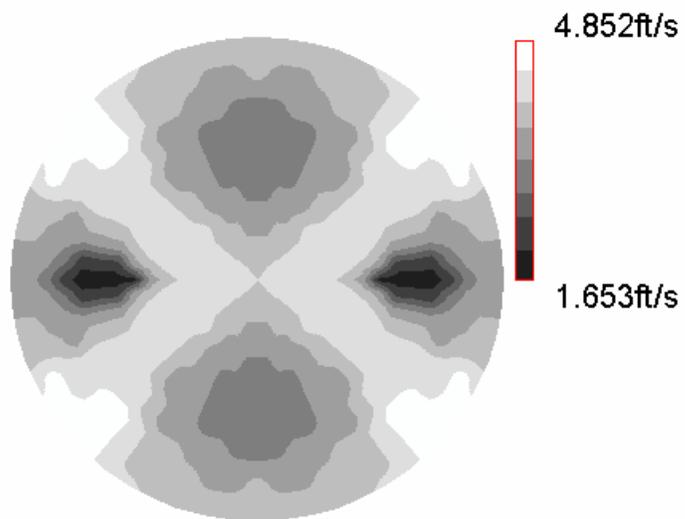
Figure 13. Fluctuations of streamwise velocity contours at x/D=0.1
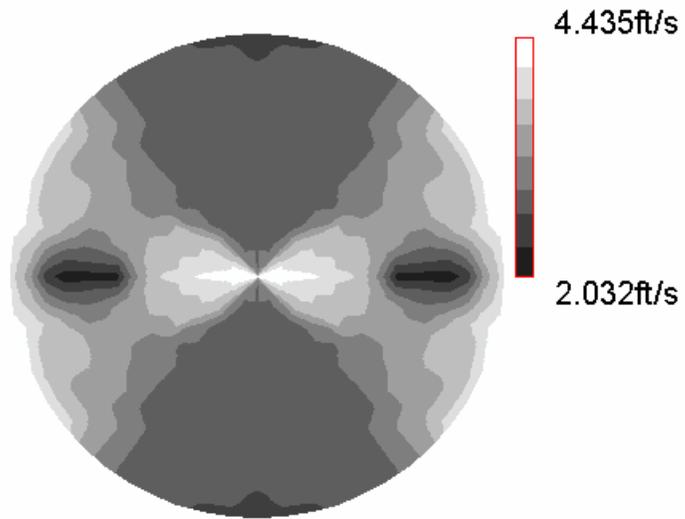
Figure 14. Fluctuations of vertical velocity contours at x/D=0.1
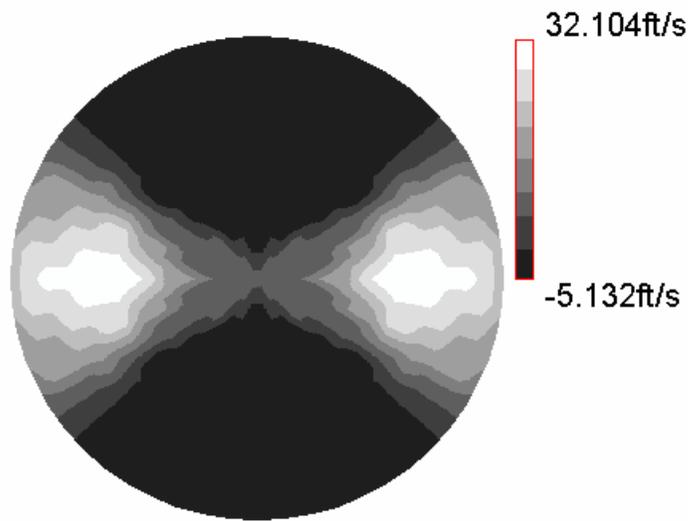
Figure 15. Streamwise velocity contours at x/D=0.33
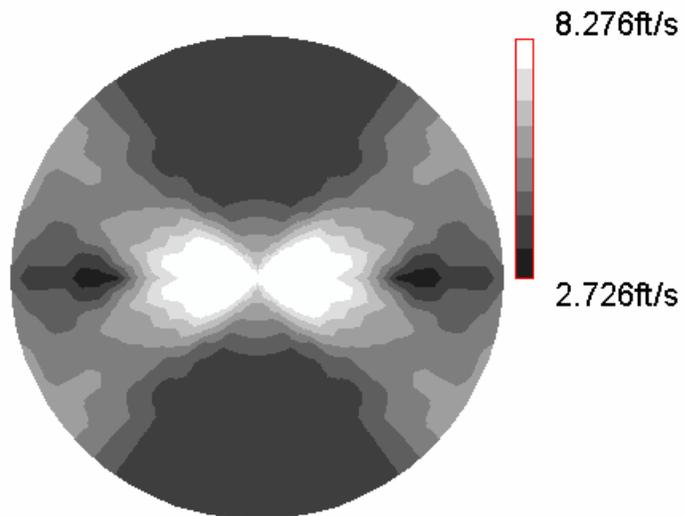

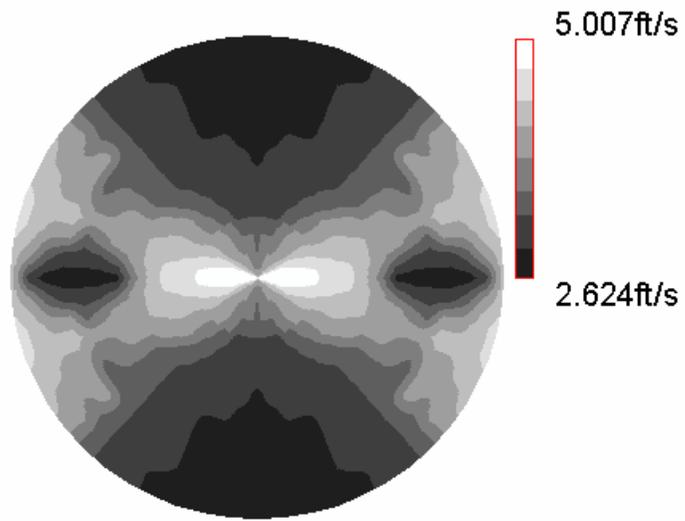*Figure 16. Fluctuations of streamwise velocity contours at x/D=0.33*
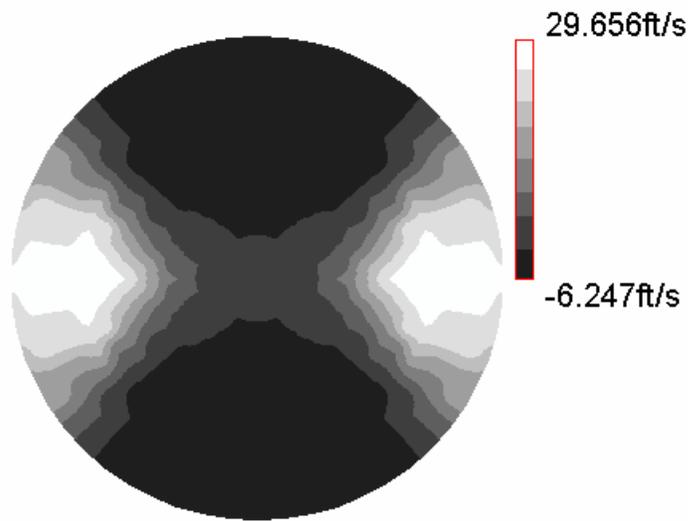
Figure 17. Vertical velocity contours at x/D=0.33

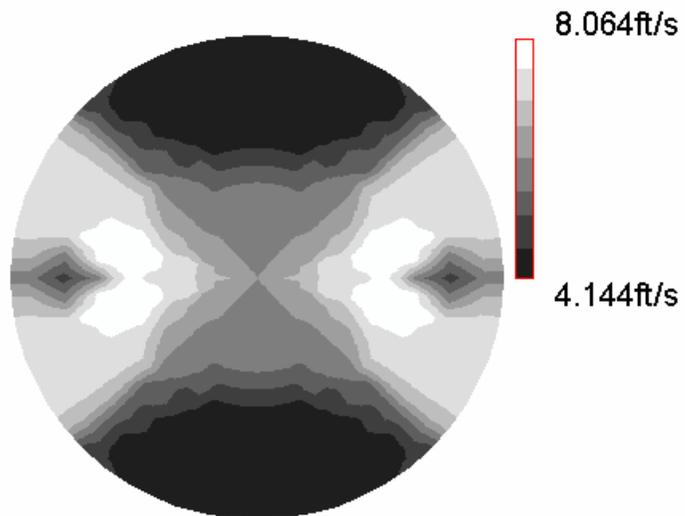*Figure 18. Streamwise velocity contours at x/D=0.5*

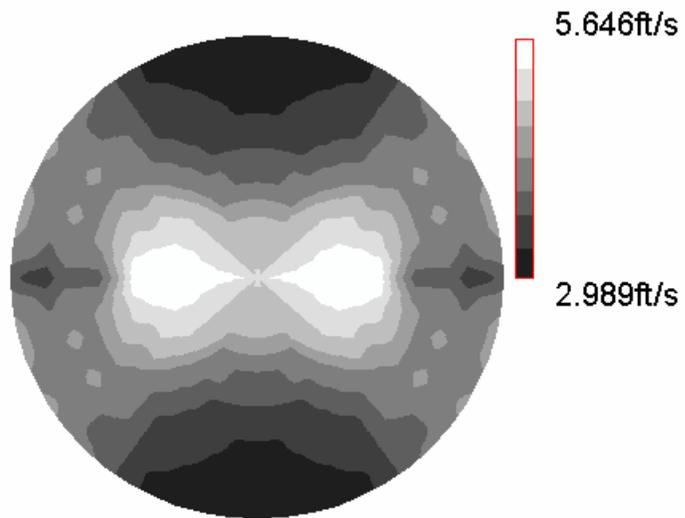*Figure 19. Fluctuations of streamwise velocity contours at x/D=0.5*

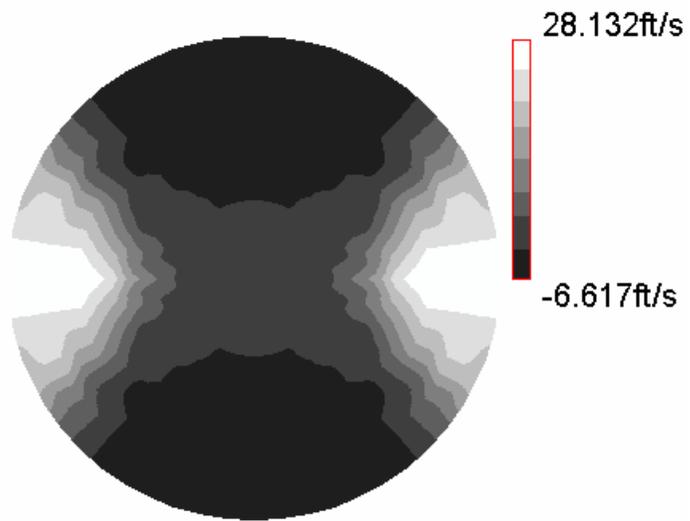*Figure 20. Vertical velocity contours at x/D=0.5*

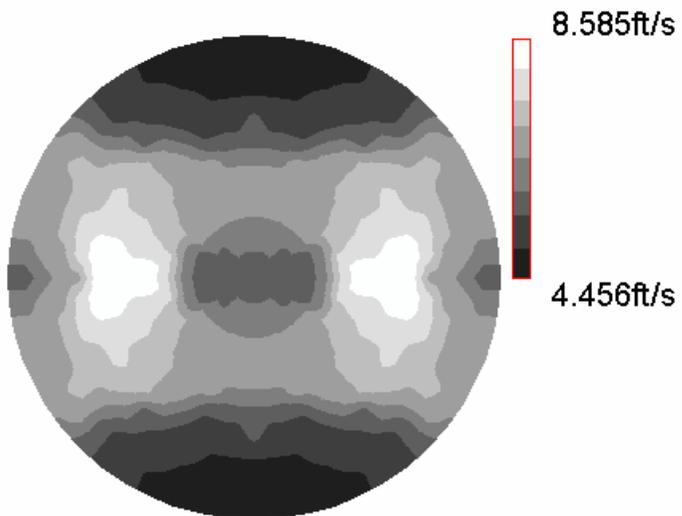*Figure 21. Streamwise velocity contours at x/D=0.67*

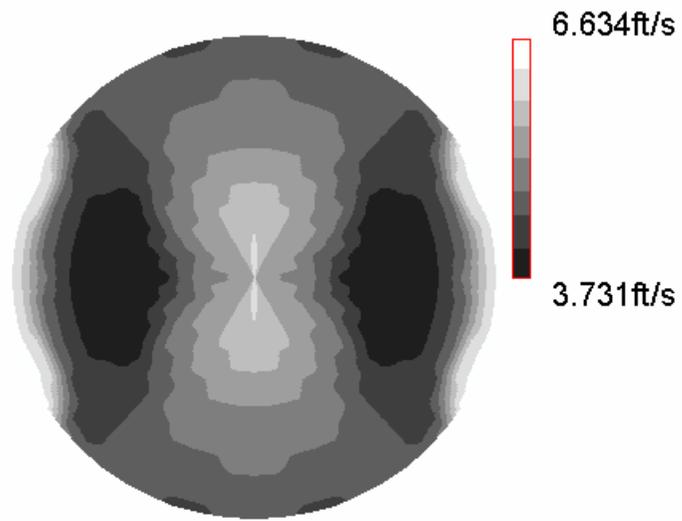*Figure 22. Fluctuations of streamwise velocity contours at x/D=0.67*

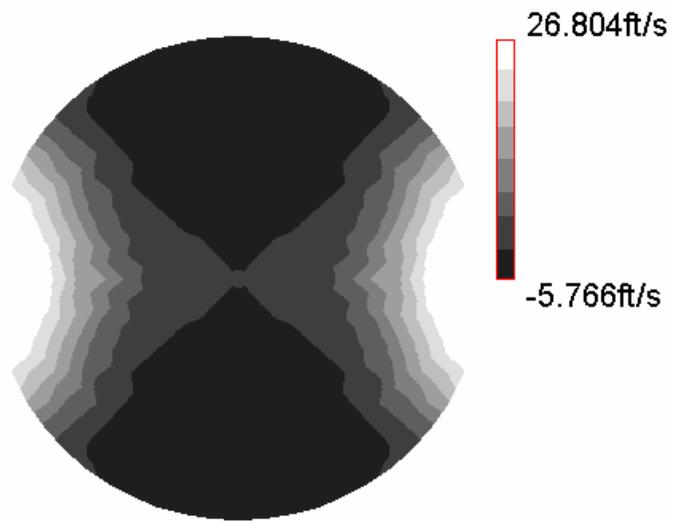*Figure 23. Vertical velocity contours at x/D=0.67*

Figure 24. Streamwise velocity contours at x/D=1.0
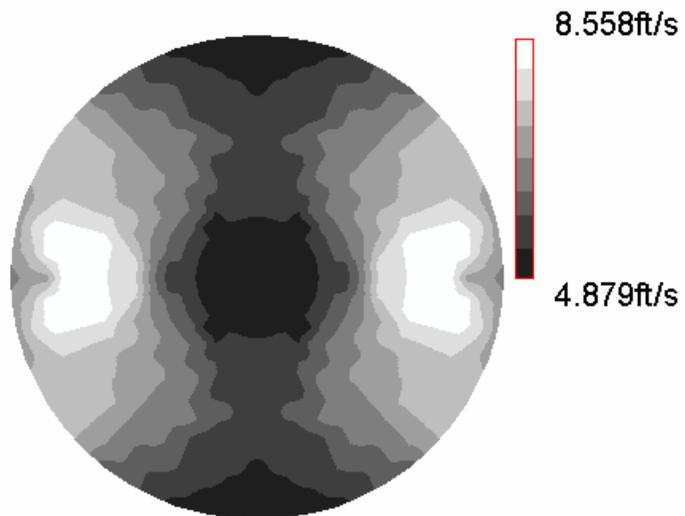
Figure 25. Fluctuations of streamwise velocity contours at x/D=1.0

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5.229ft/s

3.410ft/s

Figure 26. Vertical velocity contours at x/D=1.0

Figure 27. Streamwise velocity contours at x/D=1.33
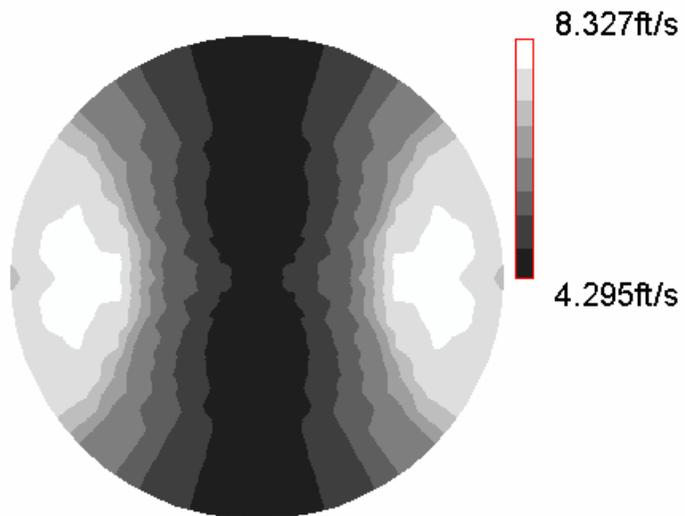
Figure 28. Fluctuations of streamwise velocity contours at x/D=1.33

Figure 29. Fluctuations of vertical velocity contours at x/D=1.33
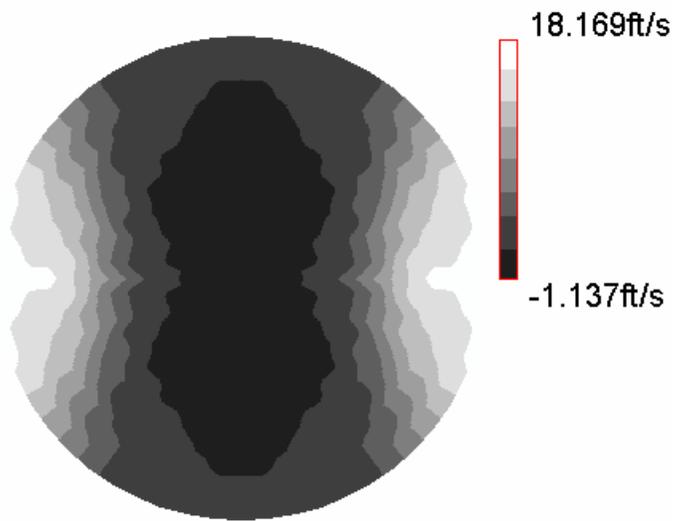
Figure 30. Streamwise velocity contours at x/D=2.0

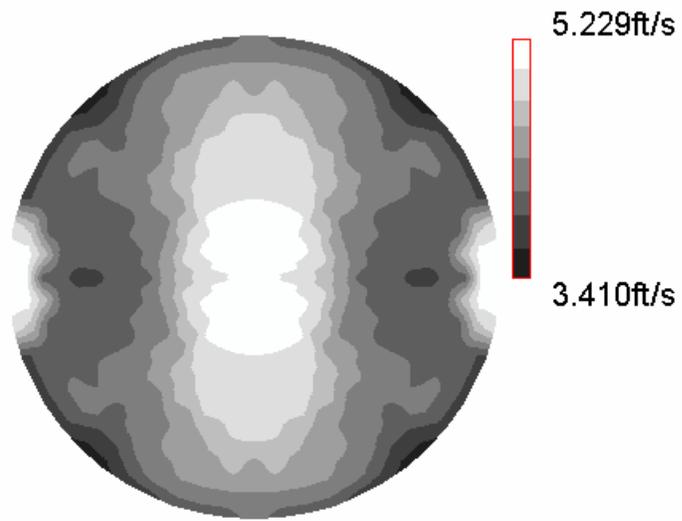*Figure 31. Fluctuations of streamwise velocity contours at x/D=2.0*
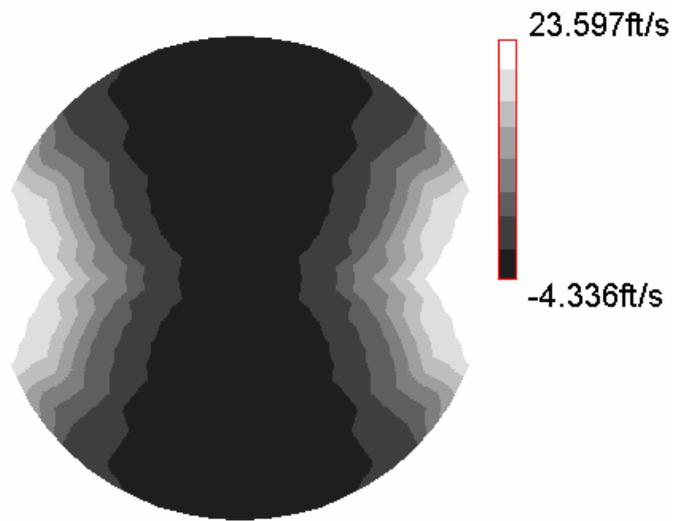
Figure 32. Streamwise velocity contours at x/D=2.67

Figure 33. Fluctuations of streamwise velocity contours at x/D=2.67

Figure 34. Streamwise velocity contours at x/D=3.33

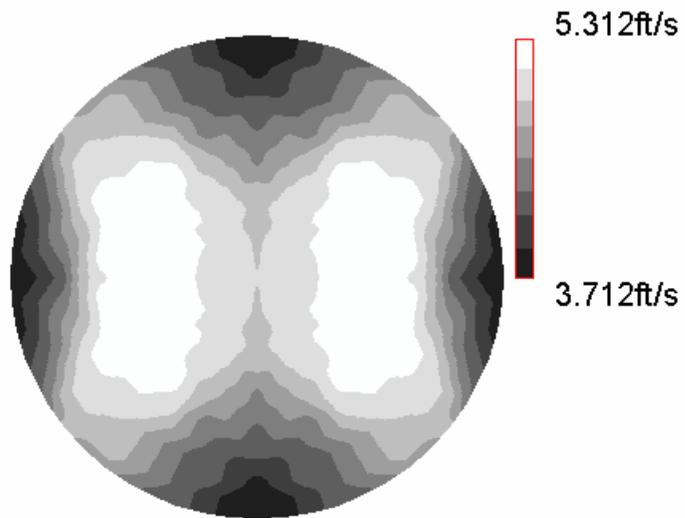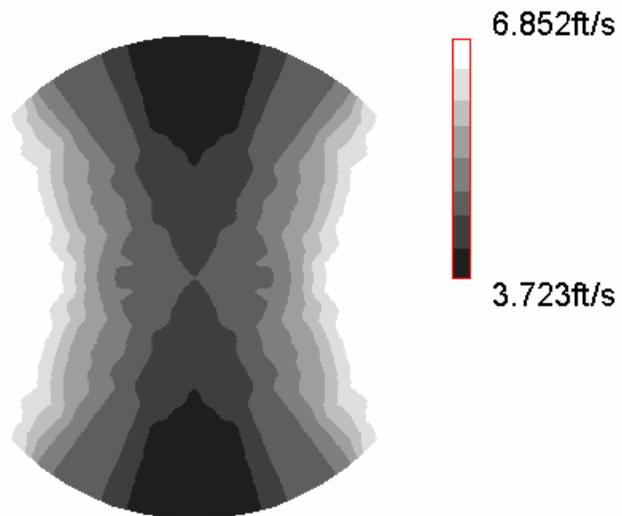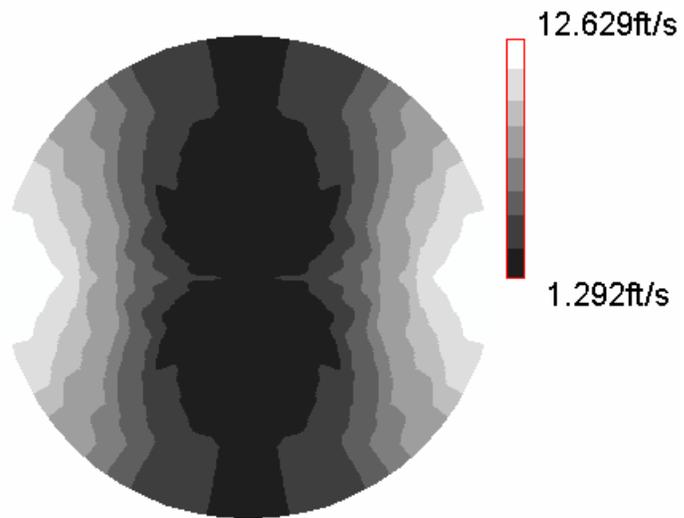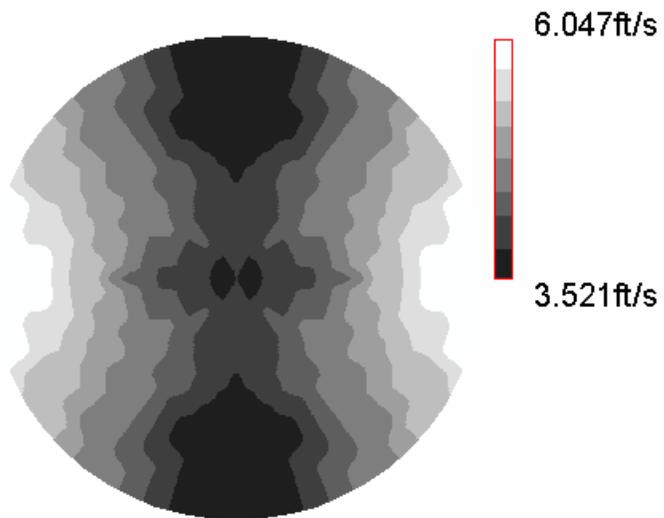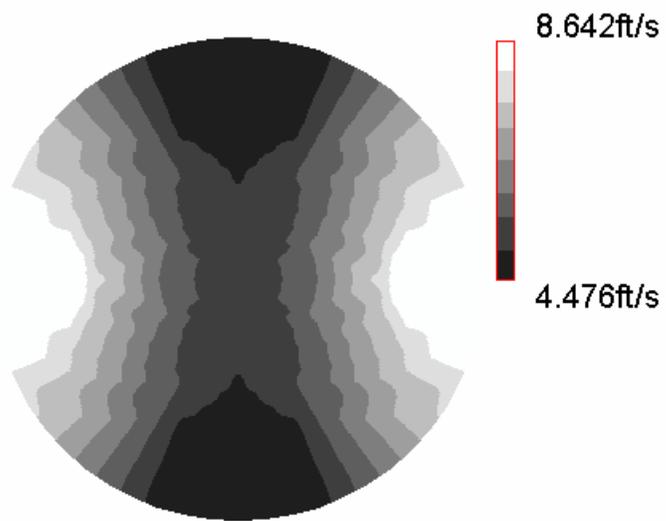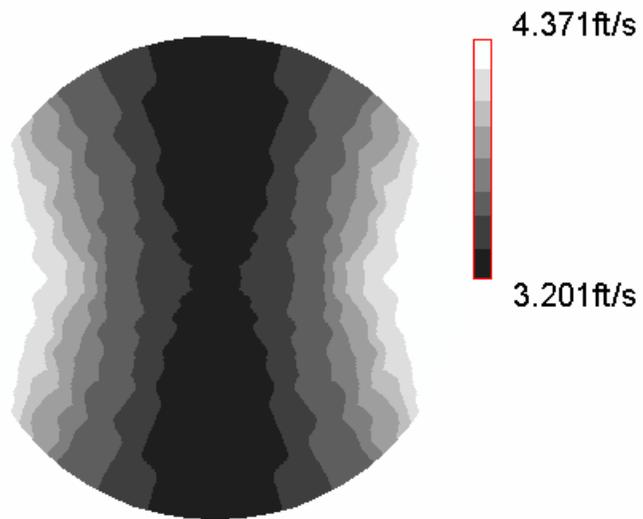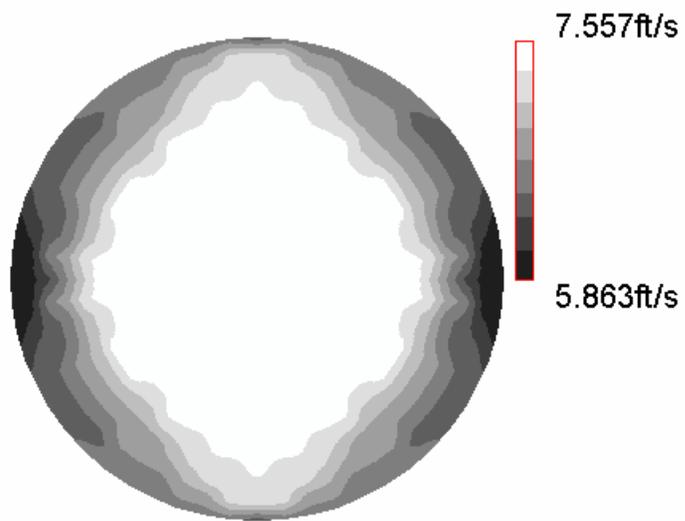*Figure 35. Fluctuations of streamwise velocity contours at x/D=3.33*

7.557ft/s

5.863ft/s

Figure 36. Streamwise velocity contours at x/D=8.0
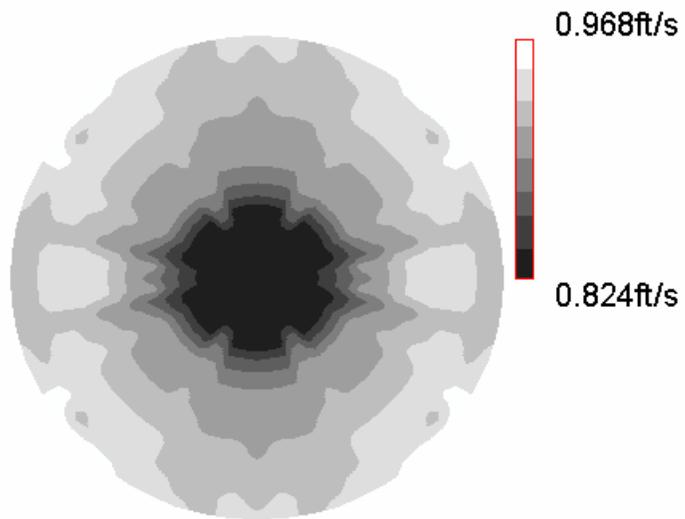

0.968ft/s

0.824ft/s

Figure 37. Fluctuations of streamwise velocity contours at x/D=8.0

4.0 DISCUSSION OF RESULTS

The two focal points of this study were measurement of pressure loss through the Westfall Mixer and measurement of the flow-field in the wake of the Westfall Mixer.

The pressure loss measurements agreed very well with those previously published. The measured value was 13.6 based on the average flow velocity and pipe diameter. To assess how reasonable this result is, the mixer can be considered in comparison to a sharp edged orifice with a similar area reduction. The observed pressure loss is consistent with that expected from a sharp-edged orifice with a 60% reduction in area.

In application of the Westfall mixer, unmixed fluid will approach from upstream and be forced through the mixer restriction to form a high speed flow. Additive will be injected into the low-speed reversed flow region downstream of the mixer tabs. It is the way in which the low speed fully mixed fluid and the high speed unmixed interact and mix which drives the mixer performance. The velocity field measurements provided wealth of information regarding the underlying fluid mechanics associated with the Westfall mixer performance. Three velocity component statistics have been selected for presentation and discussion, the mean streamwise component, fluctuations in the streamwise component and fluctuations in the vertical component.

The dominant feature in the Westfall mixer is the production of two very strong streamwise jets emanating from the open areas in the cut-out plate. Velocities in the cores of these jets reach five times that of the mean upstream pipe flow. Large reverse flow regions surround these jets and very high amplitude shear layers exist in between the jets and the reversed flow. The effective area where high shear layers exist is largely due to the dual jet structure and the non-circular nature of the plate cut-outs.

The association of high turbulence intensity with regions of high shear can be seen through inspection of the mean and fluctuation velocity contours. Peaks in the turbulence intensity occur where rapid changes in the mean velocities are found. Reynolds stresses are the correlation between fluctuating velocity components. When the vertical and streamwise velocity components are simultaneously high, a positive combination to the Reynolds stress occurs. High Reynolds stresses are associated with high transport of momentum, temperature, and passive scalars. Because Reynolds stress is well correlated with velocity fluctuation amplitude, transport across the shear layer will also be high in these regions. Consequently, contours of fluctuating velocity can be interpreted as contours of mixing effectiveness, with the greatest mixing occurring where the turbulence intensity is the highest. The Westfall mixer effectively speeds mixing by increasing the contact area between high speed fluid and low speed fluid.

Because the tabs in the Westfall mixer are slightly swept back in the direction of the mean flow, the jets emerge at an angle with respect to the flow axis toward the walls

of the pipe. The mean velocity contours track the core of the jet as it grows closer and closer to the pipe wall, eventually being contorted into a very thin layer near the wall. This contortion of the jet shape further enhances the mixer performance because the jet surface area increases drastically.

The core velocity of the jet decays slowly over the first pipe diameter downstream of the mixer. In this region the jet behaves roughly as if it were in a free field. However, once the jet has been drastically changed in shape by the presence of the wall, the core velocity drops dramatically. Between 1.0 and 2.67 diameters downstream of the mixer the core velocity drops by a factor of 2. This drop in velocity is tied to the increase in surface area of the jet and the associated increase of momentum transport between the jet and the low speed fluid. As previously noted, momentum and scalar transport are very well correlated. The change in jet geometry due to its interaction with the pipe walls enables an exchange of transported properties between the jet and the low speed fluid to take place rapidly. The rapid rise in the fluctuating velocity components in this region is further evidence of enhanced mixing due to the walls.

There has been discussion that an important hydrodynamics mechanism contributing to the Westfall mixer operation is the action of large streamwise eddies. Owing to the very high fluctuations in streamwise and vertical velocities as compared to the mean vertical velocity component, the transport associated with bulk fluid motion is small compared to the influence of turbulence. In addition, review of flow visualization and unreported test data support the assertion that these eddies do not significantly contribute to the mixer effectiveness.

An unusual feature was observed in the streamwise development of velocity fluctuations. The amplitude of fluctuation initially rises with distance downstream of the mixer. It is likely that the increased interaction of the jet with the pipe walls causes the turbulence intensity to rise.

In addition to the turbulence measured within the mixer, there is another significant source of unsteadiness with the device. The two jets formed by the mixer and the recirculating zones behind the tabs do not exist together in a stable pattern. Based on flow visualization and observation of the instantaneous velocity signals, it was observed that the flow slowly oscillates from preferring a large circulation behind one tab and then to preferring a circulation behind the other. Measurements of spectra did not show any identifiable periodicity to this behavior but it was clearly observed when dye was injected into the mixer and observed. It was also observed in the velocity signal time traces. The mean velocities at any given point slowly oscillated (1 second or longer period) over a wide range, indicating a bi-stable flow. The impact on mixing is unknown. It is likely that the increased interaction of the jets with the walls improves mixing.

A sensitivity test was conducted by injecting dye into the pipe at a range of locations aft of the mixer. The disturbance caused by the injection of dye caused the flow to switch to a state where circulation behind one of the tabs dominated (opposite the point

of injection). Which circulation zone dominated the flow was a function of how the dye was injected.

The Westfall mixer functions well because it makes effective use of shear layers. Transport of momentum, energy, and passive scalars across these shear layers is determined by the area of, the velocity ratio across, and the turbulence intensity in the shear layers. The Westfall mixer design has effectively enhanced these quantities by using a unique orifice plate design and interactions of the flow with the pipe walls.