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PROPRIETARY INFORMATION

# VELOCIMETRY WITH REFRACTIVE INDEX MATCHING FOR COMPLEX FLOW CONFIGURATIONS

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# VELOCIMETRY WITH REFRACTIVE INDEX PATCHING FOR COMPLEX FLOW CONFIGURATIONS

## PHASE I FINAL REPORT

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## Project Summary

The purpose of the Phase I and II research is to develop refractive-index-matching techniques for velocity measurements in the large Reynolds number complex flows found in rocket engines. In the Phase I study, the feasibility of obtaining detailed velocity field measurements in large Reynolds number flow of the SSME main injector bowl was demonstrated using laser velocimetry and the developed refractive-index-matching technique. An experimental system to provide appropriate flow rates and temperature control of refractive-index-matching fluid was designed and tested. Velocity measurements were obtained with laser velocimetry in a specially-prepared complex model of the SSME main injector bowl. Test results are presented to establish the feasibility of obtaining accurate velocity measurements that map the entire field including the flow through the LOX post bundles: sample mean velocity, turbulence intensity and spectral results are presented. The results indicate that a suitable fluid and control system is feasible for the representation of complex rocket-engine configurations and that measurements of velocity characteristics can be obtained without the optical access restrictions normally associated with laser velocimetry.

The refractive-index-matching technique considered here needs to be further developed and extended to represent other rocket-engine flows where current methods either cannot measure with adequate accuracy or they fail. Potential industrial developments would include the provision of refractive-index-matching rigs, models, and associated instrumentation. The refractive-index-matching approach could also be used on a commercial basis to provide valuable experimental results in a wide range of complex internal geometries including, for example, rocket-engine ducts, manifold, pumps, turbine heat exchangers and bearings.

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# INTRODUCTION

The measurement of internal flows confined by complex boundaries is often restricted by accessibility difficulties. These may be due to flow obstruction when using sensor probes in narrow flow passages or to optical restrictions imposed by the geometry of the model boundaries when using optical measurement techniques. The non-intrusive nature of laser velocimeters (LV), combined with their insensitivity to fluid properties and flow conditions, renders their use particularly attractive for the study of complex flow configurations, provided that adequate optical access can be ensured. The use of optically flat windows or transparent models may well provide the necessary optical access in many flow configurations but in some cases the presence of multiple solid boundaries, often with complex surface curvature, poses additional measurement limitations. These difficulties arise from differences in refractive indices of the fluid and the boundaries of the transparent model along the path of the laser beams which form the measurement volume of the laser velocimeter. These may affect the measurement position and sensitivity factor of the laser velocimeter, but in most cases they will prevent measurement because the laser beams will not intersect and will not form the interference measurement volume. The simplest possible case of the effect of a curved optical boundary of a cylindrical duct on the measurement position and sensitivity factor of a laser velocimeter is outlined in Appendix 1 of this report. Only measurements of the axial and transversal velocity components are possible in this case and even these require corrections to be applied. If the plane of the laser beams does not coincide with either the axial or lateral plane of the cylindrical duct, a laser-beam intersection will not occur unless the refractive index of all media with non-planar optical boundaries is the same. It is on this observation that the principle of the refractive-index-matching technique is based.

The absolute refractive index (n) of a transparent medium is defined as the ratio of the velocity of propagation of light waves in vacuum to that in the medium and depends on light wavelength and temperature (Ref. 1). Most information on fluids with refractive indices matching those of transparent solids comes from crystal microscopy and forensic glass identification methods (e.g., Refs. 2, 3). The use of refractive index liquids in fluid flow studies, however, requires other fluid properties, such as viscosity and density, to be within acceptable margins.

One of the pioneering applications of refractive-index-matching in LV measurements concentrated on a simpler circular duct flow with emphasis on the near wall regions (Ref. 4). This work concluded that "disturbance-free measurements in the near wall region of the pipe were possible, using the refractive-index-matching technique and were in agreement with theoretical results derived from the momentum equations". Measurements as close as 300 μm near to the wall were obtained as opposed to 1-1.5 mm when using conventional hot-wire or hot-film sensor probes. The liquid used to match the refractive index of the glass wall (Duran 30 or Pyrex, $n_D = 1.4718$) was a mixture of light fuel oil ($n_D = 1.463$) and dibutylphthalate. The resulting mixture matched the refractive index of the glass within $\Delta n = 10^{-4}$ but its viscosity was higher than that of water. A number of suitable fluids and mixtures to match the refractive index of glass were also examined and classified according to toxicity, chemical aggressivity and flammability. In general, these fluids were organic solvents, not suitable for use with acrylic components.

A more recent application of refractive-index-matching (Ref. 5) concentrated in velocity field measurements in a rod bundle and between cylindrical roughness elements in boundary layers. Most of the optical boundaries were made of glass and the matching fluids were primarily mineral and silicone oils. This resulted in high viscosities and the typical Reynolds numbers for these experiments were in the laminar regime.

Considering the difficulties of manufacturing complex models with glass, the alternative choice leads to clear cast acrylics which have excellent machinability and transparency. Their disadvantage lies with their vulnerability to chemical agents such as inorganic solvents. The typical refractive index of a cast acrylic is about 1.5 for the sodium D line at 20° C (Ref. 6), while its light transmittance is 92% at $\lambda = 600$ nm, independent of thickness and makes it perfectly suitable for fabrication of transparent flow models. An example of the use of acrylic models for flow studies using LV and refractive-index-matching techniques is given in (Ref. 7) where a number of converging swirl chambers were examined. The fluid used for the matching of the refractive index of the cast acrylic was a mixture of oil and turpentine with tetrahydronaphthalene and allowed detailed scanning of the flow field, despite the irregularities of the flow boundaries.

Preliminary studies of refractive-index-matching technique are reported in Refs. 8-11 and demonstrate the usefulness of the technique as a research tool. The flow field behind a confined disc in a circular duct has been studied in detail (Ref. 8) using refractive-index-matching techniques and the results were compared to those obtained in air flow (Ref. 12) and were found to be in very good agreement. Furthermore, the feasibility of obtaining accurate velocity measurements in two-phase flows with high particle concentration (up to 100% solid volume fractions) was demonstrated in Refs. 9 and 10 by matching the refractive index of the transparent solid particles (Diakon spheres) thus minimizing their effect on the laser beam path.

Laser velocimetry with refractive-index-matching was also used for single- and two-phase flow measurements around the transparent blades of the impeller of a mixer (Ref. 11) and the mapping of the steady flow field inside a transparent model of a directed port of an internal combustion engine. Another favorable application of the technique is the flow through rod bundles of heat exchangers, with emphasis on the flow induced vibrations of the rods, as reported in (Ref. 14).

The evidence in the literature to date suggests that refractive-index-matching is a powerful technique which can allow accurate velocity field measurements to be obtained with laser velocimetry in flow configurations with multiple flow boundaries and irregular geometry including near-wall regions. This prompted the present attempt to develop and apply this technique to measurement of the flow through a model of the Main Injector Bowl of the Space Shuttle Main Engine. This particular configuration is characterized by complexity of the flow boundary, by larger Reynolds numbers than previously used with refractive-index-matching techniques, and by the large number (over 600) of internal tubular LOX posts which occupy most of the flow area. The area of particular interest is the wake behind the LOX posts which, being so closely spaced, do not permit the use of any probe-based measurement technique.

The feasibility of obtaining detailed velocity field measurements in the large Reynolds number complex flow through a model of the SSME Main Injector Bowl is demonstrated here using laser velocimetry and the developed refractive-index-matching technique. The design considerations of the experimental system are described and sample measurements in the complex flow field around the simulated LOX tubes are presented. Suggestions for improvements to the experimental procedures are made, based on the experience acquired during this

initial study. This report describes the design considerations of the transparent model of the SSME Main Injector Bowl and the experimental facility built around it for the flow and temperature control of the refractive-index-matching-fluid. Test results are also presented to establish the feasibility of obtaining accurate velocity measurements through the LOX posts: sample velocity and turbulence results are presented in a 32% SSME Injector Bowl model configuration.

## THE TRANSPARENT MODEL

The model of the SSME Main Injector Bowl used in this study originates from the Model No. 517 Assembly used in the NASA-MSFC water test facility. A schematic of this model is shown in Fig. 1 and represents a half-scale model of the actual SSME Main Engine. The transparent model built for the refractive-index-matching studies is shown in Figs. 2a and 2b. Its internal geometry is identical to that of the Model No. 517, scaled down to 64%. This smaller size was chosen in order to reduce the volume of the refractive index fluid, while the exact scaling was dictated by the availability of clear cast acrylic rods of the required diameter (3 mm), in order to simulate the LOX posts. The external shape of the transparent model is rectangular to improve optical accessibility. The material used is clear cast acrylic with refractive index $n_D = 1.4893$ at 23.4°C for He-Ne laser light at $\lambda = 632.8$ nm. The finished model underwent a 38-hour annealing process at 85° C in order to relieve the mechanical stresses induced by the machining. This is an essential process since it was found that the fluid contains an inorganic solvent which attacks the acrylic, preferentially in regions of concentrated stresses.

The LOX post assembly is simulated by 464 solid rods made of the same acrylic as the Bowl model and annealed at 90° C for 12 hours. The positioning of these rods is identical to that of the Model No. 517 and provision was made to extend their number to the original 600, if required. Due to the small diameter of the simulated LOX posts (3 mm), the incorporation of bleeding holes at their end as in the Model No. 517 (see Fig. 3a) was not feasible and, instead, an annular passage arrangement was adopted as shown in Fig. 3b. The whole LOX post assembly is supported between two aluminum plates and can be easily removed from the model. It also incorporates two shields of similar geometry to those of the Model No. 517, made of thermo-formed acrylic sheet,

but positioned only in front of the exits of the two pairs of the transfer ducts. Provision was made to enable the positioning of additional LOX shields around the LOX post assembly if required.

The two pairs of transfer ducts of the original model are simulated by two pairs of pipes extending more than twenty diameters upstream of the model (Fig. 4) so as to ensure swirl-free, fully developed turbulent flow at the entry to the model. This also allowed the use of Pitot probes for the monitoring of the flow rate in each of the transfer ducts. Finally, the exit of the model consists of a straight pipe, extending ten diameters downstream of the model, to avoid any upstream effects from the rest of the piping system.

## THE EXPERIMENTAL FACILITY

The minimum flow rate through the model which would ensure Reynolds numbers of approximately 20,000 in the transfer ducts is three hundred l/min and the combined volume of the piping associated with the model is eighteen litres. Considering the need for fine temperature control of the refractive index fluid, a maximum of one recirculation of the full amount of fluid every 15 s was estimated to be satisfactory, (this limit was set in conjunction with the choice of the heating element as discussed below), and a minimum fluid volume of 150 litres in the system was chosen.

The flow circuit and arrangement of the temperature controlled storage tank are shown in Fig. 5. It is made of galvanized steel sheet and is equipped with a heating element of 2.6 kW and a cooling coil positioned co-axially with the heater. The power of the heating element is sufficient to raise the temperature of the 150 litres of circulating fluid by 0.2° C in 15 s and easily balances the heat losses of the system. Two independent centrifugal pumps drive the fluid to the 'oxygen' and 'hydrogen' side of the model through a series of control and by-pass valves. The flow through the latter is also used to ensure continuous stirring of the working fluid in the storage tank.

The temperature of the fluid is monitored at the exit of the model by a platinum film (Pt100) sensor and is controlled by a PID (Proportional-Integral-Differential) temperature controller. The primary output of the controller operates the heating element while a secondary output enables, via a solenoid valve, the flow of tap water through the cooling coil. This type of temperature control, combined with the thermal inertia of the system and the

relatively low temperatures involved (less than 27° C) ensures temperature stability better than 0.05°C.

The flow rate in the transfer ducts is measured by four separate Pitot probes, using water filled U-tube manometers. The small difference in specific weight between water and refractive index fluid (1 kg/l vs. 0.895 kg/l) was advantageous with respect to the sensitivity of this simple monitoring system.

## SYSTEM PERFORMANCE

Preliminary tests of the experimental facility revealed difficulties associated with aeration of the refractive index fluid, which presents a tendency to foam. This problem was cured by raising the fluid level in the storage tank and modifying the return pipe to prevent aeration. Another difficulty associated with the properties of the working fluid is its tendency to penetrate easily through ordinary pipe fittings. It appears that the most suitable piping system would consist of copper pipes with compression fittings.

The maximum flow rate achieved through each of the transfer ducts was 90 l/min and 170 l/min at the 'oxygen' and 'hydrogen' side resulting in Reynolds numbers of 32,000 and 45,000, respectively. At these flow rates the temperature control system also performed satisfactorily, maintaining constant temperature within measurement accuracy, (better than 0.1° C).

## THE REFRACTIVE INDEX FLUID

The fluid chosen to match the refractive index of the cast acrylic model for this study was a mixture of oil of turpentine with 1, 2, 3, 4-tetrahydronaphthalene (Tetralin). This mixture was chosen for its low toxicity and flammability, combined with its relatively low cost. One particular advantage of this liquid is the low viscosity as compared with many mineral oils which are suitable for refractive-index-matching. Its main disadvantage is the effect of the Tetralin on the cast acrylic, the surface of which softens and crazes after six months in contact with it and dissolves after one year (Ref. 6). The small content of Tetralin in the mixture (less than 30%) and the thermal treatment of the transparent model, however, prolong its life to more than one year without obvious effects on the surface quality. Despite the inert nature of the mixture there are some precautions to be taken

with respect to fire hazard and ventilation of the working area. The fumes of the mixture are irritating and prolonged exposure may cause injury to the kidneys and lungs (Ref. 15).

The refractive index of cast acrylic (1.49) lies between the refractive indices of the oil of turpentine (1.468) and Tetralin (1.546). It is therefore feasible to obtain a mixture of the two fluids which, at a given temperature, will match that of the acrylic. The effect of mixture concentration ($C_m$) in Tetralin on the refractive index as a function of temperature is shown in Fig. 6, which clearly indicates its sensitivity to both parameters. Figure 7 shows the variation of mixture refractive index with temperature, as a function of Tetralin concentration and light wavelength. This graph also shows the effect of temperature on the refractive index of two common qualities of clear cast acrylic (Perspex and Diakon). It can be concluded that many combinations of temperature and concentration will achieve refractive-index-matching between the two media. Figure 7 also demonstrates that the matching temperature may increase sharply by a small increase in Tetralin concentration (7° C for 1.7% increase in Tetralin content). Since high temperatures will shorten the useful life of the transparent model, the best practice is to set the temperature slightly above ambient (e.g., 25° C) and adjust the content of Tetralin to match the refractive index of the acrylic.

Typical characteristics of a mixture of oil of turpentine (70% volume) and Tetralin (30% volume) are given in Table 1 below, while the effect of temperature on the kinematic viscosity of the mixture is shown in Fig. 8.

TABLE 1

TYPICAL PROPERTIES OF MIXTURE $C_m$ = 30 at 20°C

| | |
|---|---|
| Density | $\rho = 0.893$ kg/dm$^3$ |
| Kinematic viscosity | $\nu = 1.740\times10^{-6}$ m$^2$/s |
| Refractive Index | $n_D = 1.4897$ at $\lambda = 632.8$ nm |

## THE LASER VELOCIMETER

A dual-beam, forward-scatter laser velocimeter was used for the present preliminary tests. A detailed description of the system is given in Ref. 16 and only a brief outline is given here. It consisted of a 5 mW He-Ne laser and a rotating diffraction grating-based optical head on the transmission side and integrated photomultiplier optical unit on the collection side. The signal processing system was based on a Doppler burst counter processor interfaced to a microcomputer for data acquisition and processing. Typical characteristics of the laser velocimeter are given in Table 2.

TABLE 2

CHARACTERISTICS OF THE LASER VELOCIMETER

| | | |
|---|---|---|
| Laser wavelength | 632.8 | nm |
| Beam intersection half angle | 5.97 | deg |
| Length of measurement volume | 780 | μm |
| Diameter | 80 | μm |
| Fringe spacing | 3.04 | μm |
| Frequency shift (variable) | 0-7 | MHz |

The receiving optics of the system were suitable for off-axis light collection which proved to be particularly useful for the present flow configuration in terms of reducing the effective dimensions of the measurement volume and improving the signal-to-noise ratio of the optical system.

## PRELIMINARY TESTS

Three stages of preliminary tests were conducted prior to the final assembly of the experimental setup. The first two of these three preliminary tests were conducted as part of other programs (Refs. 9, 10, 11 and 13) and are included here for completeness in view of their support of the viability of the refractive-index-matching concept for the present application.

The first test is depicted in Fig. 9 and was designed to examine the ability of the chosen mixture to perfectly match the refractive index of the acrylic. The axial mean and turbulent velocity components of an air jet were measured with both beams of the laser velocimeter crossing a transparent temperature controlled tank containing the refractive index fluid and three pairs of crossing rods.

Two sets of results are shown in Fig. 10: one obtained with the laser beams passing through the rod bundle and one with the beams passing only through the fluid. Both sets of results agree within experimental accuracy, suggesting that neither the position nor the fringe spacing of the probe volume were altered when the acrylic rods were in the pathway of the beams. This test proved that the matching of the acrylic material was feasible with the chosen mixture and allowed the further design of the test rig.

The second test is illustrated in Fig. 11. The complete LOX post assembly was immersed in a temperature controlled bath of refractive index fluid. The laser beams of the velocimeter were made to cross the whole depth of the assembly and their intersection point was projected with a microscope objective lens onto a screen. The actual crossing of the beams was then tested at the matching temperature and the quality of the interference pattern was examined. Both were found to be acceptable, indicating that the surface quality of the rods was adequate to allow accurate measurements to be obtained in the model. Some sample measurements were also obtained inside the tank to prove this point.

The purpose of the third test was to evaluate the ability of the system to maintain constant temperature all over the model space and to allow the matching of the refractive index of the fluid under nearly normal operating conditions. It should be emphasized here that temperature gradients inside a model may be present, particularly near the walls and could obstruct the near-wall measurements (Ref. 13). The design of the present model was such that, due to the considerable thickness of the outer walls and the low temperature of the fluid, wall temperature gradients should be minimal. In addition, the size of the rods and their arrangements inside the model should be ideal for the uniform temperature distribution inside the model.

During this test, the outlet of the model was blocked with a flat plate with the temperature sensor positioned in its center. The fluid was then circulated, using one single pump, entering the model at the oxygen-side and

exiting from the hydrogen-side transfer ducts. This operation mode also eliminated the initially observed aeration problems of the fluid. Under these flow conditions, the time constants of the electronic temperature controller were adjusted to keep the fluid temperature constant within 0.1° C. The matching of the refractive index of the fluid was then performed using the procedure described in Refs. 7 and 8. A single laser beam was passed through the solid boundary of the model and projected on a screen, a few meters away. The laser beam was then traversed horizontally by a given amount so as to cross the outer edge of the curved boundary at the exit nozzle of the model. The refracted laser beam was then observed, having moved significantly further. The fluid temperature was kept constant at 23.4° C and pure Tetralin added to the circulating mixture until the refracted beam returned to its due position. A finer adjustment of the mixture was also performed by traversing the laser beam through the LOX post assembly and observing the excursion of the projected beam on the screen. Small temperature adjustments finalized the matching process.

The positive outcome of all three tests confirmed the feasibility of obtaining accurate velocity measurements in the complex flow configuration of the model of the SSME Main Injector Bowl, using the refractive-index-matching technique. Some sample velocity measurements in this configuration are presented in the following section and suggestions for further improvements of the experimental system are made in the last section of this report.

## VELOCITY FIELD MEASUREMENTS

Mean and turbulent component measurements were obtained in several locations inside the model, configured as described in the above third test. The measurement locations are indicated by letters A-E in Figs. 12-13.

The axial velocity distribution at the exit of the 'oxygen' transfer ducts (location A-A) is shown in Fig. 14. The velocity profile exhibits characteristics of fully developed pipe flow with maximum velocities of 1.9 $ms^{-1}$ and measurements were obtained as close as 0.5 mm to the pipe wall. It should be noted that during these measurements one of the laser beams was crossing the curved optical boundary of the race track at incidence angles of the order of 70° and this would have caused total reflection of the beam under normal circumstances. However, the matching of the refractive indices allowed

these measurements to be obtained in a straightforward manner with relative ease.

Axial velocity measurements were also obtained along a traverse through the LOX post assembly (B-B) and are shown by Fig. 13. Although each of the laser beams crossed a large number of acrylic rods under these conditions, the signal quality was adequate for reliable measurements to be obtained. The limit of obtaining measurements at the near-wall region of the rods was found to be the length of the measurement volume so that measurements were obtained as close as 300 μm to the surfaces of the rods, when part of the measurement volume was located inside the solid boundary. In this case, the collection optics had to be slightly out of focus and the photomultiplier pinhole was adjusted to 'see' the free part of the light measurement volume. It was at these conditions that off-axis light collection was found to be particularly useful.

The ability of the system to measure very close to the surfaces is demonstrated in Fig. 15 which presents axial velocity measurements between two rods in location C. In this case the diameter of the measurement volume was the limiting factor and since it was smaller than its length (80 vs 780 μm), allowed measurements to be obtained as close as 100 mm from the surface. These results also illustrate the complex nature of the wake of the rods and the high turbulence intensity in these regions.

Figure 16 presents measurements obtained again in location C, but of the vertical velocity component. They were obtained with the model operating under normal conditions (i.e. flow entering from all transfer ducts and exiting through the nozzle). Similar detail as that of Fig. 15 could be obtained, demonstrating the ability to measure two orthogonal velocity components.

A test of the effect of fluid temperature on the measured velocity and data rate was also conducted in two locations of the model, D and E, and the results are shown in Fig. 17. At the first location (D), the axial component was measured outside the LOX post assembly for fluid temperatures ranging between 21° and 23.5° C. The effect of refractive index mis-match on the mean velocity and data rate was found to be small, but was larger on turbulence intensity. This behavior was attributed to the fact that the laser beams at this point (D) only crossed the outer boundary of the race track of the model; a mis-match of the refractive indices would only cause elongation of the measurement volume and distortion of the fringe pattern, thus sustaining a high data rate and increasing the apparent turbulence intensity.

The test conducted at point E of the model was more severe since, not only the laser beams were crossing part of the LOX post assembly, but their plane was also positioned at an angle of 30° to the horizontal. The ability to measure under these circumstances demonstrated the feasibility of obtaining shear as well as normal stress measurements by rotating the plane of the laser velocimeter by +45° and -45° (Ref. 17). The effect of temperature variation on the velocity and data rate measurements at this point is also shown in Fig. 17 and indicates that the refractive index mis-match affected the data rate as well as the mean and turbulent velocity measurements due to the resulting partial crossing of the laser beams and the simultaneous distortion of the range pattern on the measurements volume. It is shown that a temperature excursion of 0.7° C from the matching point may lead to 100% error in mean velocity measurements.

Finally, an attempt to measure turbulence spectra at two locations in the model was made. This is an important capability of the system if vortex-shedding characteristics of the rods need to be studied. For this test, a frequency tracker and FFT (fast Fourier transform) analyzer were used, although the frequency counter system could be adapted to perform the same task, with proper data analysis software. The main limitation in this case comes from the valid signal data rate which, with the present configuration and without artificial seeding of the flow was of the order of 100 samples/s. The turbulence spectra shown in Fig. 18 may not be a reliable measurement of the high frequencies. The addition of seeding particles in the flow, however, would improve their reliability. It should also be noted that vortex shedding frequencies are expected to be in the low frequency range, of the order of a few Hertz, in which case, the turbulence spectra measurements will be easier to obtain.

The question of seeding particles is important, since the addition of commonly used latex particles in the fluid is not desirable as they may affect its properties. The choice of solid, inert particles may be considered as a better solution provided that their abrasive characteristics can be tolerated. The use of aluminum oxide or kaolin powder particles would also be under consideration in Phase II.

## CONCLUDING REMARKS

This report has presented a study of the feasibility of applying refractive-index-matching and laser velocimetry methods for the detailed velocity measurement of the flow field in the complex geometry of a model of the Main Injector Bowl of the SSME. The preliminary tests and measurements revealed the following:

1. A fluid mixture consisting of oil of turpentine and tetrahydronaphthalene was found to be suitable for matching the refractive index of clear cast acrylic at near ambient temperatures and to have excellent rheological characteristics.
2. The manufacture of a transparent model of the SSME Main Injector Bowl in clear cast acrylic was feasible and a test facility of the flow and temperature control of ther refractive index fluid was constructed and tested.
3. Measurements of three velocity components and of the corresponding normal and shear turbulent stresses is possible in most locations of the transparent model. The accuracy of the measurements is similar to that of ordinary laser velocimetry provided that the refractive indices of the two media match closely. Temperature control of the fluid within 0.10° C is necessary and can be obtained in the experimental facility developed.
4. Near-wall velocity field measurements are also possible and are limited by the dimensions of the velocimeter's probe volume. Reliable velocity measurements as close as 100μm to the surfaces of the LOX posts were shown to be possible.
5. The measurement of turbulence spectra in the model was also shown to be feasible but limited accuracy was attained because of the arrival rate of the seeding particles.
6. Several issues requiring further work were identified, mostly regarding technical aspects of the test facility. Those were the following:
   - Incompatibility between ordinary pipe fittings and working fluid.
   - Artificial seeding of the flow is required.
   - Fluid aeration problems may have to be reconsidered.

- Data analysis software for turbulence spectra measurements with the Doppler frequency counter needs to be developed.
- Fine micropositioning of the laser velocimeter is required for the near-wall measurements.

7. Refractive-index-matching techniques are applicable to the study of SSME and rocket-engine configurations, although there is a need to quantify the similarity and measurement accuracy that can be attained.

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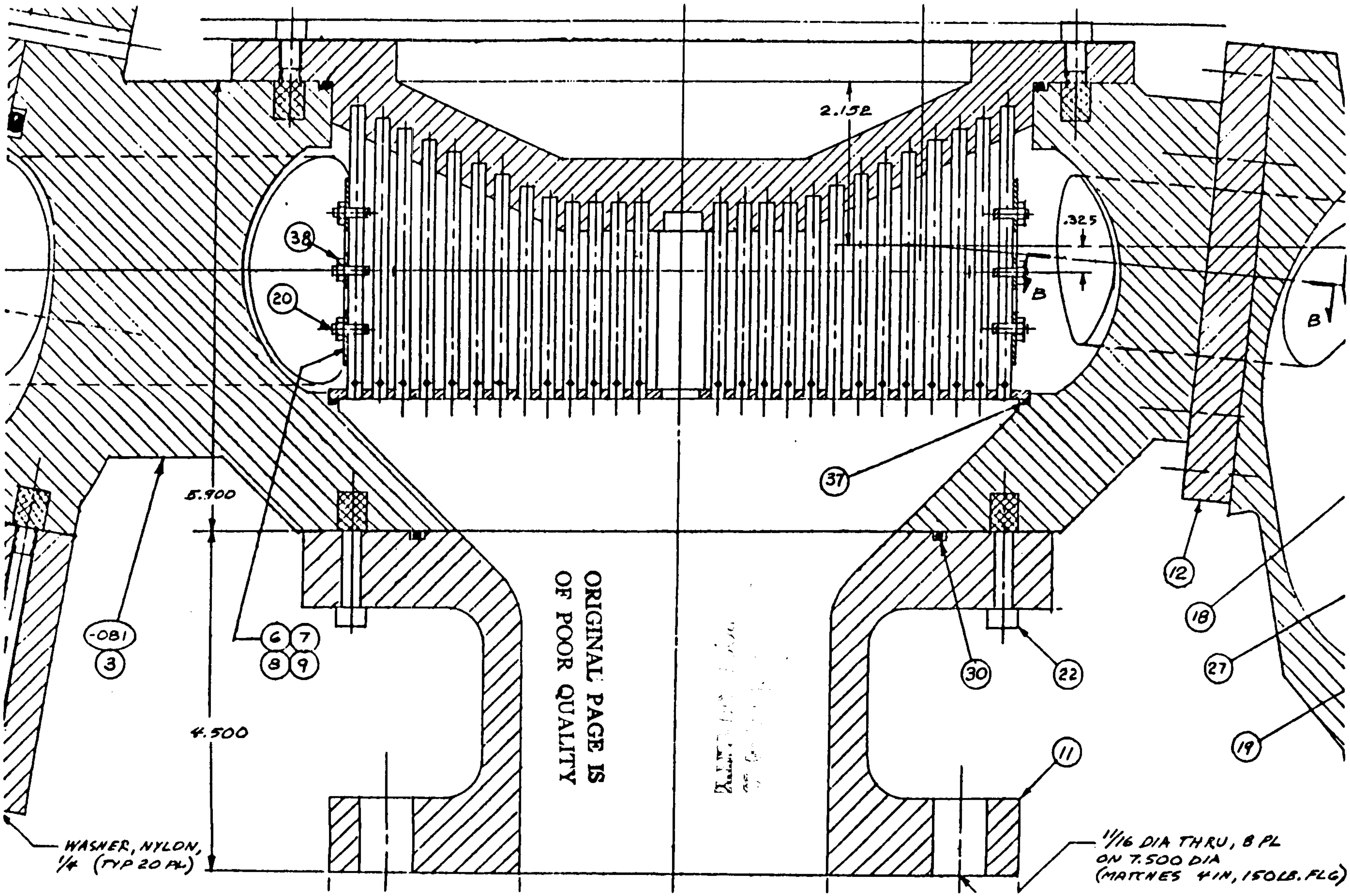



Figure 1a. SSME Main Injector Bowl, Model No. 517 - Side View.

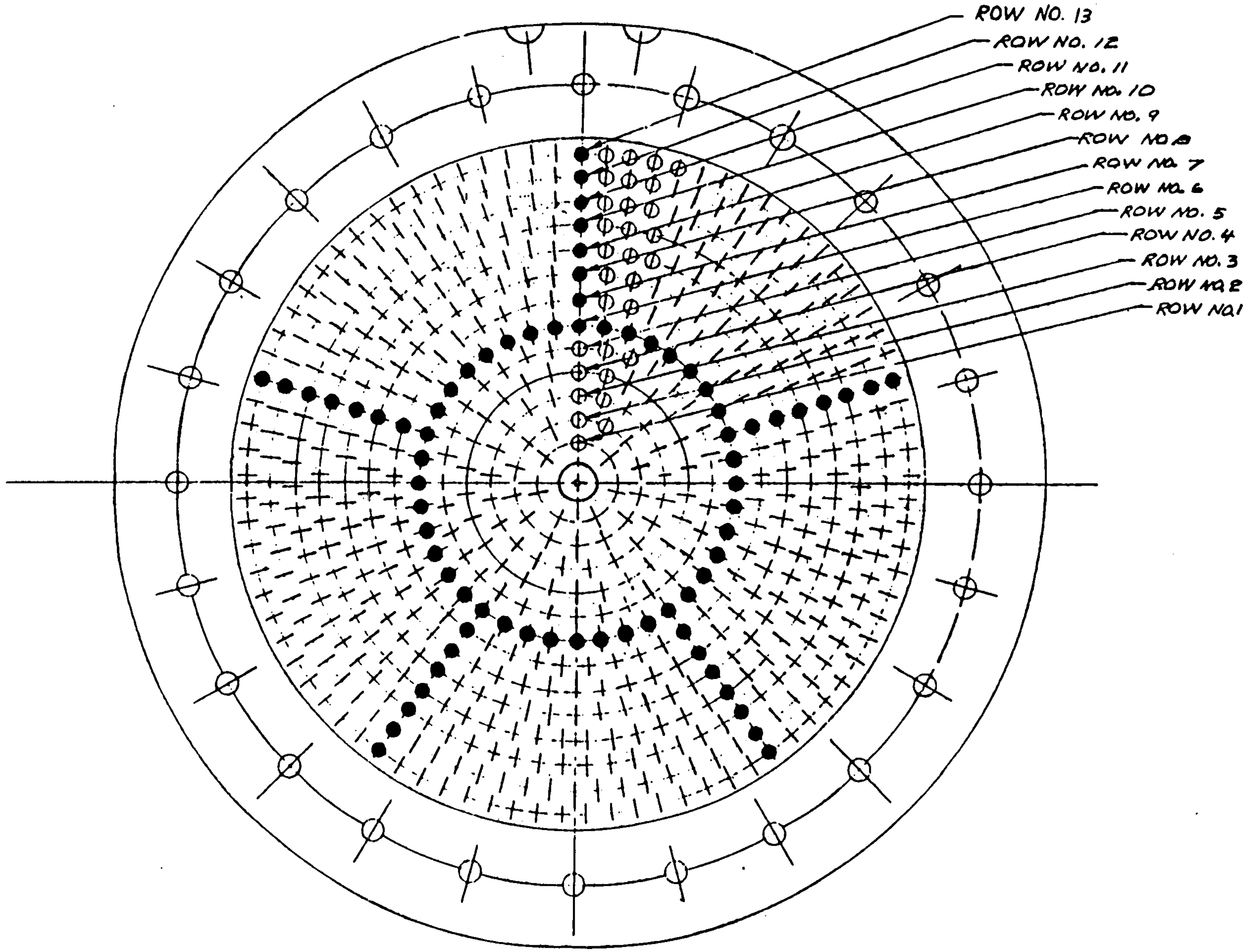



Figure 1b. SSME Main Injector Bowl, Model No. 517 - Top View.

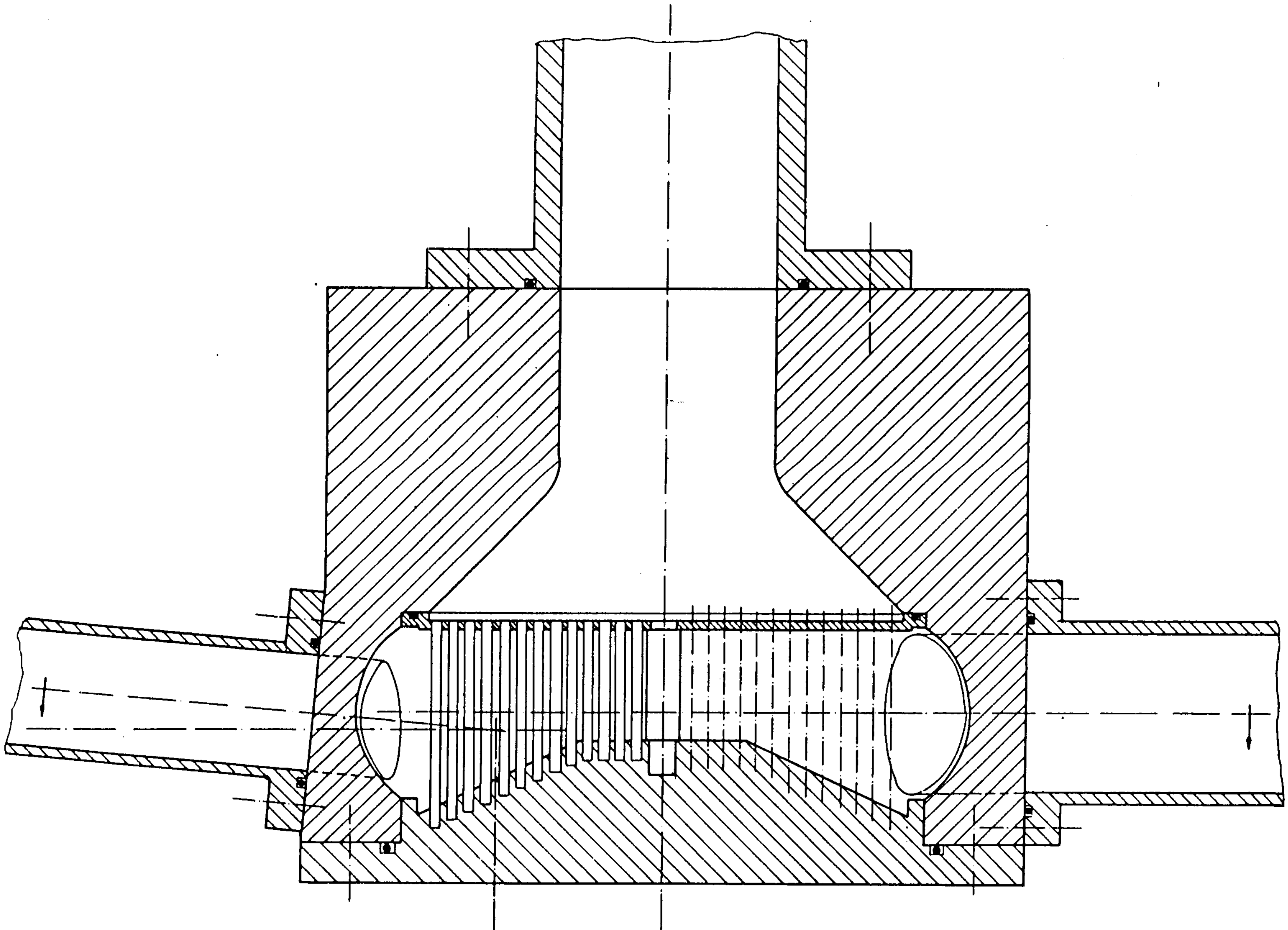


Figure 2a. Transparent Acrylic 36% Model of SSME Main Injector Bowl - Side View.

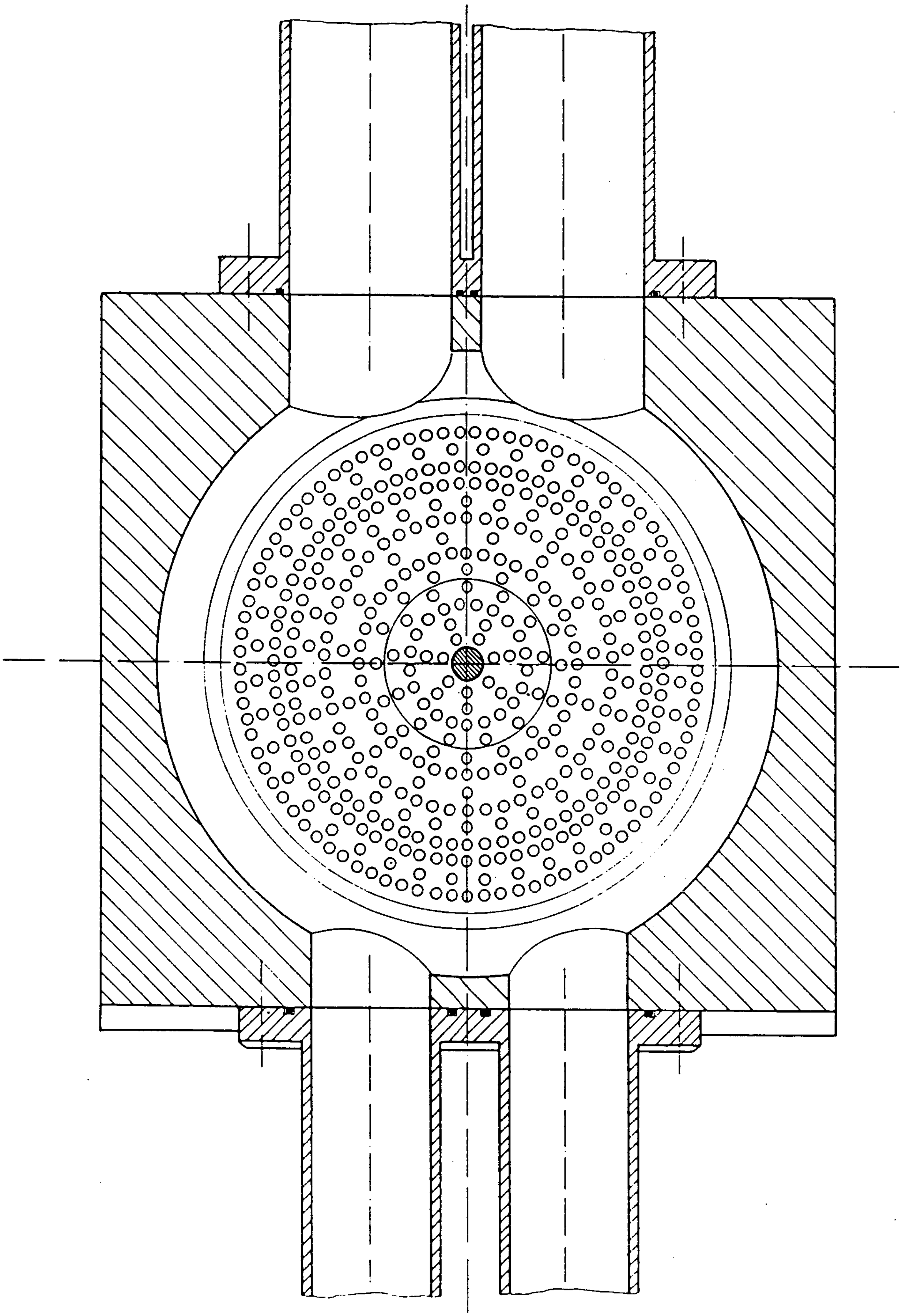
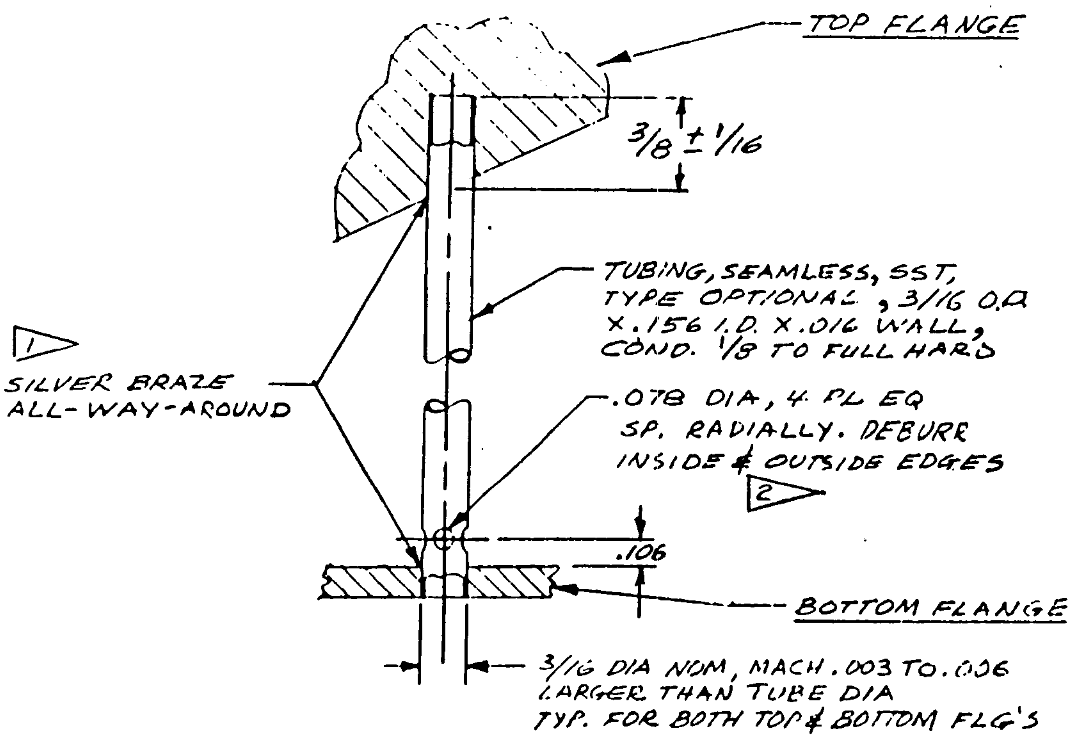
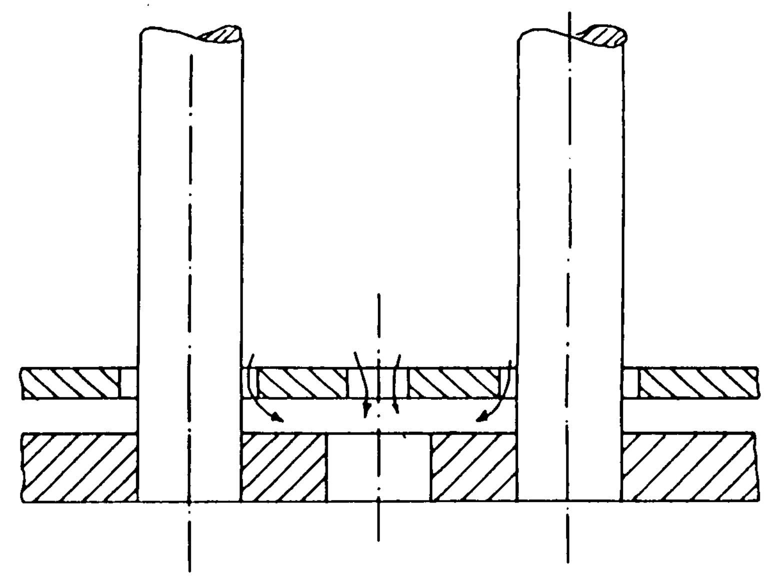


Figure 2b. Transparent Acrylic 36% Model of SSME Main Injector Bowl - Top View.




(a) Model No. 517



(b) 36% Model

Figure 3. LOX Post Bleed Holes.

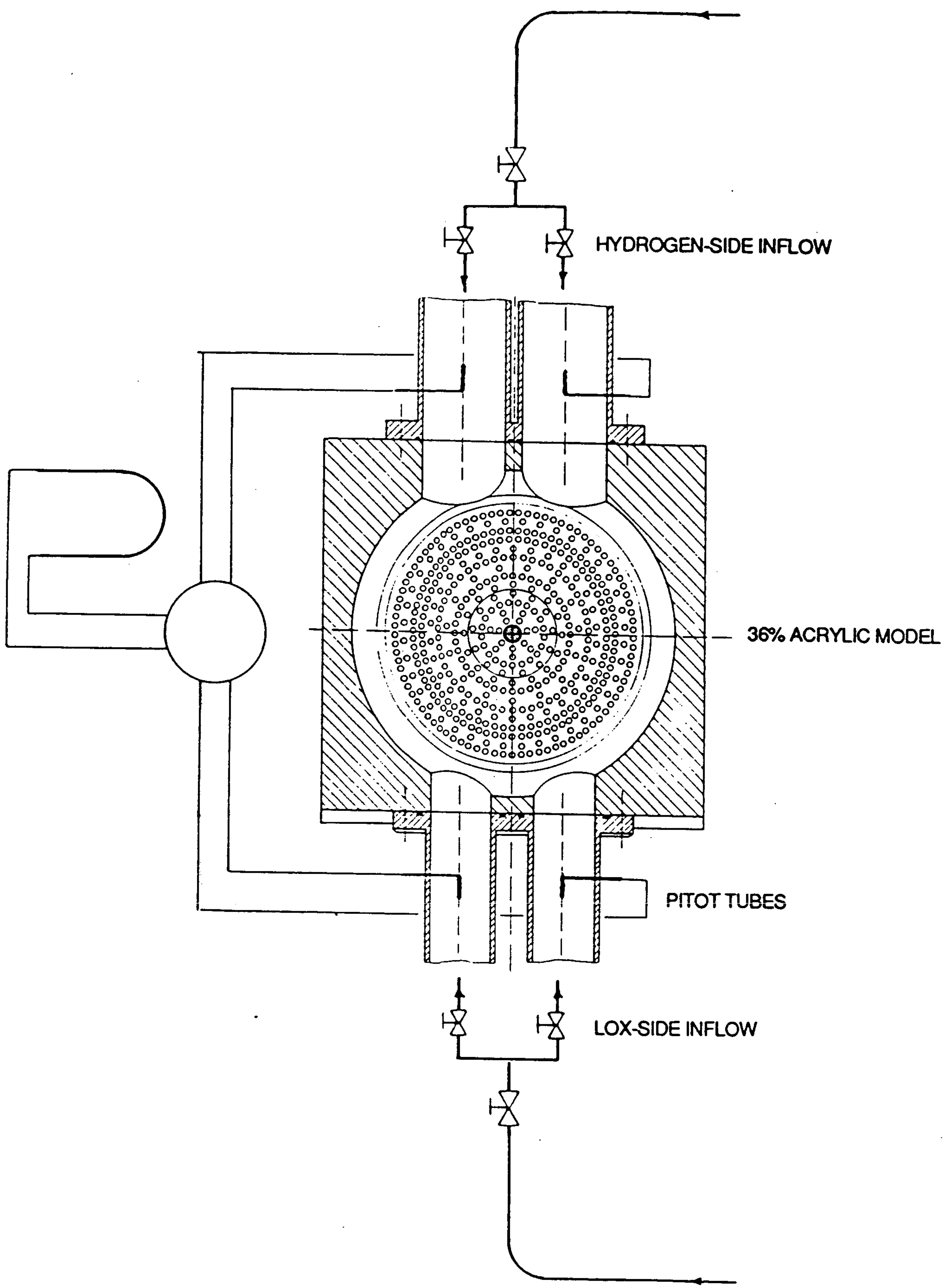



Figure 4. 36% Model Configuration.

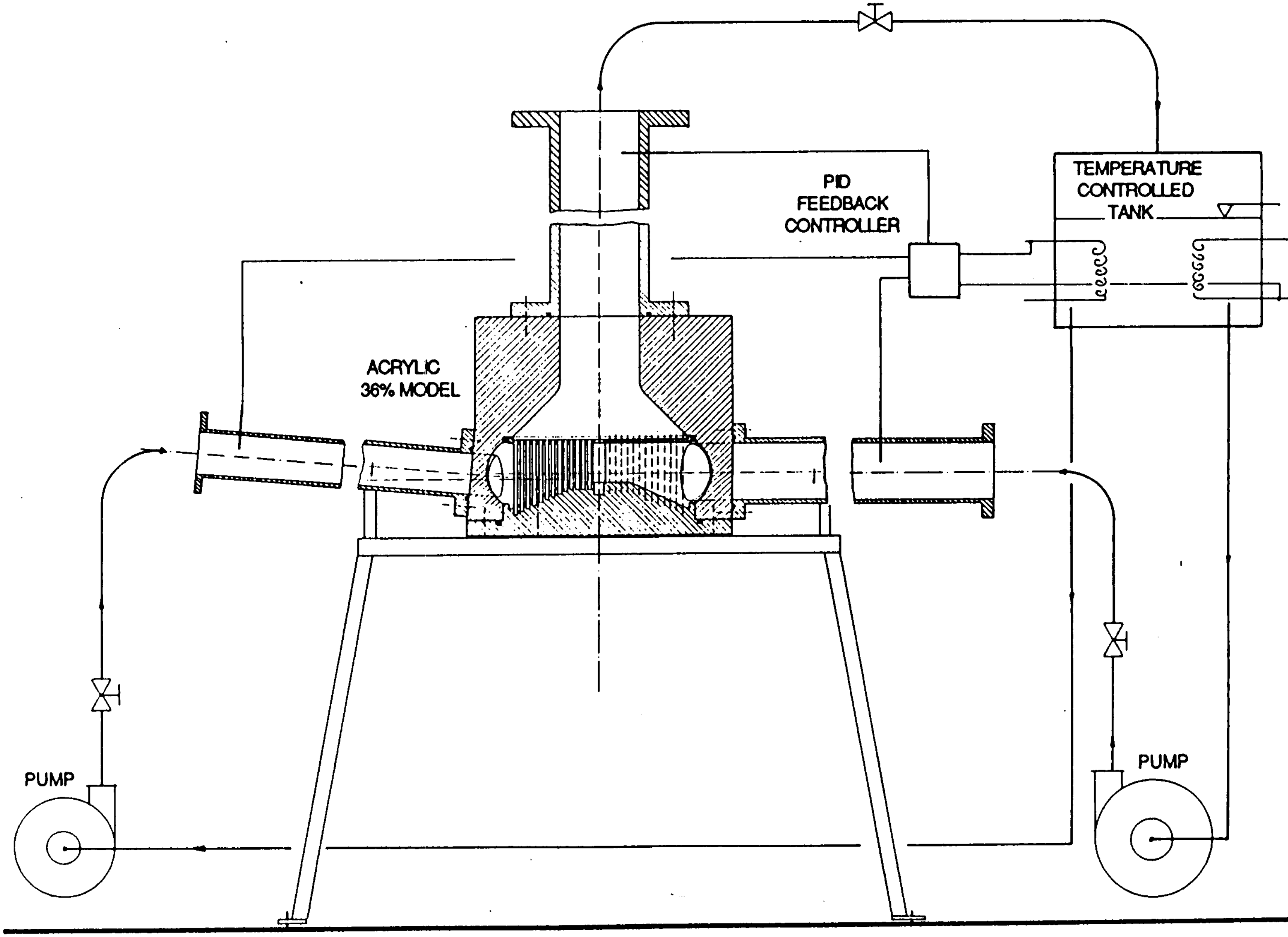



Figure 5a. Flow Circuit.

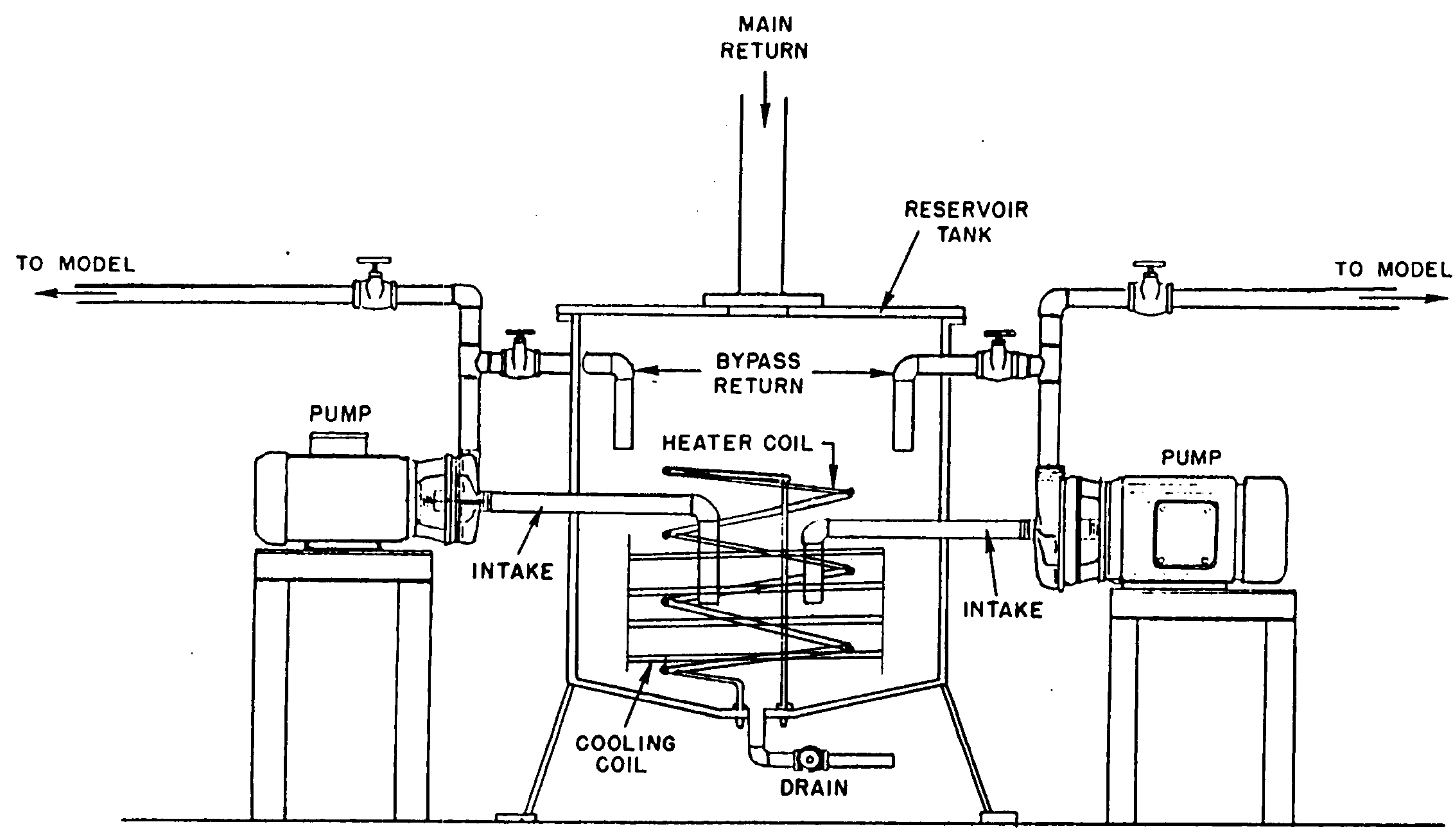



Figure 5b. Temperature Controlled Storage Tank.

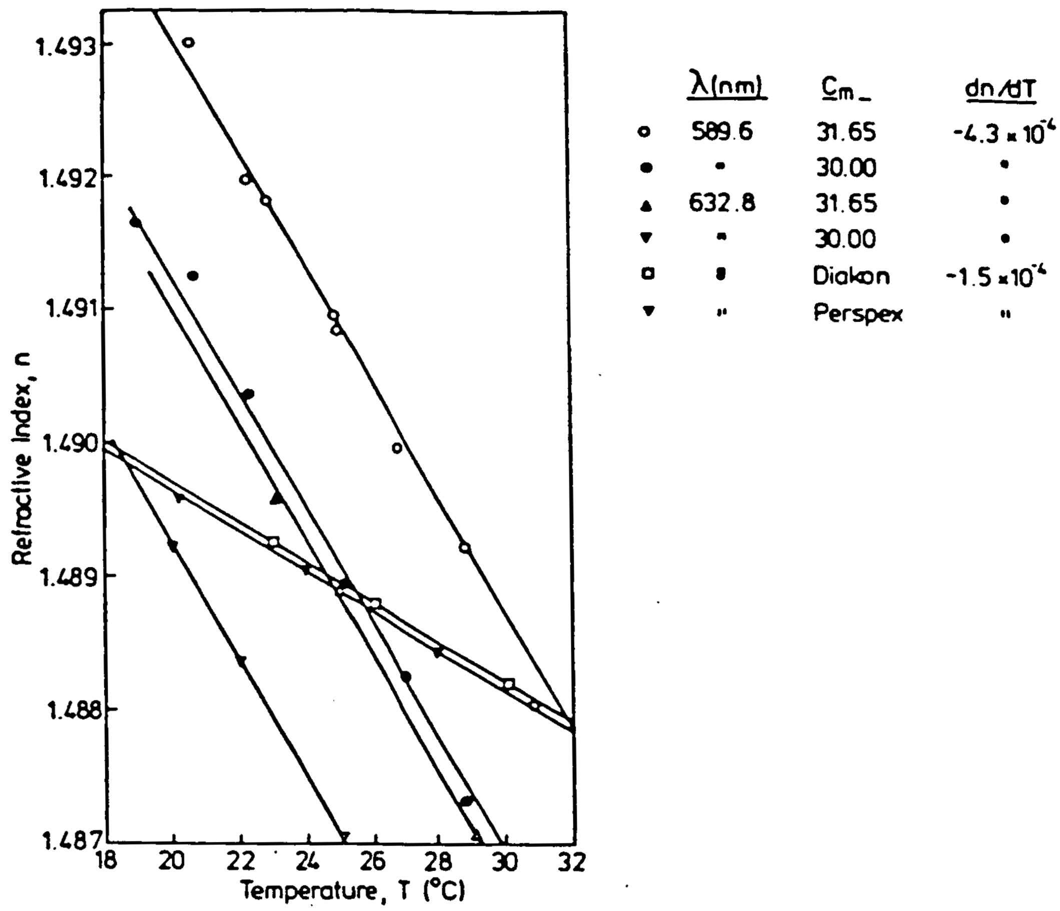



Figure 7. Variation of Mixture and Model Refractive Index.

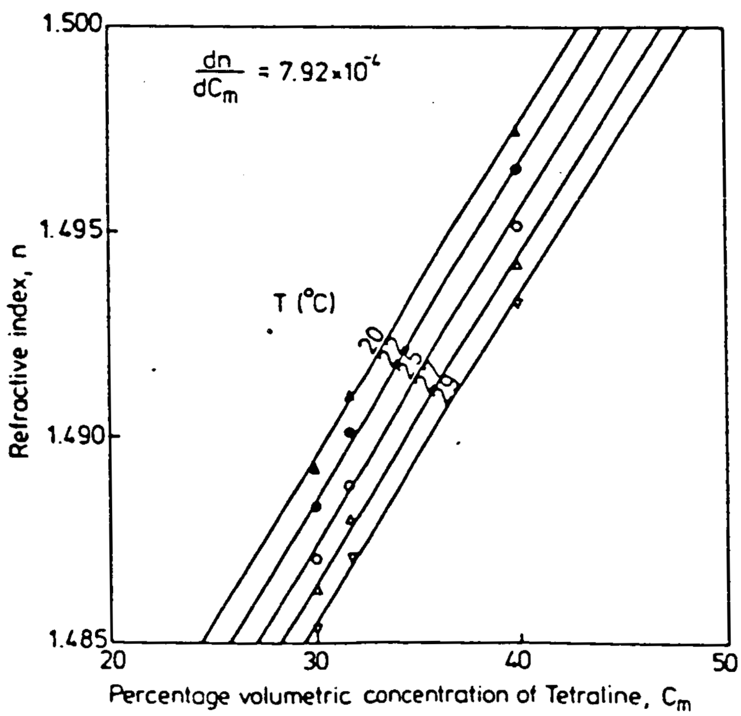



Figure 6. Variation of Refraction Index with Temperature and Concentration.

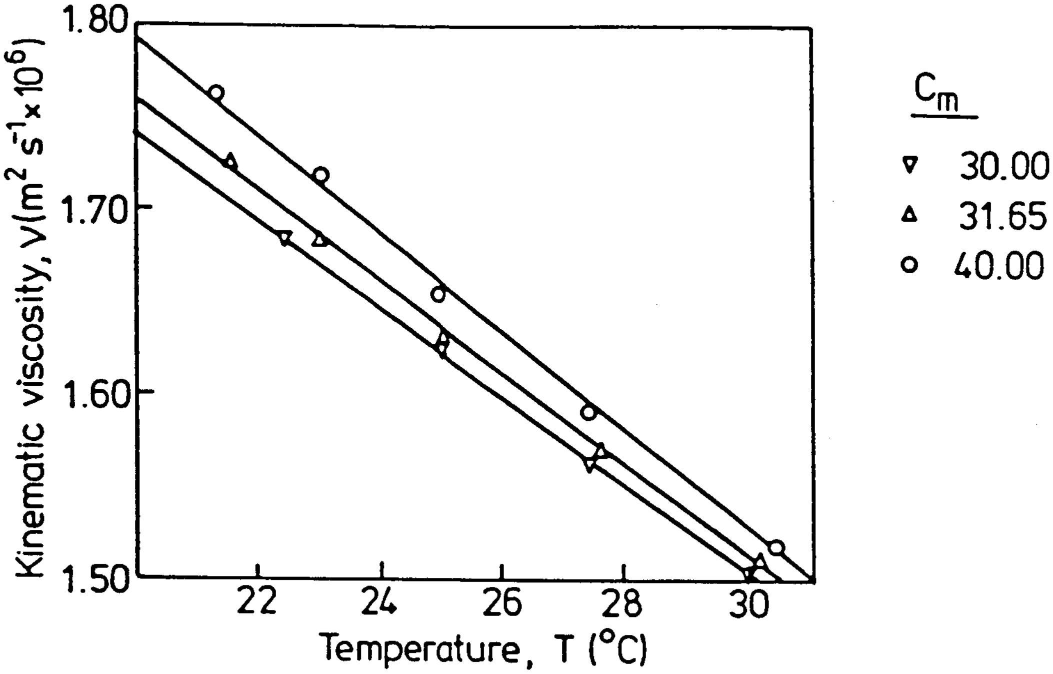



Figure 8. Mixture Kinematic Viscosity.

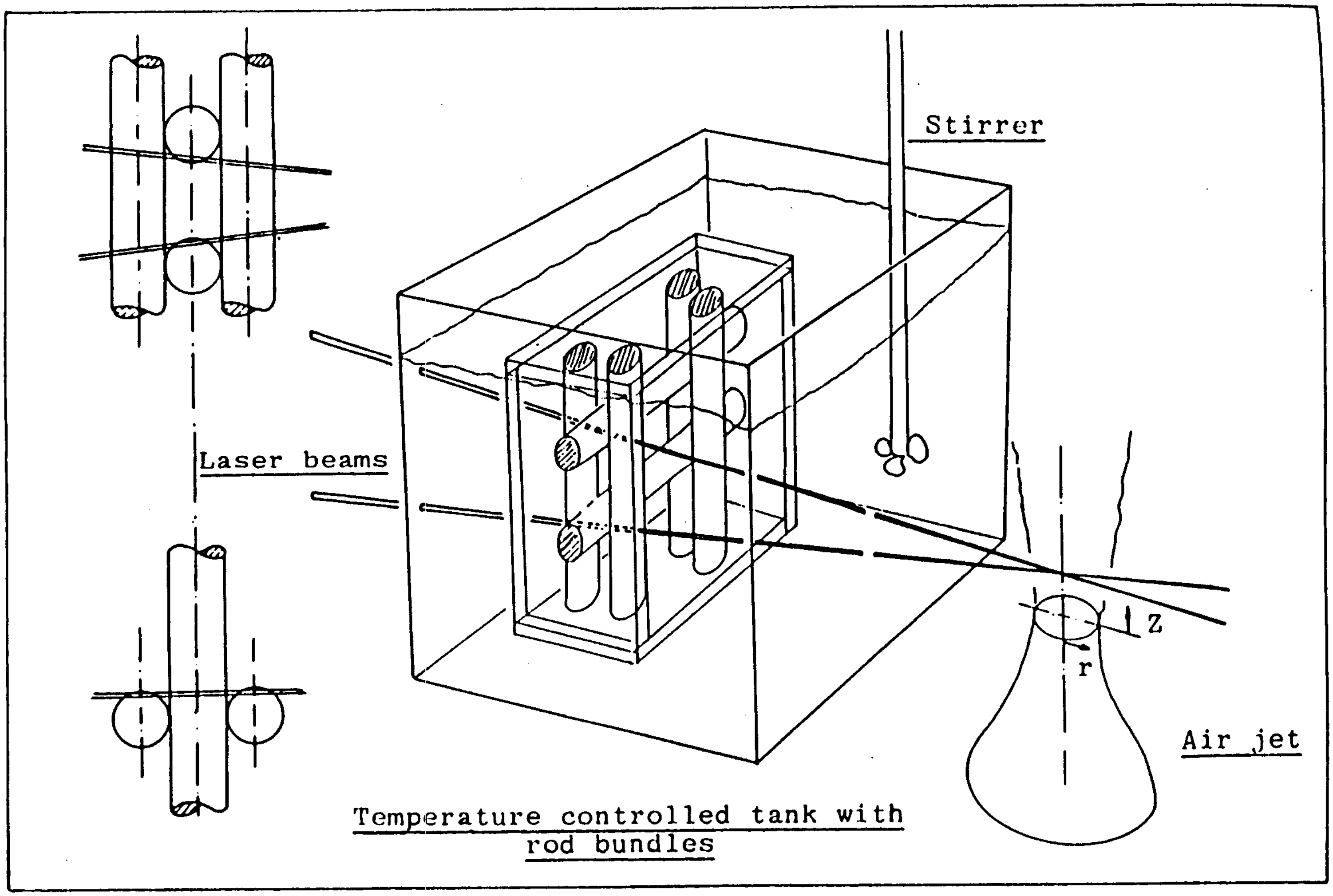



Figure 9. Rod Bundle Flow Configuration.

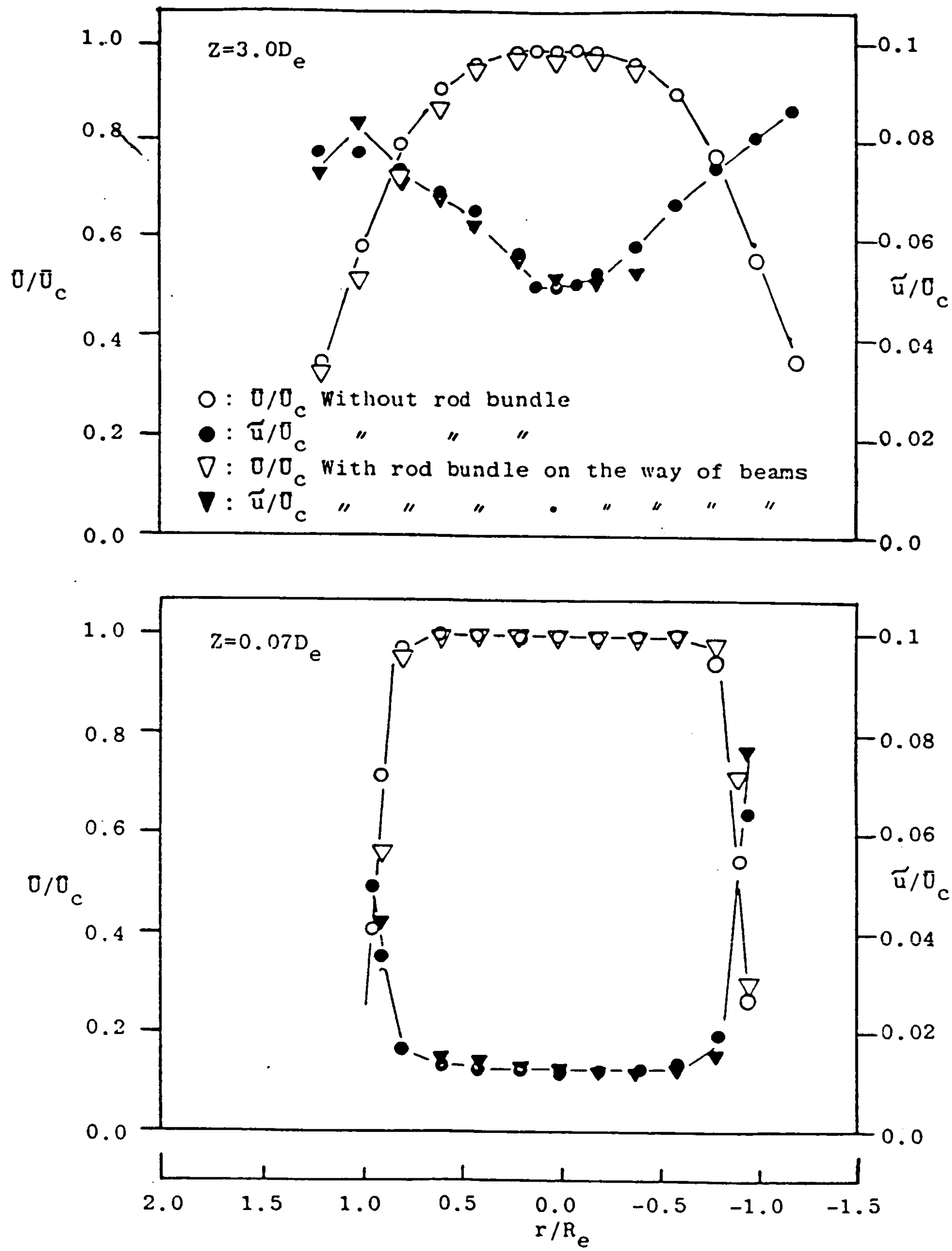



Figure 10. Mean Velocity and Turbulence Intensity in a Rod Bundle.

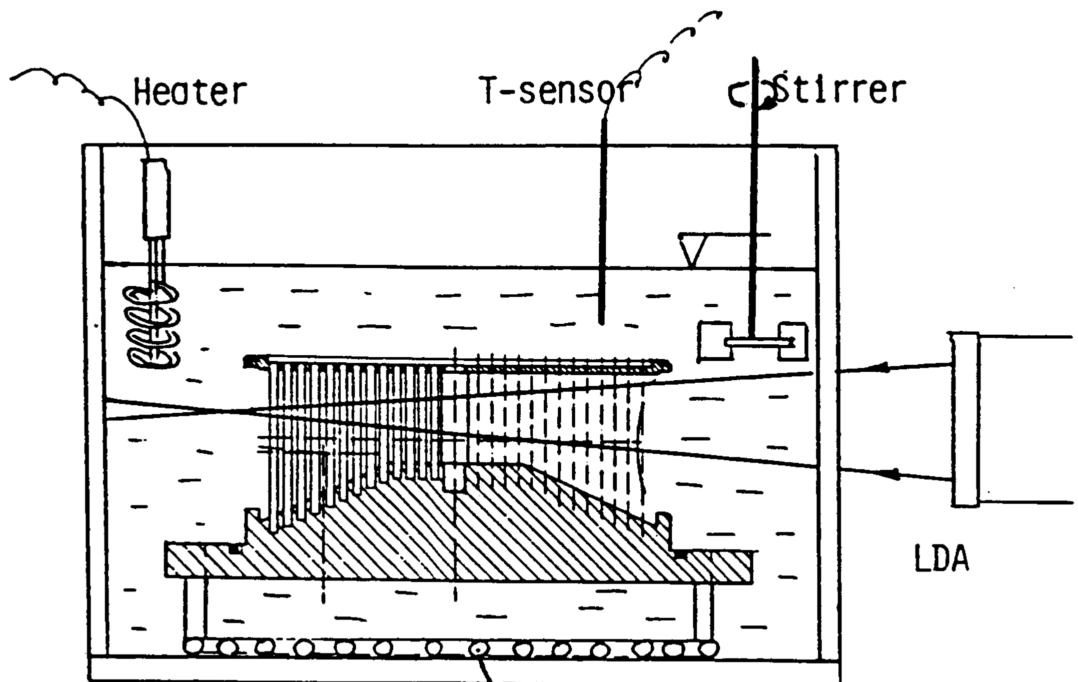



Figure 11. 36% Model Immersed in a Mixture Bath.

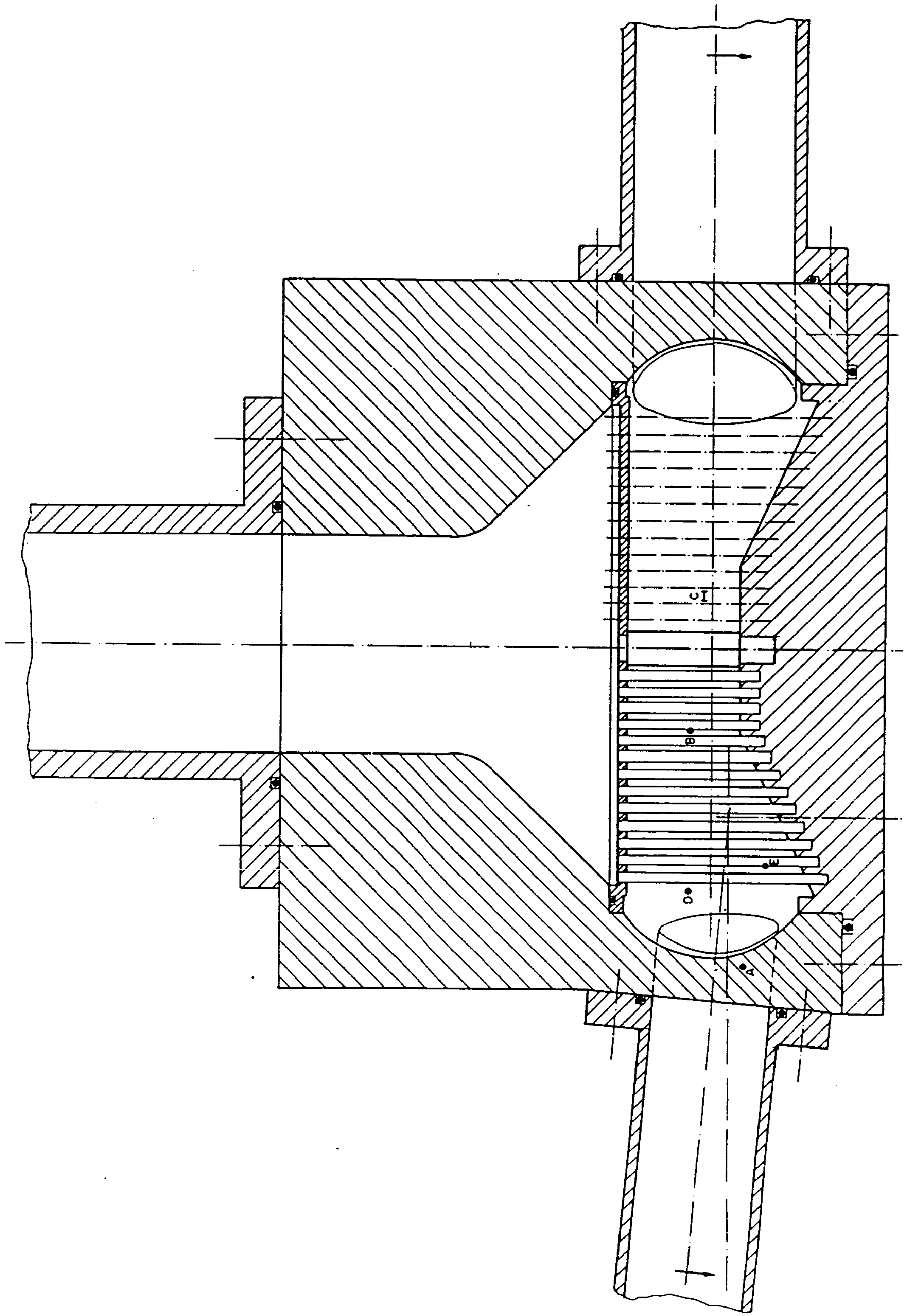



Figure 12. Measurement Locations - Side View.

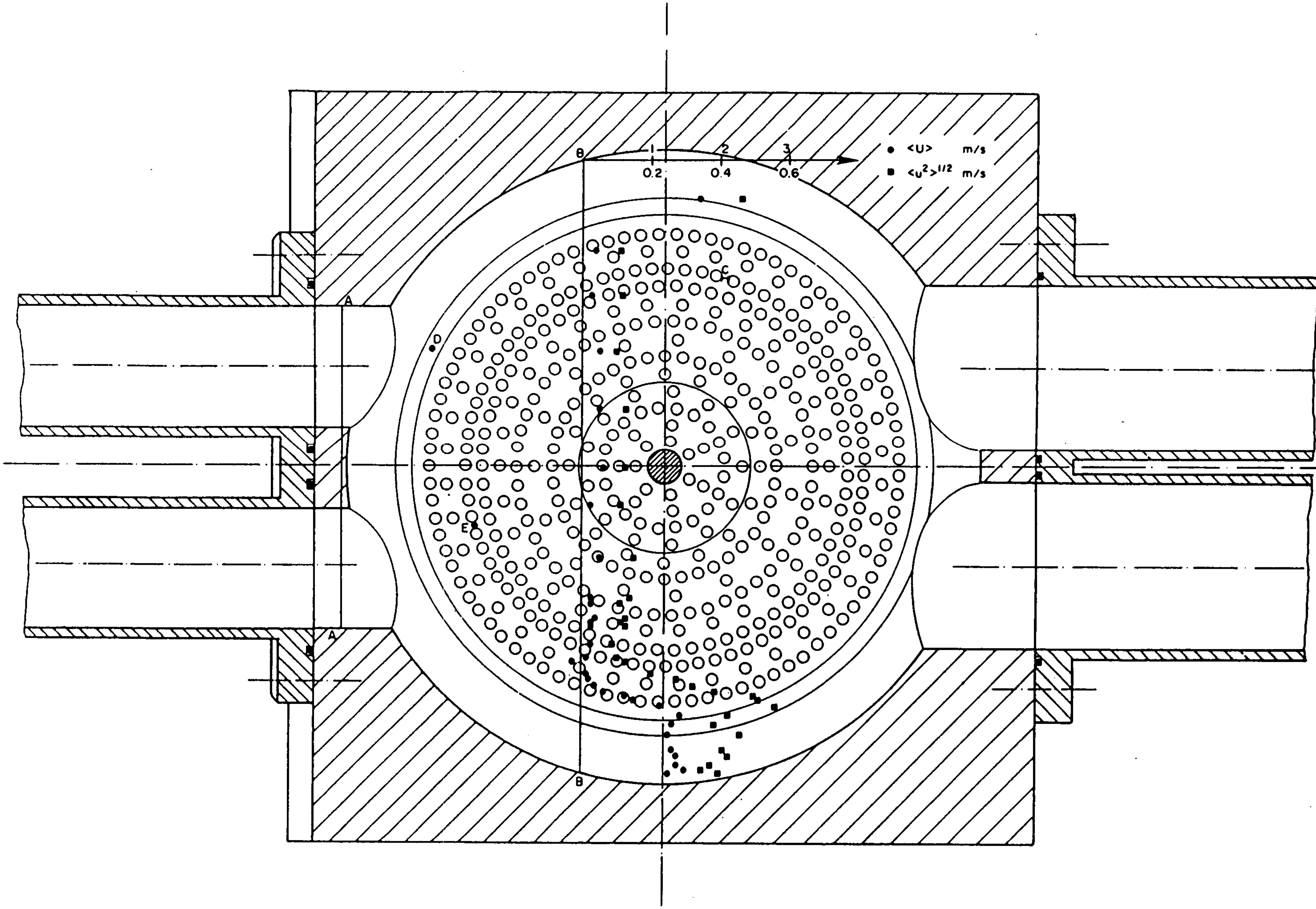



Figure 13. Mean Velocity and Turbulence Intensity Distribution across the Tube Bundle. Also Measurement Locations - Top View.

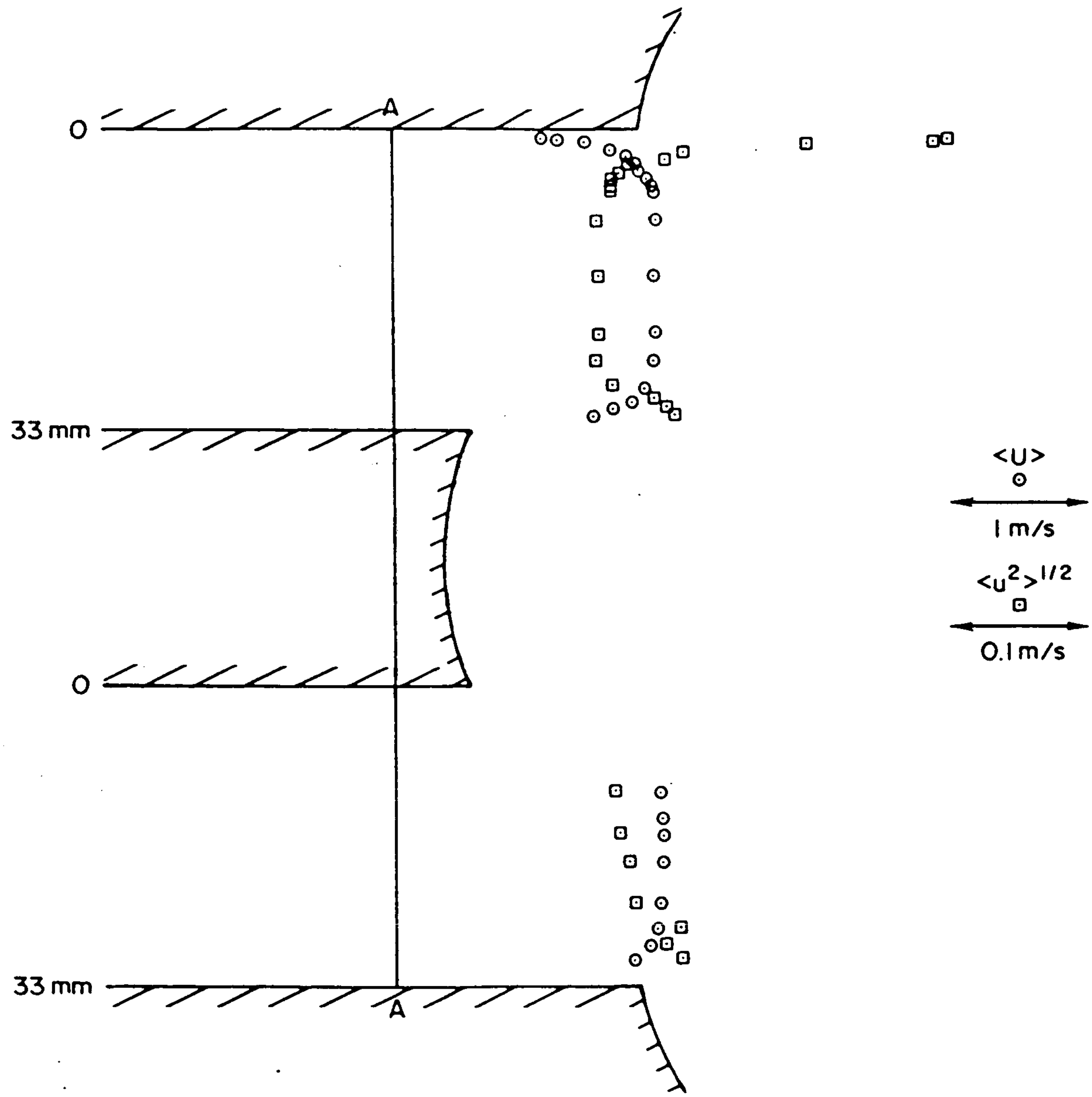



Figure 14. Mean Velocity and Turbulence Intensity Distribution at the Exit of the Inlet Ducts.

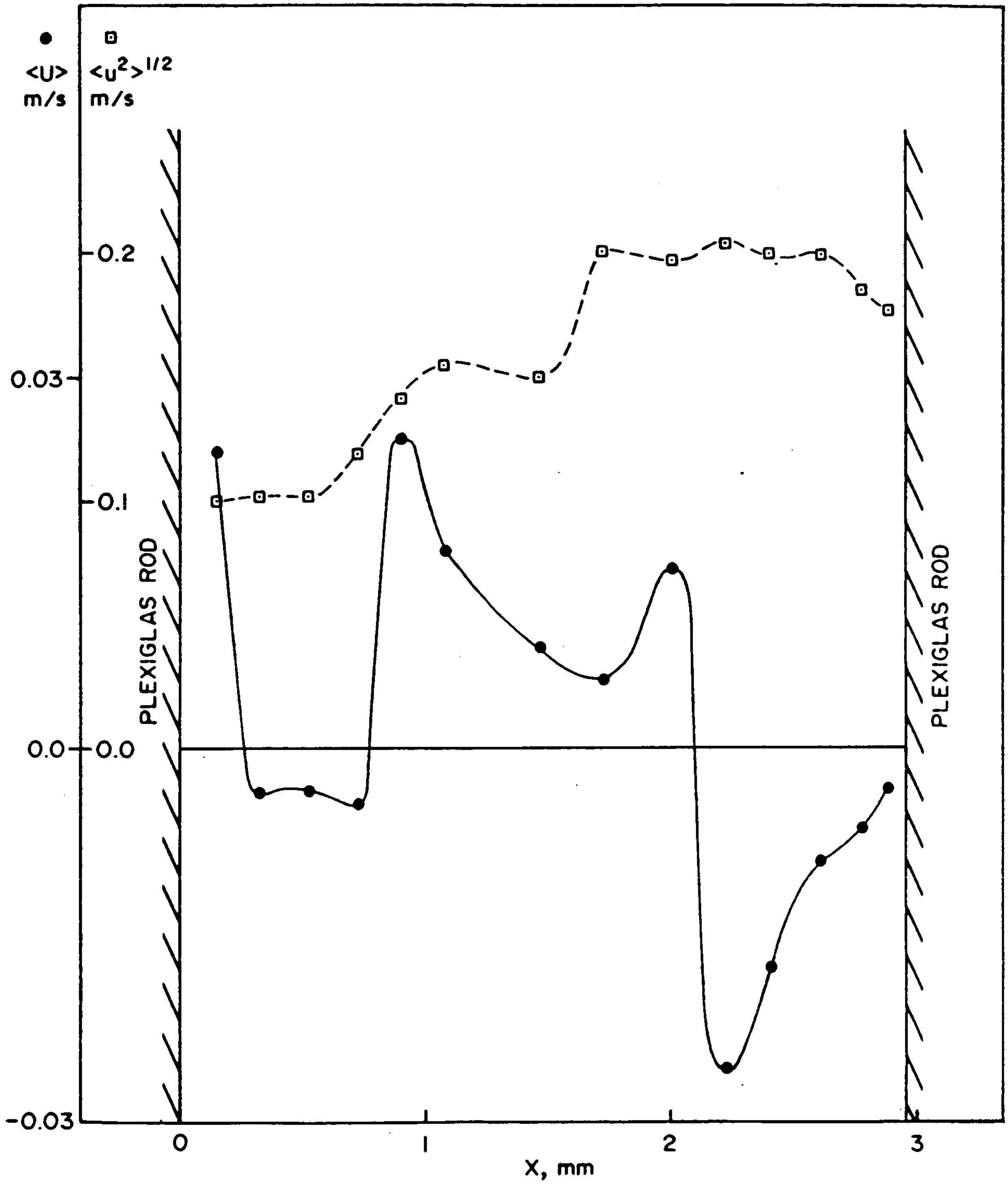



Figure 15. Mean Horizontal Velocity and Turbulence Intensity Distributions Between Two Posts. (Profile C on Figures 12 and 13.)

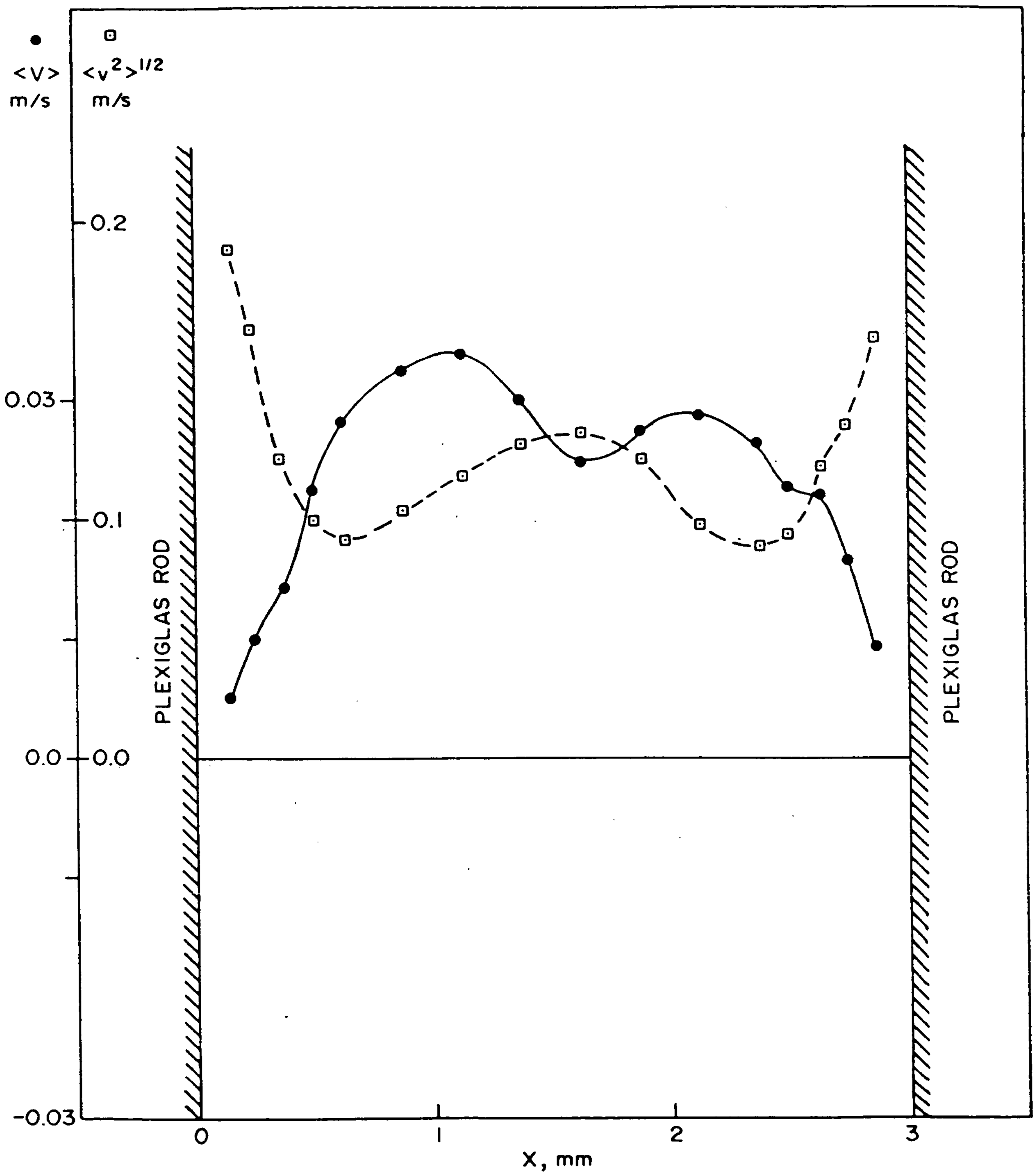



Figure 16. Mean Vertical Velocity and Turbulence Intensity Distributions Between Two Posts. (Profile C on Figures 12 and 13.)

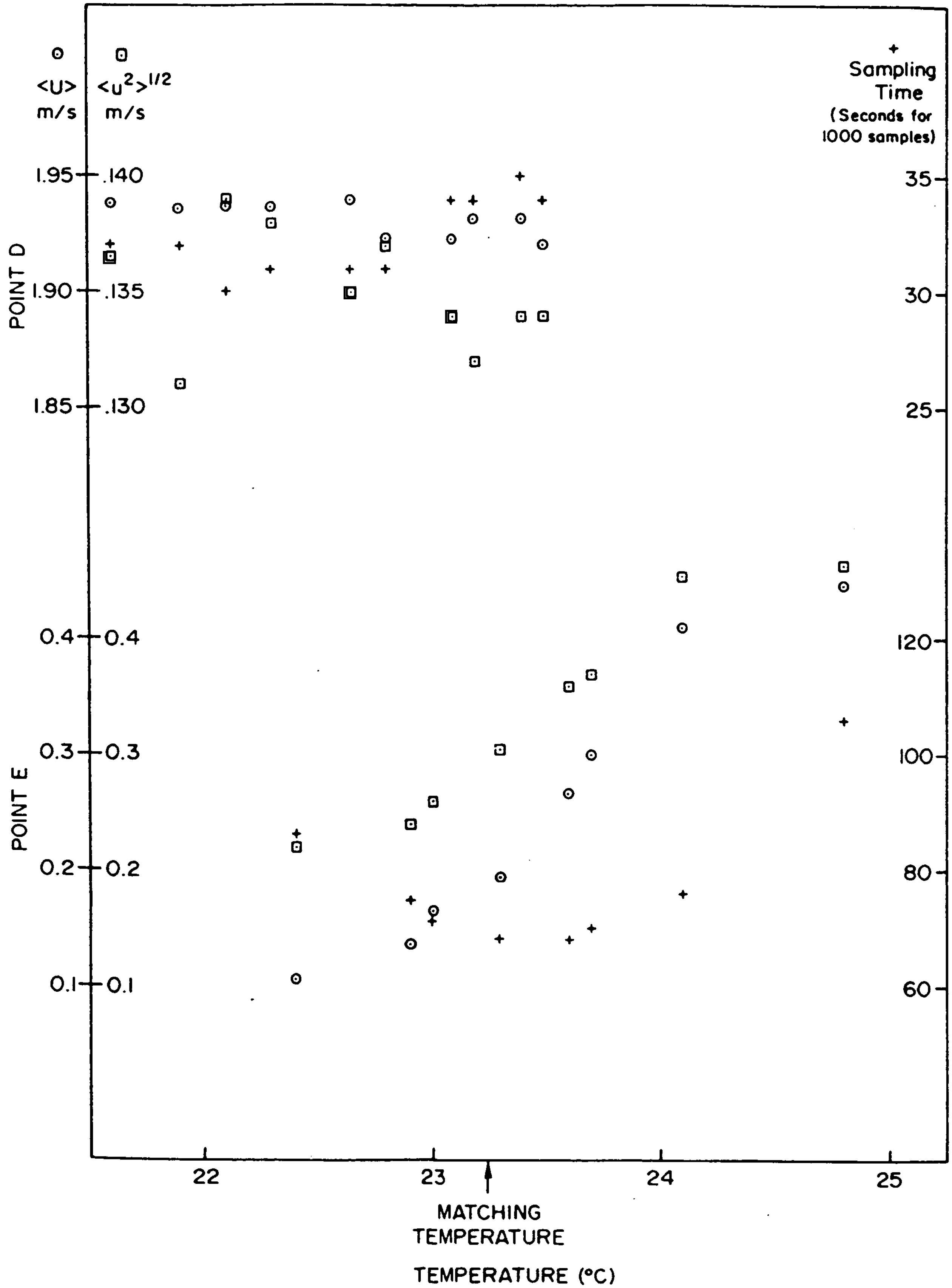
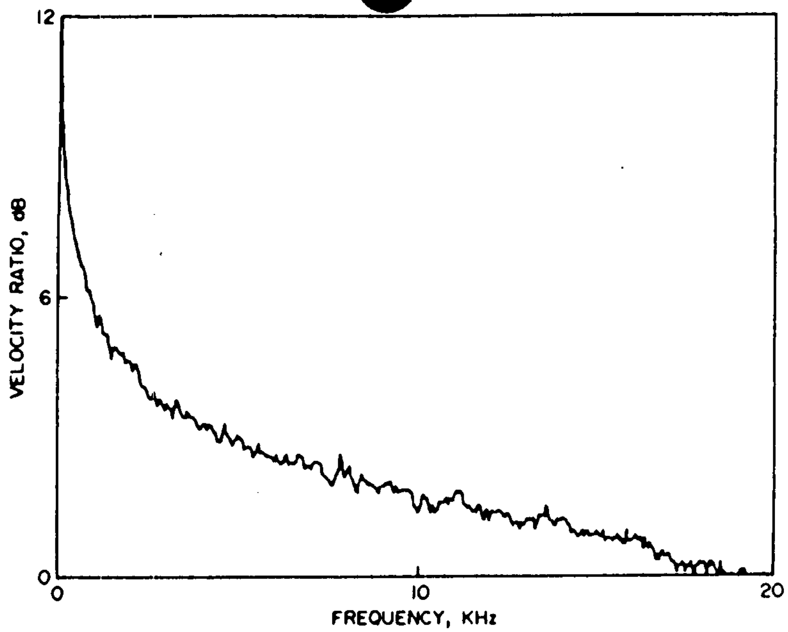
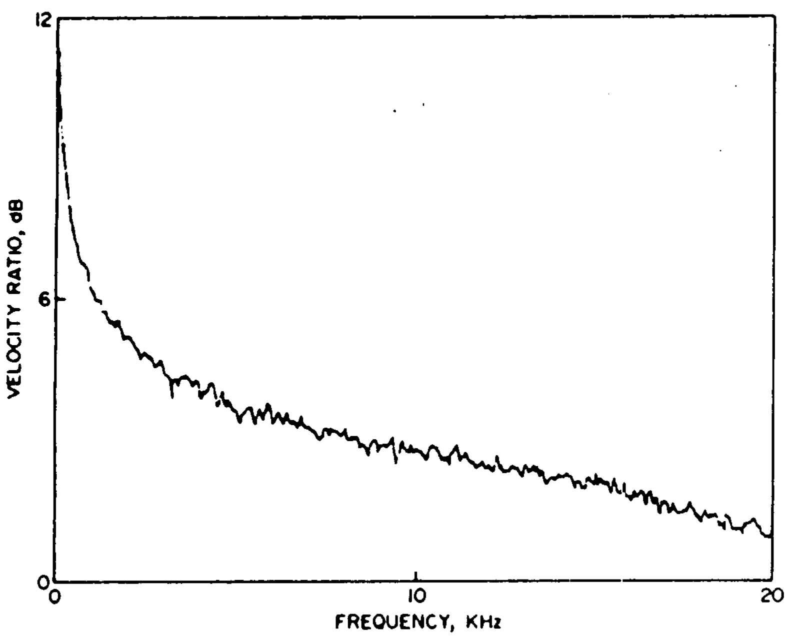


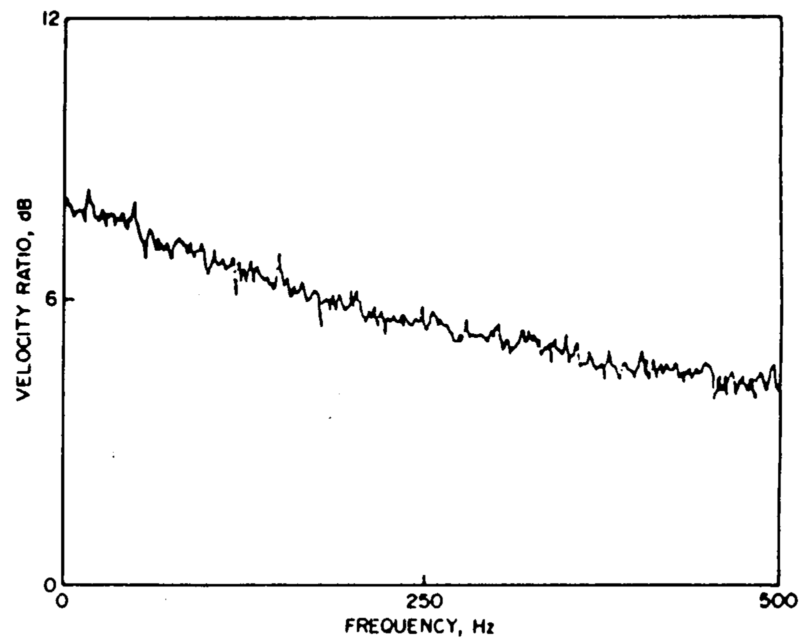

Figure 17. Mean Horizontal Velocity, Turbulence Intensity, and Sampling Time vs. Temperature. Results Obtained at Points D and E as Indicated.




a) At Exit of Inlet Duct




b) In Tube Bundle Near Location E




c) In Tube Bundle Near Location E

Figure 18. Frequency Spectra.

APPENDIX 1

## Refraction Correction for Cylindrical Optical Boundaries

The actual position ($X_N$, $Y_N$) of the measuring volume inside the engine cylinder is calculated from the position of the optical system (x,y) relative to the cylinder axis as follows:

1. Transverse Plane (v,w components, Fig. A1)

$$\tan k = \frac{y}{x}$$

$$r = \sqrt{y^2 + x^2}$$

$$\sin a_{f1} = \frac{\sin (a_a - k)}{R_1} \cdot r$$

$$\sin a_{f2} = \frac{\sin (k - a_a)}{R_1} \cdot r$$

$$\frac{\sin a_{f1}}{\sin a_{w1}} = \frac{\sin a_{f1}'}{\sin a_{w1}'} = \frac{n_w}{n_a} \qquad \frac{\sin a_{w1}}{\sin a_{w2}} = \frac{\sin a_{w1}'}{\sin a_{w2}'} = \frac{R_2}{R_1}$$

$$\frac{\sin a_{w2}}{\sin a_{f2}} = \frac{\sin a_{w2}'}{\sin a_{f2}'} = \frac{n_f}{n_w}$$

$$\sigma = a_a + (a_{f1} - a_{w1}) - (a_{f2} - a_{w2})$$

$$\rho = a_a + (a_{f1}' - a_{w1}') - (a_{f2}' - a_{w2}')$$

$$\phi = \sigma + \rho$$

$$\frac{1}{\tan \theta} = \frac{1}{\sin \theta} \left[ \frac{\sin a_{f2}}{\sin a_{f2}} + \cos \phi \right]$$

1. Transverse Plane Continued

$$r' = R_2 \frac{\sin a_{f2}'}{\sin \theta}$$

$$k' = -a_a + a_{f1}' - a_{w1}' + a_{w2}' - a_{f2}' + \pi - \theta$$

$$y_N = r' \cdot \sin k'$$

$$x_N = r' \cdot \cos k'$$

From the above relations the actual position of the measuring volume ($x_N$, $y_N$), the actual beam intersection angle ($\phi$) and the angle of the sensitivity vector ($\sigma$, $\rho$) can be calculated.

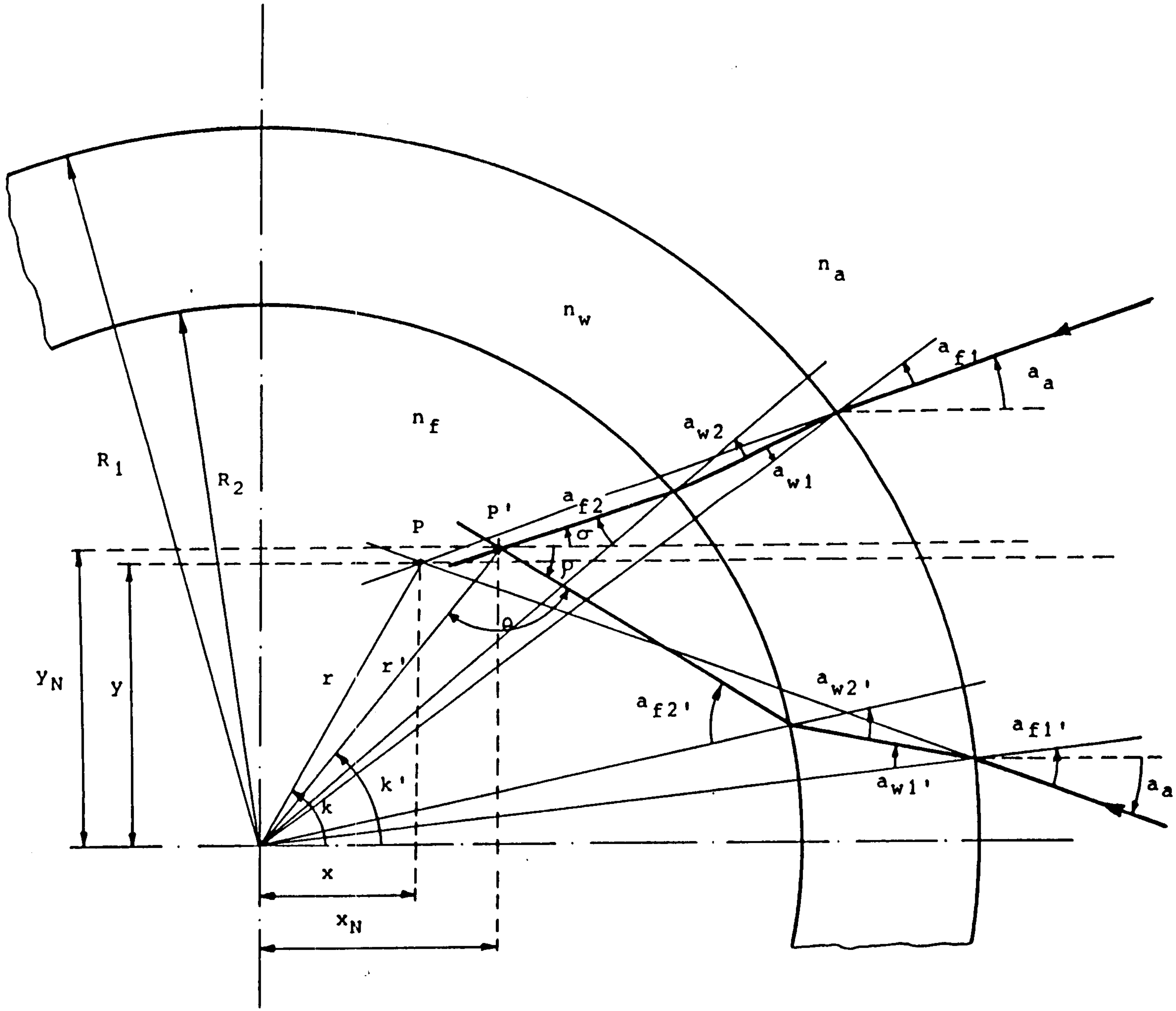



Figure A1. Cylindrical Optical Boundaries.

2. Plane Parallel to the Axis (U component, Fig. A2)

$$\tan a_{f1} = \frac{y}{R_1}$$

$$\frac{\sin a_{f1}}{\sin a_{w1}} = \frac{n_w}{n_a} \qquad \frac{\sin a_{w1}}{\sin a_{w2}} = \frac{R_2}{R_1} \qquad \frac{\sin a_{w2}}{\sin a_{f2}} = \frac{n_f}{n_w}$$

$$\rho = (a_{f1} - a_{w1}) - (a_{f2} - a_{w2})$$

$$t' = R_2 \cdot \frac{\sin (a_{w2} - a_{w1})}{\sin a_{w1}} \cdot \cos (a_{f1} - a_{w1})$$

$$(t' = R_2 - R_2 \text{ for } y = 0)$$

$$t = R_1 - R_2$$

$$A = \sqrt{\frac{n_f^2}{n_a^2} - \sin^2 a_a} \qquad B = \sqrt{\frac{n_w^2}{n_a^2} - \sin^2 a_a}$$

$$d_e = (1 - \frac{A}{B}) \cdot (t' - t)$$

$$x_N = x - d_e$$

$$y_N = R_2 \cdot \sin (\rho - a_{f2}) - \left[R_2 \cdot \cos (\rho - a_{f2}) - x_N\right] \cdot \tan \rho$$

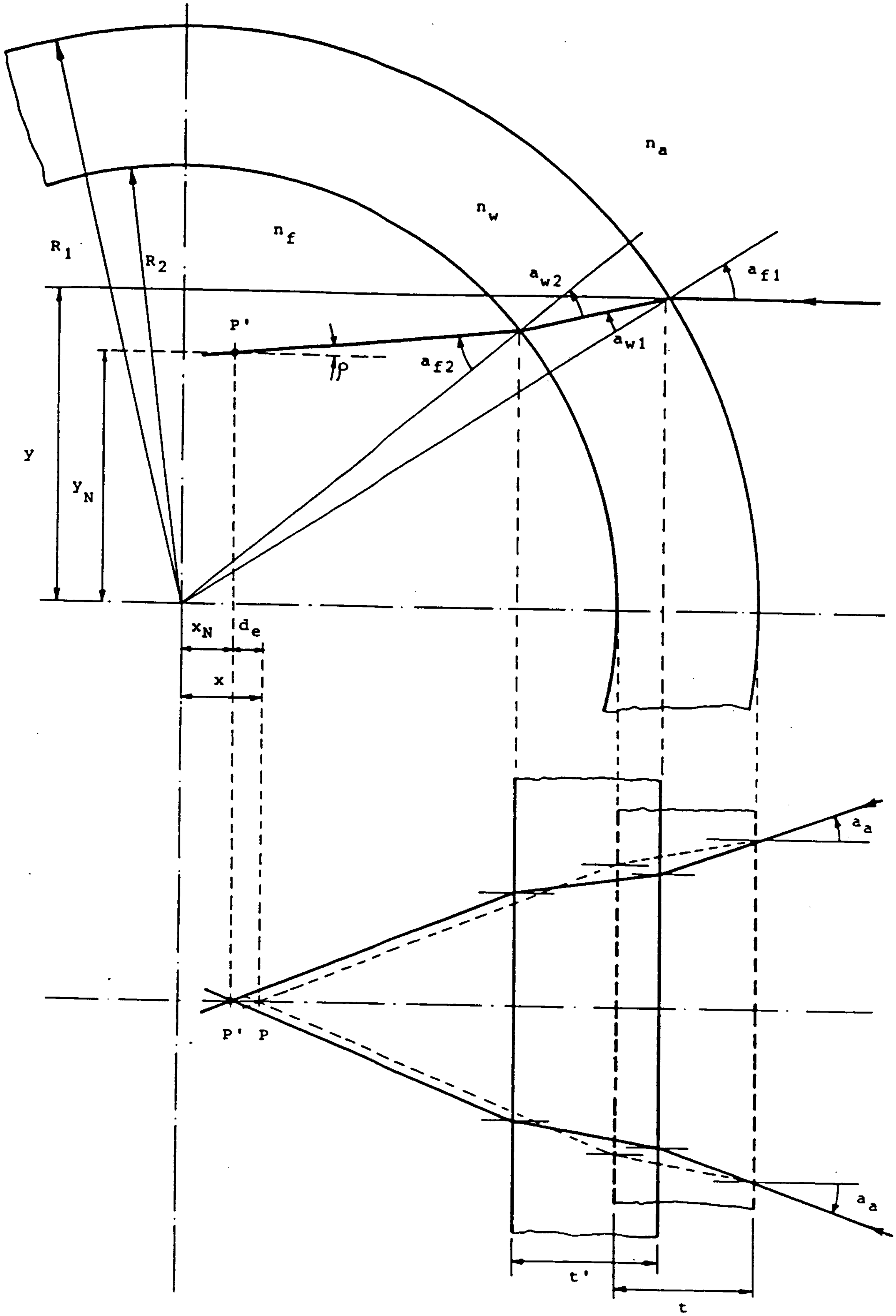



Figure A2. Refractive Index Positional Corrections.