Department of the Navy
Bureau of Ordnance
Contract NOrd 9612

Report on Design and Construction of

THE AXIAL FLOW PUMP TEST FACILITY

T. W. Fuller

and

A. J. Acosta

Hydrodynamics Laboratory
California Institute of Technology
Pasadena, California

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Approved by
A. Hollander

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INTRODUCTION

In studies concerned with the application of pumps to underwater jet propulsion, it has been pointed out that cavitation may be avoided or suppressed by enclosing the pump (or propeller) in a suitably shaped shroud.* The advantages of avoiding cavitation are clear; namely, the elimination of much noise, damage and vibration in addition to increasing the allowable speed. However, a general discussion of the various flow processes which lead to cavitation is not yet possible. For propellers, cavitation is observed in helical trailing vortices and also on the blade surface proper, but for other types of propulsion systems, notably pump jets, neither is the location known nor the cause completely understood. Roughly speaking, cavitation will occur when local pressures reach the vapor pressure of the flowing liquid, however, the magnitude and location of these local underpressures depend upon the complete history of the flow as it passes through the machine. Consequently, minimum pressures may occur in the free stream in some cases, or upon the blade surface itself in others. Thus, in order to study cavitation phenomena, it is first necessary to investigate the detailed behavior of the flow.

Apart from cavitation and noise, there are also other problems of considerable importance in rotating axial flow machinery. Among the most prominent of these is the behavior of the fluid in the boundary layer near the rotor and stator blade tips, and the off design performance in the region of stalled flow. These questions are of great concern in the design and application of axial flow compressors and, as long as compressibility effects are negligible, they may be investigated just as well in water as in air. Moreover, inasmuch as the kinematic viscosity of air to that of water is thirteen to one (at atmospheric conditions), machines can be made to operate in water at the same Reynolds numbers as in air at much reduced speeds, sizes, power consumptions and blade stresses, and as a result of these facts the installation and operational costs are also lower than for the comparative air machine. The cost of the blading of a compressor is a major portion of the total cost of the machine and, therefore, the high expense of installing different blade designs for research purposes prohibits extensive

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*Wislicenus, G. F., "Fluid Mechanics of Turbomachinery," McGraw Hill, 1947, p. 409.

investigation. In 1951 the Hydrodynamics Laboratory at the California Institute of Technology developed a method of making inexpensive precision lead-alloy blades for axial flow pump test impellers. As a result of this work, interest was expressed by personnel of the Naval Ordnance Test Station and staff members of the Institute in the application of such blade-making techniques for air compressor and underwater propulsion research. It was estimated that blades could be made for about one-eighth of the cost per blade row of those in a research compressor currently operating at the Institute. This attractive estimate lead to the consideration of an axial flow compressor run in water as a pump at relatively low speeds so that research on cavitating and noncavitating flow could be done without prohibitive expense. Under this contract, NOrd 9612, an axial flow pump with its enclosed circuit was constructed and preliminary tests on a single stage of blading were run by the first week of November, 1952. It is the purpose of this report to describe the installation and show its usefulness for research.

OBJECTIVES

The principal objectives of this installation are the design of a suitable facility to observe and study cavitation and cavitation noise phenomena, and, furthermore, the development of blade-making techniques so that stage characteristic measurements can be obtained on a variety of blade types rapidly and inexpensively. In general, in experimental work on turbomachines, two types of information are sought. The first is the determination of over-all performance, i.e., flow rate, head, torque and efficiency; the second is the knowledge of the internal flow details, for example profiles of internal velocity, pressure and direction. Hence, in order to provide for a maximum utilization of the facility, arrangements were made for obtaining both kinds of information.

Apart from these considerations, wherever possible emphasis was put on obtaining a highly flexible installation so that work would not be restricted to any particular design.

In order to show some of the advantages obtained by water operation of an axial flow turbomachine, the following table was prepared:

TABLE I

Ratio of water to air machine parameters at the same Reynolds number, blade solidity and for similar characteristic curves. The last case (with the asterisk) represents the design of the test facility described herein.

Diameter	Speed	Power	No. of Blades
1.00	0.08	0.39	1.00
0.28	1.00	1.40	1.00
0.39	0.54	1.00	1.00
1.00	0.04	0.05	0.50
0.20	1.00	0.25	0.50
0.05	16.00	1.00	0.50
0.39*	0.27	0.15	0.53

DESCRIPTION OF FACILITY

General Description

The foregoing objectives led to the design of a vertically mounted test unit installed in a simple closed hydraulic circuit using water as the working fluid. The rotor is externally driven and provides the only power for flow circulation .

The circuit itself consists of the test pump which discharges into a vaned elbow and thence into a diffusing section. Another vaned elbow directs the flow through a second diffusor and hence into an internal "lattice" type throttling device. The circuit is closed through two more vaned elbows and a 6:1 contraction nozzle. The component parts, i.e., diffusors, elbow, etc., are fabricated from 1/4-in. galvanized plate. All elbows are constructed with 90° turning vanes which have a spacing chord ratio of 0.46. The first two elbows have contoured vanes, i.e., of varying thickness, whereas the last two have vanes rolled from 3/16-in. stock.

The test unit and dynamometer are mounted separately on rigid steel bases grouted to a concrete wall. Auxiliary pressurizing and evacuating circuits are provided so that the ambient pressure in the circuit can be arbitrarily fixed between 25 psi and 20 in. Hg of vacuum. The test unit is about 40 in. long and 14 in. inside diameter, and can accommodate up to three stages of blading. Although rotative speeds of about 600 rpm are obtainable with the power available, speeds as low as 200 rpm may be used and still obtain Reynolds numbers based on blade chord of about eighty thousand. A general view of the test flow and pumping circuit is shown in Figs. 1, 2, and 3.

Test Unit

The test unit is vertically mounted and is split longitudinally in halves, as can be seen in Fig. 3. The general design features are shown in Fig. 4. One-half of the pump case is bolted and dowelled to the mounting plate and the other half is removed by a roll-a-way jig assembly which is permanently attached to the structure. The same jig is also used for the removal of the rotor assembly. The removable casing-half contains a lucite viewing window which runs the full length of the rotor and extends over 45° of the blade tip circumference. Flow surveying ports are also installed in the removable casing-half behind each of the four stationary blade rows as well as a single surveying hole behind each of the rotor row positions. Static piezometer take-offs are located in the fixed casing-half between every blade row.

The stationary blades (i.e., entrance, stator and straightening) are attached to 2-in. wide circular segments which are fastened into grooves machined in the casing halves with countersunk screws. There are eighteen stationary blades per row and sixteen rotating ones. The rotor blades are attached by means of segments in the same manner as the stator blades.

The casing is grooved at each end to receive the rotor bearing supports but, when in operation, the rotor shaft is supported by means of the drive line from the lower dynamometer motor bearing, the two bearing supports in the casing merely acting as guides for the rotor. The rotor is keyed onto the hollow shaft and held against thrust by a snap washer. The upper end of the rotor shaft is connected to a universal joint. The drive shaft then passes through a guide sleeve in the first elbow where leakage is prevented by a mechanical seal.

Streamline ogival sections are mounted in front of and behind the hub section.

Immediately preceding the test unit is a loose spool piece and packing assembly for easy removal of the case-half. A surveying plate is provided immediately downstream of the contraction nozzle so that the flow distribution entering the test unit can be determined.

Both rotor and case are cast in red brass. All shafting is of stainless steel and all bearing surfaces are hard chrome plated and ground. The bearing guides are of lead-bronze and are water lubricated. The test unit can be disassembled with the rotor removed in about three man hours.

Dynamometer and Power Supply

As can be seen in Fig. 1, the dynamometer is vertically mounted about three feet above the pump. The dynamometer motor is supported from below by a large, deep-groove helicopter bearing and is guided at the top by a self-aligning ball bearing. Through an 18-in. arm fastened to the motor body torque may be measured by balancing the reaction with pan weights supported by a wire and pulley system. Electrical contacts on the torque arm indicate motion of 0.005 in. or so, and for accurate balance a Statham electrical strain gage is used. The sensitivity of the torque measuring system is about 0.1 in. lbs.

The motor is rated at 30 hp at 1750 rpm, 230 volts dc, corresponding to 1,100 in. lbs torque. Power is supplied by a 30 kw thyratron rectifier. A differential gear box, supplied by Boller and Chivens of South Pasadena, is used to establish speed in unit rpm increments from about 150 rpm through the full range. With this controller speed regulation is maintained to within one part in ten thousand on the average.

Instrumentation

The measurement o torque and speed has already been mentioned. The other over-all quantities which must be determined are the flow rate and head. The pressure drop across the contraction nozzle upstream of the test unit provides a convenient signal for determination of the system flow rate. The nozzle is calibrated by means of a velocity survey taken at its exit section (Fig. 4). As an aid in determining over-all head rise, total head rakes with nine probes each are set flush and faired into each of the three legs of the downstream bearing support. A multitube manometer bank is then used to measure the total head rise across the complete machine.

The details of the internal flow may also be measured through the surveying ports installed in the casing. Each of the ports, or slots, behind the stationary blade rows extends approximately over two blade passages so that, if necessary, minutely detailed surveys of the stationary blade wakes could be obtained. However, in the interest of simplicity and in order to avoid sealing problems, the probing instruments are located by a plug, which fits into the slot and which has holes drilled in it in radial increments of 4°. The plug is so machined that when it is rotated 180° the radial holes are shifted by 2°, hence allowing surveys to be made in 2° angular increments across the two blade passages. When not in use, the holes in the plug are filled with insert pieces, and blank plugs are used to fill the remaining ports. A special probe holding device was made so that the probe could be positioned radially and angularly to within 1/64 in. and $1/4^{\circ}$, respectively. The probe holder, probe and plug assembly ready for installation into the surveying port are shown in Fig. 5. The probe holder may also be mounted in a surveying station behind each of the rotor blade rows. An assortment of various types of probing instruments has been made, i.e., a venturi-type total head probe (Kiel), boundary layer probe, static pressure probe, and a claw-type direction measuring probe. The direction and static probes are calibrated in the discharge jet of a large ratio contraction nozzle using air as the medium. These probes are shown in Fig. 6.

For the determination of the pressure signals from the probing devices a 1-psi liquid service, Statham differential pressure, electric strain gage is used in conjunction with a Baldwin-Southwark strain gage bridge. With the use of this transducer, pressures can be measured to 1/1000 of the full-scale reading, and the flow angle can be determined to within $1/2^{\circ}$. A differential carbon tetrachloride-water manometer is used to measure the pressure drop across the contraction nozzle and, for the determination of system pressure, a mercury-water manometer is used.

In order to know accurately the rotor blade tip clearances as installed in the machine, four equally spaced holes are provided in the case at the first and third rotor row locations for depth micrometer measurements.

A hydrophone tap for the detection of cavitation noise is situated behind the first rotor blade row. Acoustic equipment for listening in the range of 20 - 100 kc is available in the Laboratory.

An instrumentation feature which, although not novel to this facility, is still quite unusual, is an arrangement for making flow surveys relative to the moving rotor. These measurements are made possible by the hollow drive shaft. Pressure signals, i.e., total head, static, etc., are transmitted through small tubing from the rotor through the drive shaft to a manometer which is mounted on and runs concentric with the drive shaft outside the machine (Fig. 1). The pressure readings can then be read with the aid of stroboscopic illumination.

One of the main features of this facility is the viewing window. This window allows cavitation phenomena to be directly observed, and with the injection of suitable flow tracers, the flow relative to either the rotor or stator blades can be visualized,and with the use of suitable photographic techniques quantitative data can be taken.

BLADE-MAKING TECHNIQUE

The test unit is designed for a maximum of three stages of blading. The stationary blade rows have eighteen blades each, and the rotor rows sixteen each. A maximum chord of about two inches is all that can be used and, as a result, the blade aspect ratio is about 1-1/2. The use of fewer blades of lower aspect ratio than is common for compressor designs results in higher strength blades and lower cost per blade row as well. The use of water as the working fluid allows the rotative speed to be about 200 - 300 rpm and yet obtain Reynolds numbers on the order of 80,000 - 120,000 and at these speeds bending stresses in the blades are quite low so that materials of low strength can be used for blade manufacture.

For this work an alloy of lead and bismuth was selected rather than a plastic because of its superior dimensional stability and casting ease. Inasmuch as information on fabrication of blading for such research machines is not readily available, the following rather detailed description of this blade-making process is included for those who wish to do similar work.

The blades are precision cast of commercially available, low melting-point alloys (e.g., "Cerro-cast", "Cerro-dent") in plaster molds. The blade is cast onto a brass holding fixture in order to simplify the casting and attachment problems. The molds are made in two pieces, each half being formed on an accurately machined brass master blade. One master blade is provided for each of the four types of blades in the machine, i. e., entrance, rotor, stator and straightening.

The design and layout of compressor and pump blades is generally done in cylindrical coordinates. The machining of master blades is then also done in the same system in order to avoid tedious coordinate transformations.

Master Blade and Attachment Segment

The master blades are made exactly to size with no allowance for mold or casting metal expansion or shrinkage. This procedure is possible because the molds when warmed expand the same slight amount that the cast metal shrinks in cooling.

The rotor blade for the stage design chosen has considerable twist. Consequently, the master blade is first roughed out approximately 0.060 in. oversize on a pantograph milling machine. However, for blades with little twist this operation is not necessary. A double size plaster blade surface is used as a pattern, and it is made by spotting the surface of a plaster block with a pointed cutter on a milling machine and carving to shape (Fig. 7). The master blade is then roughed out from brass stock (Fig. 8) and subsequently positioned on a milling machine for the final spotting operation (Figs. 9 and 10).

The blade twists about a radial line through the centroids of the various section profiles. The rough machined brass stock is set up on the machine so that radial, angular and elevation coordinates are established from this line. For ease of the finish spotting, a Bridgeport milling head attachment is tilted normal to the average chord angle of the blade. The radial and elevation coordinates on the blade surface are obtained by using the vertical and horizontal traverses of the milling machine and a rotary table provides the angular coordinate.

A sharp conical tool spots the work by being extended against the spindle stop and then retracted out of the way while the machine is reset for the next spot. Once one side of the blade has been finished, the work is rotated 180° about the centroidal radial line without changing the original tool setting in order to locate the work for spotting the other side of the master. (The leading edge is up for spotting one side, down for the other.) For accuracy, an indicator was used to establish the elevation dimensions rather than the lead screw of the mill.

The spotted surface is carefully smoothed down by hand filing until the last traces of the spots just disappear. Figure 11 shows this process in detail, and Fig. 12 shows the completely filed master blade assembled to a segment of the rotor hub. An unmachined portion of the original stock serves as a reference plane so that the blade may be accurately positioned relative to the segment. The segment is made from a ring that fits into the grooves cut into the rotor hub. Each segment is finished to size in a combination mill and drill jig, and is held and aligned in the rotor groove by two countersunk cap screws. The same jig is used also to locate the tapped holes in the rotor shell to hold the segments. The segment attached to the master blade is the same as all others except that it does not have the milled "casting groove" shown in the segment at the right side of Fig. 17.

Mold Making

A complete mold has three parts; two plaster halves which define the blade surface and an attachment segment which ultimately becomes an integral part of the finished blade. Each of the plaster parts receive an impression from the assembled master blade and segment so that the attachment, or holding piece, has the same alignment to the blade as does the master blade and segment assembly. Thus, blade alignment is determined in the initial machining step and is carried through the operations of mold making, casting and subsequent installation in a manner similar to that of production jigging.

In detail, the mold making operation is as follows: Fig. 13 shows the master blade and segment and the various parts that comprise the mold box partially assembled. The master blade, mold box bottom, two half sides and two ends are assembled. The blade and segment are held by the right-hand mold box end and clay is filled in under the blade and trimmed carefully to the top of the mold box half sides and the leading and trailing edges of the vane (Fig. 14). With the other two half sides assembled, the box is filled with "Hydrocal B-11" plaster mix and vibrated (Fig. 15). After the plaster has set, the original half sides, bottom and the clay are removed

(Fig. 16). A good parting agent (silicone or potter's soap) is then applied to all exposed surfaces and wiped off to leave a finely lubricated surface. The two original half sides of the mold box are re-assembled and then the second mold half is poured. Figures 17 and 18 show the completed mold disassembled. The mold halves are dried in an air circulating oven at 130° F. for 72 hours, and then wiped clean of parting compound, dust and impurities with carbon tetrachloride.

Casting Procedure

A wooden box replaces all of the mold box parts except the segment-holding end piece. The wooden box is so arranged that the mold halves are clamped together and the segment-holding end, containing the segment with "casting groove", is clamped in turn against the halves (Fig. 19). This arrangement reduces parting line flash to a minimum.

The molds are heated to approximately 130° F. in an oven and then placed on a centrifugal casting machine arm. A heated carbon crucible is lined up with the mold pouring hole (Fig. 20). The alloy is melted and poured into the crucible at 350° F. The arm of the casting machine is quickly accelerated to about 300 rpm and the machine rotated for about five minutes until the metal is set. The mold and metal temperatures must be varied depending on the shape, size and thickness of the blade until a good casting is obtained. All blades are then cast using the same temperatures. It is desirable to use as cool a mold as possible to minimize thermal expansion and to preserve the surface of the mold cavity. One mold casts 15 to 20 blades before the reproduced surfaces become significantly less smooth than the master blade.

With the exception of the straightening blades, all blades were cast in "Cerrocast" since it appeared to have the most satisfactory strength characteristics of the low-melting point alloys available and, furthermore, seems to have sufficient corrosion resistance for use in water.

After fabrication a few blades were randomly selected for inspection. It was found that the cast blades were within 0.002 in. per in. and 1/10 degree chord angle of the design calculations. The outside diameter of the rotor blades and inside diameter of the stator blades are trimmed by machining a complete blade row in a jig to give the desired running tip clearances. The cost per blade including cost of the master, molds, casting, and blade trimming is less than $20.00. The original tooling, of course, may be used to make new sets of blades. A new set of entrance, stator and rotor blades can be completed in our shop within two months.

In the event that much higher rotative speeds are desired, e.g., 400 rpm and up, the blade root bending stresses exceed the allowable values for these low melting point alloys so that it becomes necessary to employ other blade-making methods. As a simple alternative, wax blades can be cast in the molds made as previously described and used as expendable patterns in an investment process to obtain aluminum, brass or beryllium copper blades. However, in order to obtain the accuracy afforded by the foregoing method, allowance must be made for the wax and metal shrinkages.

PRELIMINARY OPERATION

One stage of "free vortex" blading was manufactured by the process described in the foregoing sections. The blade design is the same as that used in a compressor research program at the California Institute of Technology.[1] The characteristics of this stage are:

$$\text{design flow rate } \phi = C_{m2}/U_2 = 0.45, \quad \psi = \frac{\Delta H}{U_2^2/2g} = 0.4$$

and the 50% reaction point is at a radius ratio of 0.70, 0.6 being the ratio of the blade root to tip. The spacing/chord ratio is about unity at the 50% reaction point with a blade aspect ratio of about 1-1/2, the chord being about 2 in. The "as-installed" tip clearance on the rotor varies between .007 and .008 in. A detailed tabulation of the characteristics of this design may be found in Ref. 1.

Profile measurements were made first across the exit section of the contraction nozzle in order to determine the volume flow rate through the machine. Two velocity traverses taken in mutually perpendicular directions, shown in Fig. 22, indicate that the flow entering the test unit is fairly

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[1] Bowen, Sabersky and Rannie, "Theoretical and Experimental Investigations of the Axial Flow Compressor", California Institute of Technology, Mechanical Engineering Department, Parts 1, 2 and 3.

uniform although there is about a 1/2-in. boundary layer at the walls. In order to check the hydraulic design of the pump and circuit, and to evaluate the usefulness of the instrumentation velocity, flow direction and total head, traverses were made across the entrance, rotor and stator blade rows at the design flow rate and are shown in Figs. 23 to 25. A more detailed investigation of the internal flow and measurement of the over-all characteristics are deferred to a later date so that the present data should be regarded as tentative. However, it is clear from these plots that there is general agreement between this data and that of Ref. 1, from which this design was taken, even though some discrepancies do appear. Apart from any effects of the different aspect ratio, these differences seem to be due to the inlet boundary layer on the wall, which is about twice as thick as that of the air machine, and the fact that the prewhirl vanes do more turning than do those of Ref. 1. It is of interest to note that the potential flow calculations of Hlavka (unpublished) afford a quite good estimate of the entrance vane turning angles (Fig. 23).

The total head rise across the rotor is not a true, weighted power average, but consists of an average head, weighted with area.

For this work the Reynolds number based on blade, chord and axial velocity was 80,000 while the rotative speed was only 200 rpm.

The maximum flow rate coefficient obtainable with the present single stage is 0.53, which is adequate for all blade designs anticipated. The mechanical details, i.e., throttling device, pressurizing and evacuating controls all worked satisfactorily over the desired range of variables.

ACKNOWLEDGMENT

The authors would like to acknowledge their indebtedness to Professors A. Hollander and W. D. Rannie for their advice, interest and support of this project. They would also like to express their thanks to Messrs. D. A. Rains, G. M. Hotz and E. Daly, without whose aid the design and construction would not have been possible; and lastly to Mr. Rudolph Lorman for the services of his exceptional instrument shop.

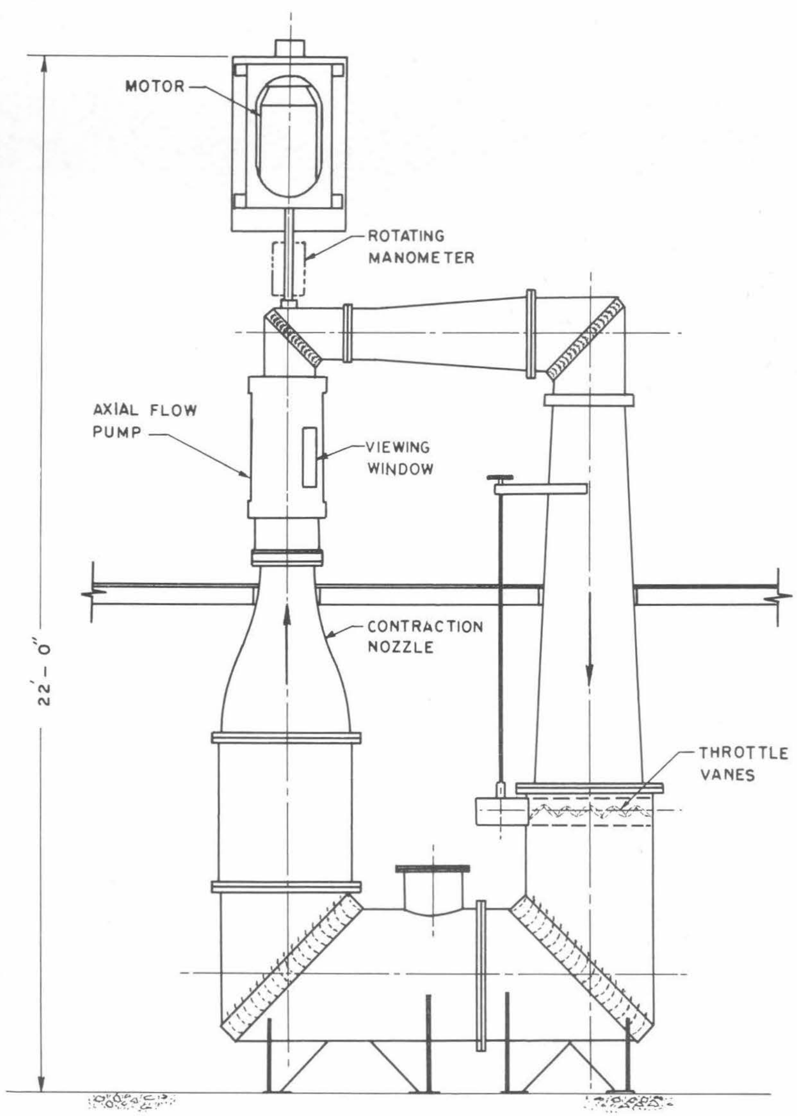

Fig. 1 - Schematic diagram of pumping circuit and installation.

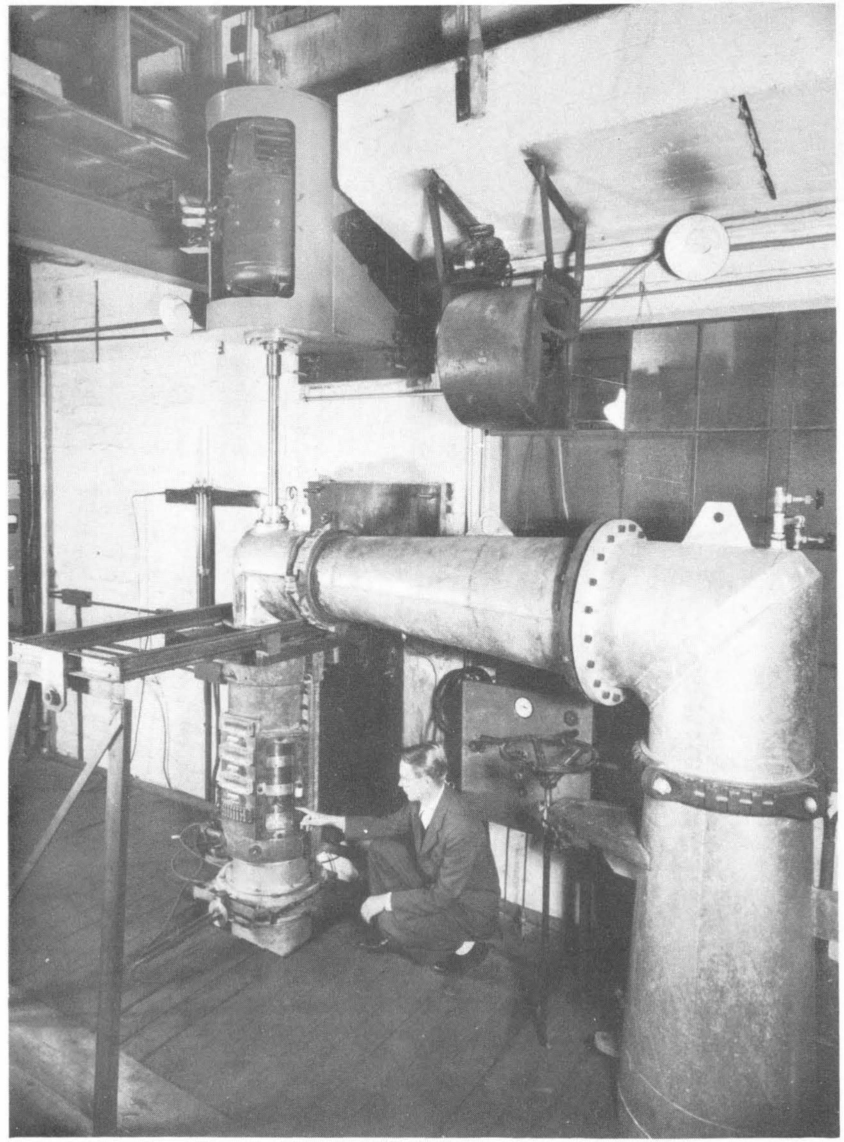

Fig. 2 - Assembly view of test floor.

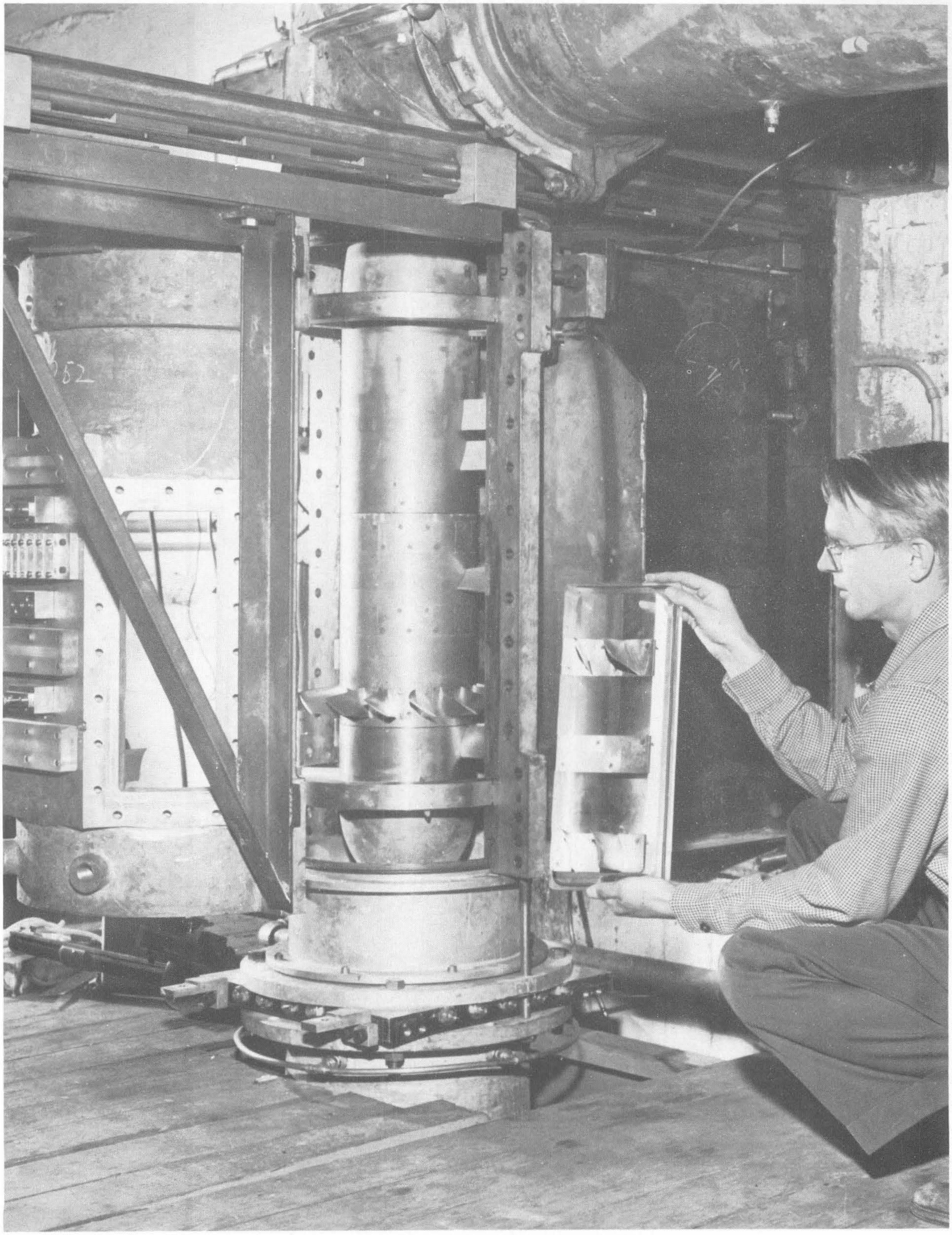

Fig. 3 - Machine open installed with one stage of blading showing the viewing window.

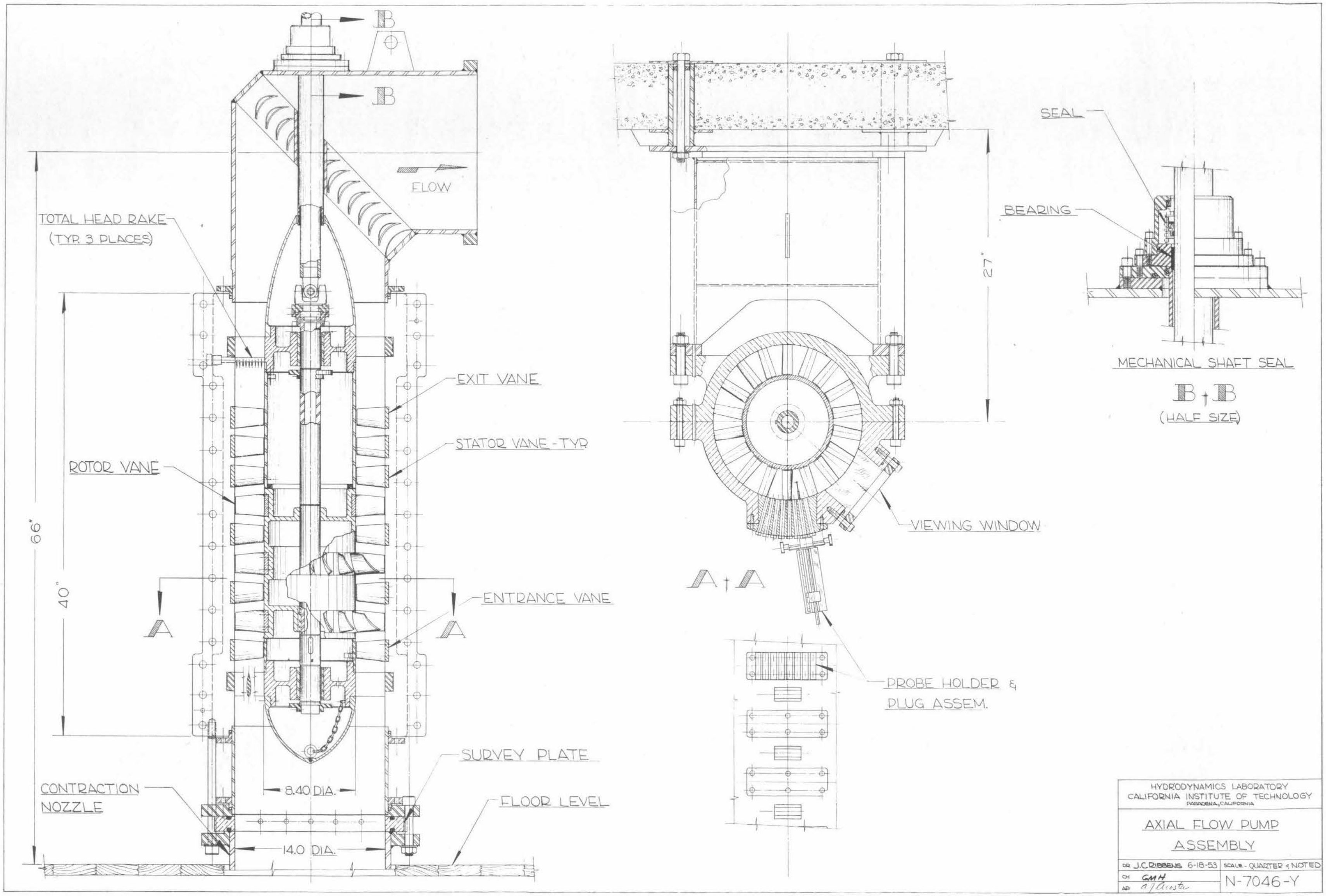

Fig. 4 - Assembly test unit.

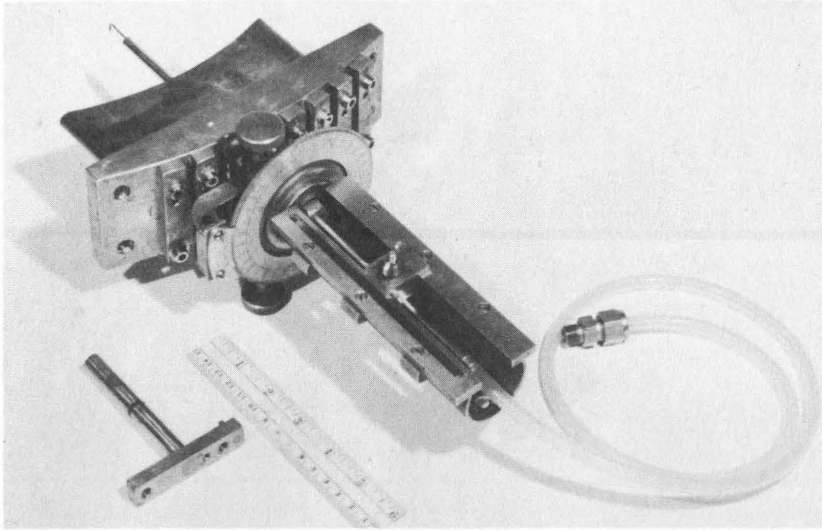

Fig. 5. Probe holder with probe in plug.

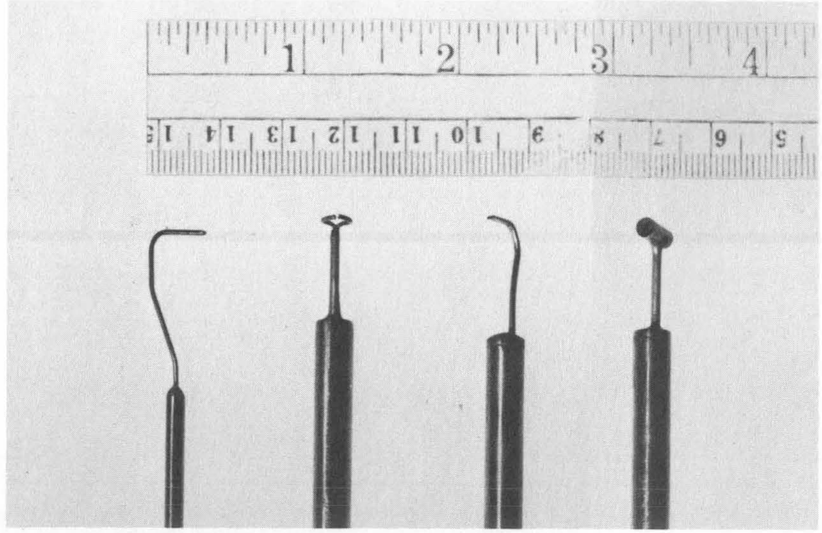

Fig. 6 - Miscellaneous probe devices.

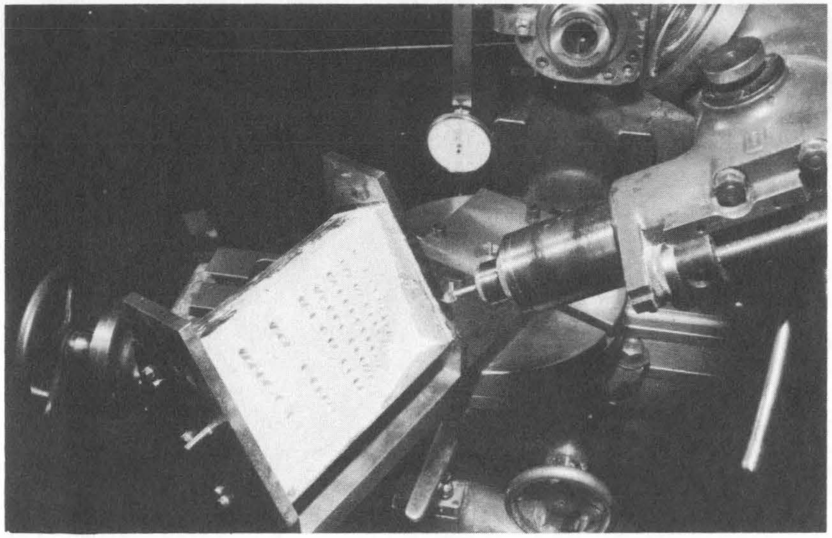

Fig. 7 - Spot machining a double size plastic surface for the pantograph milling operation.

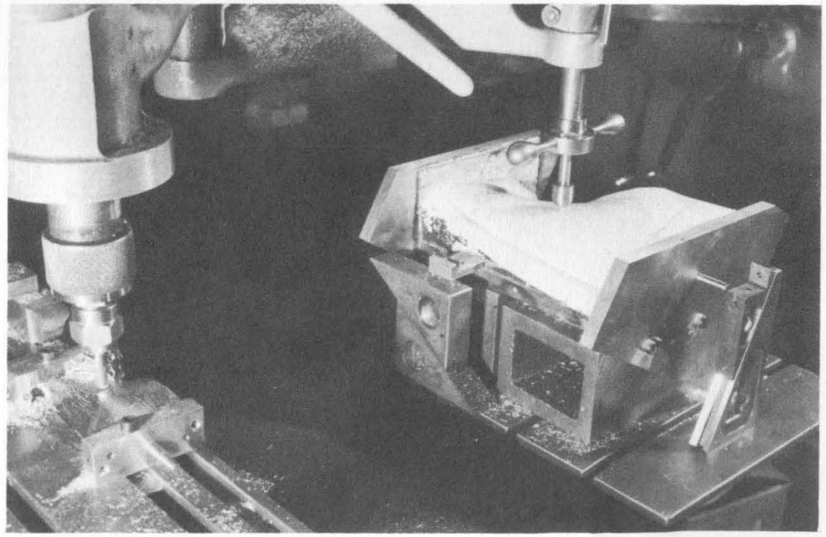

Fig. 8 - Rough machining of rotor master on pantograph mill.

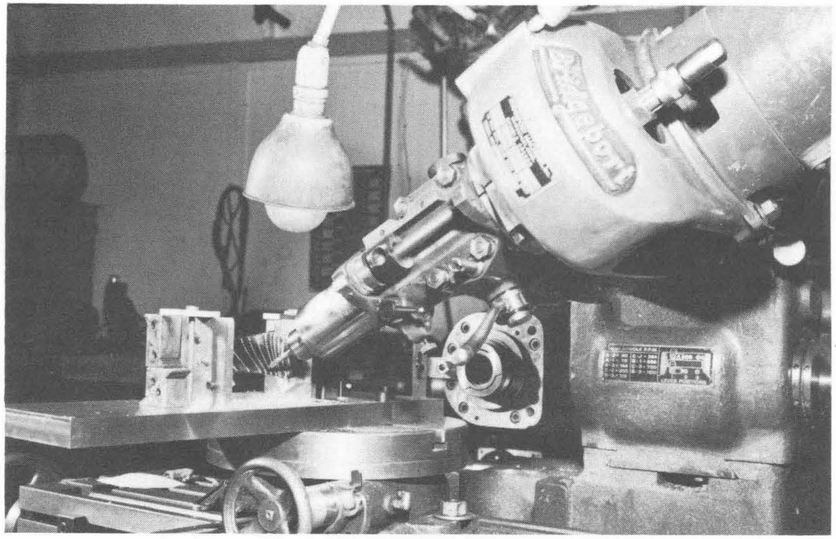

Fig. 9 - Finish spot maching of the rotor master blade.

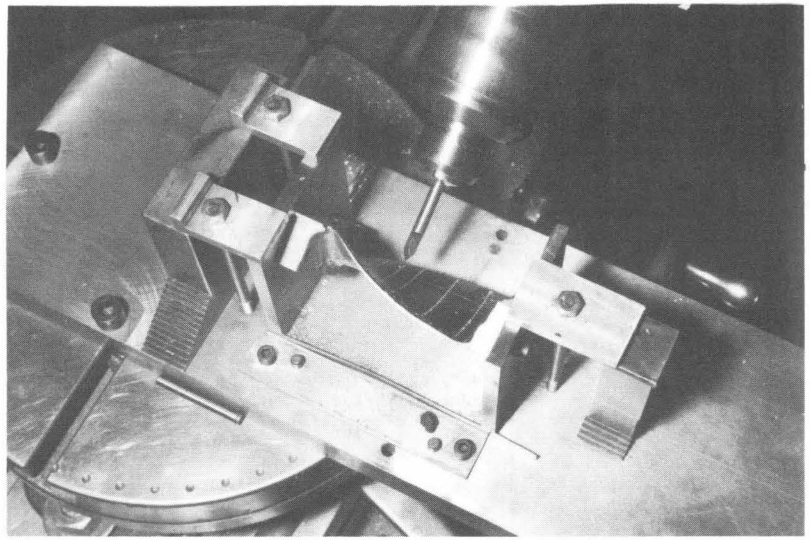

Fig. 10 - Another view of the finish spotting operation.

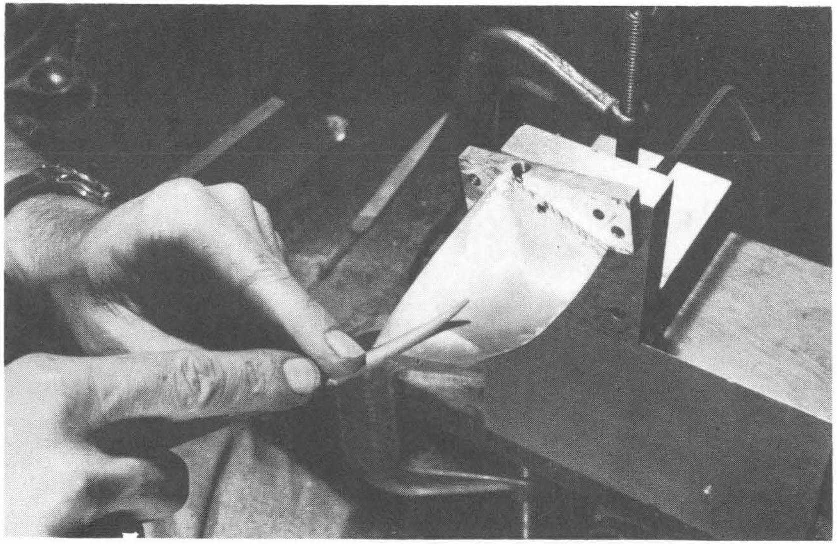

Fig. 11 - Hand filing master blade to size.

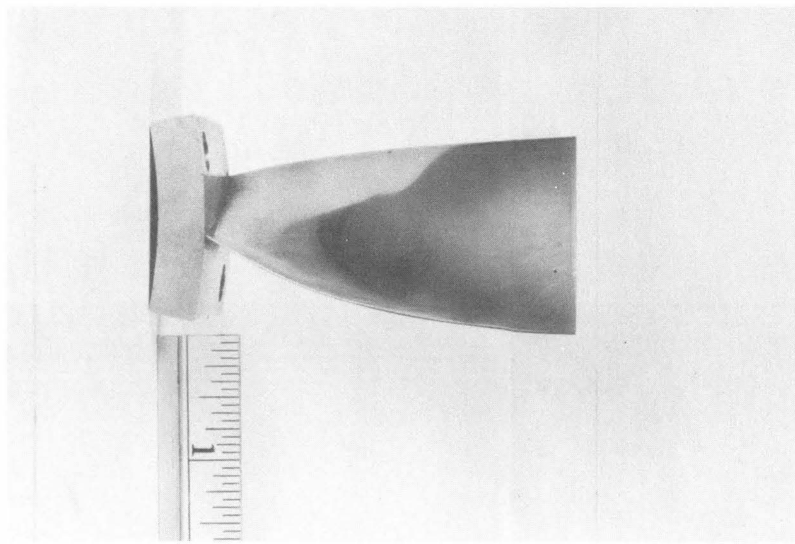

Fig. 12 - Finished master blade attached to holding segment.

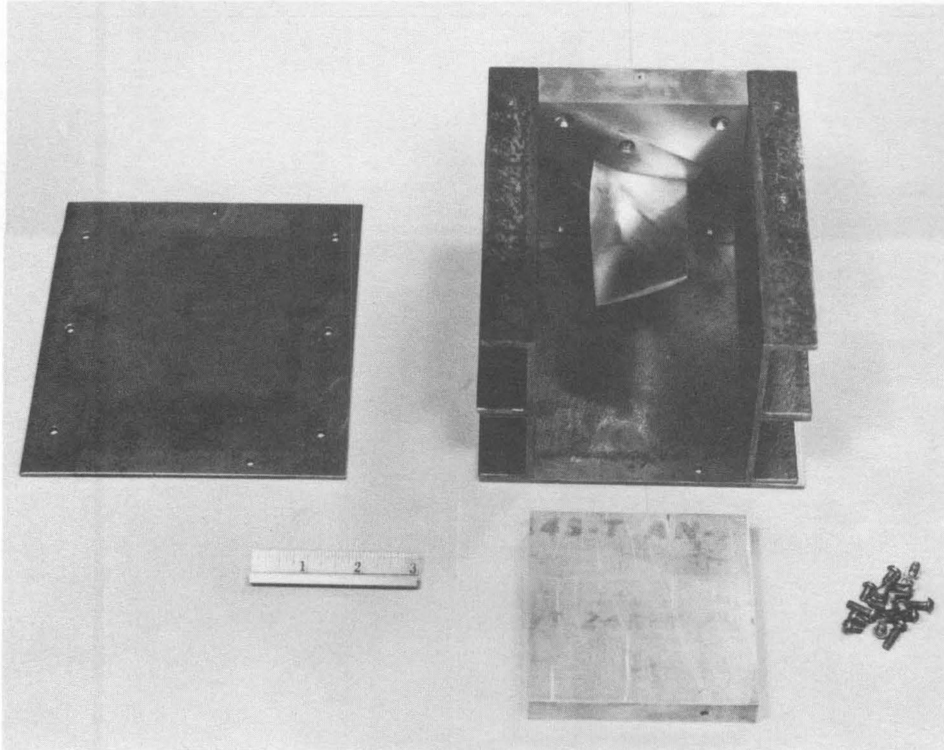

Fig. 13 - Mold box partially assembled with master blade attached to end piece.

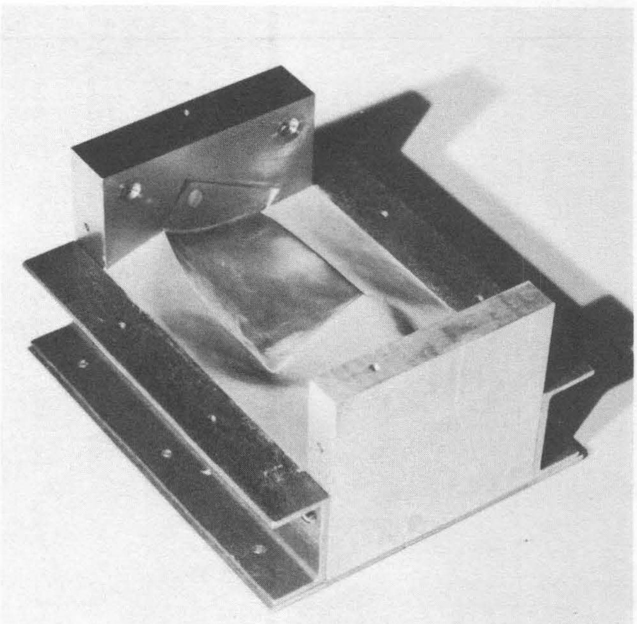

Fig. 14 - Mold box partially assembled showing clay parting surface trimmed at leading and trailing edges of the master blade.

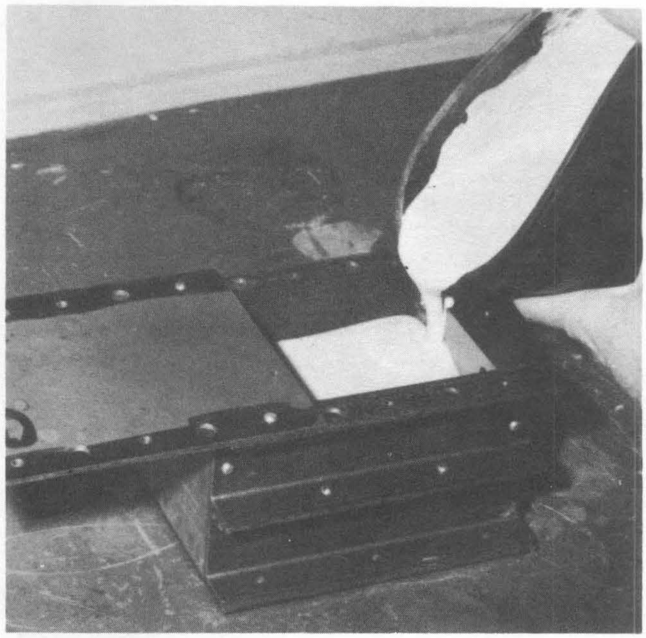

Fig. 15 - Plaster mold half being poured.

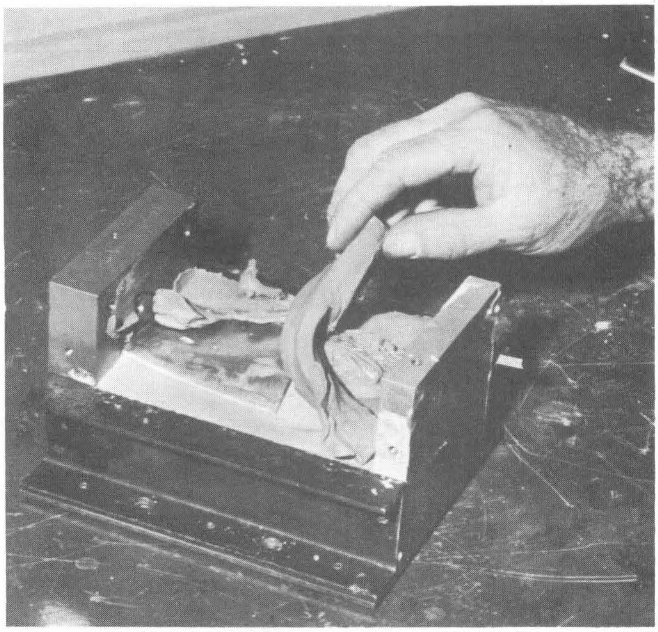

Fig. 16 - Clay parting surface being removed from first mold half.

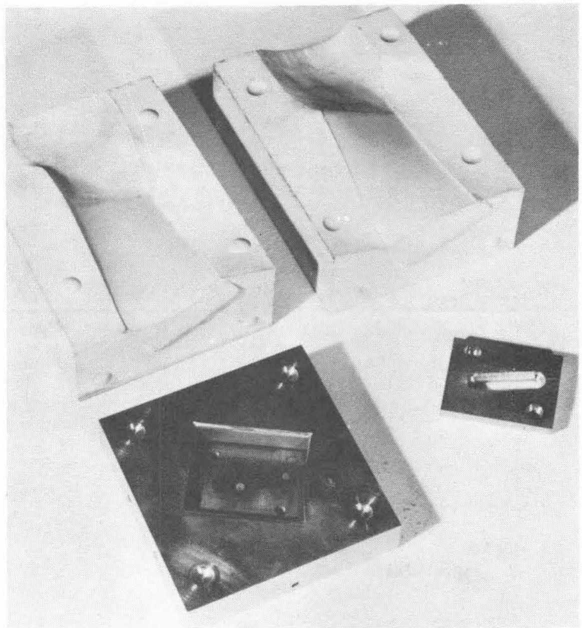

Fig. 17 - Completed plaster mold halves, mold box end and segment with casting groove.

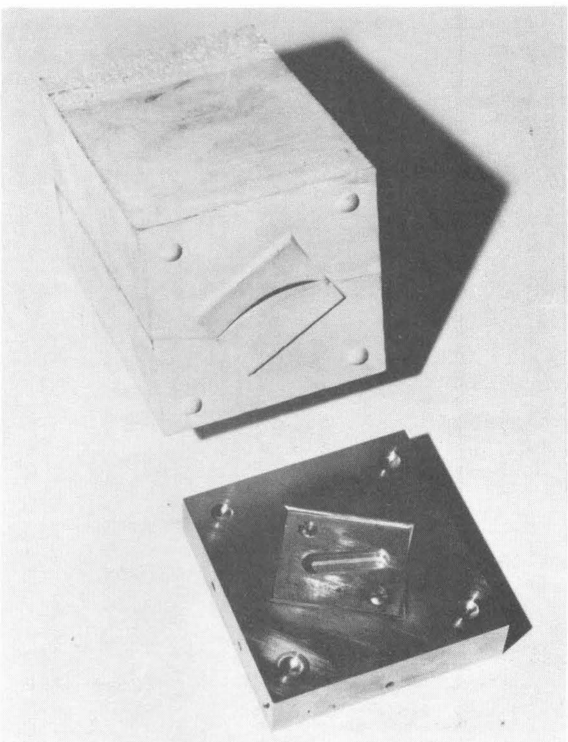

Fig. 18 - End piece ready for assembly with mold halves.

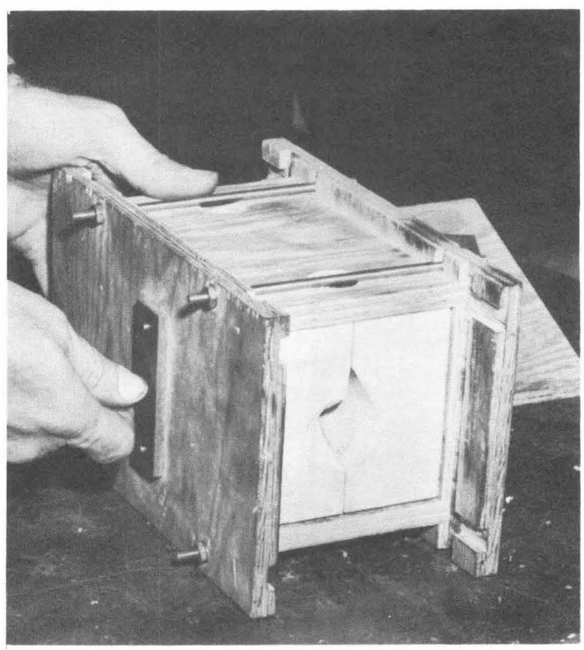

Fig. 19 - Clamping mold parts together prior to casting.

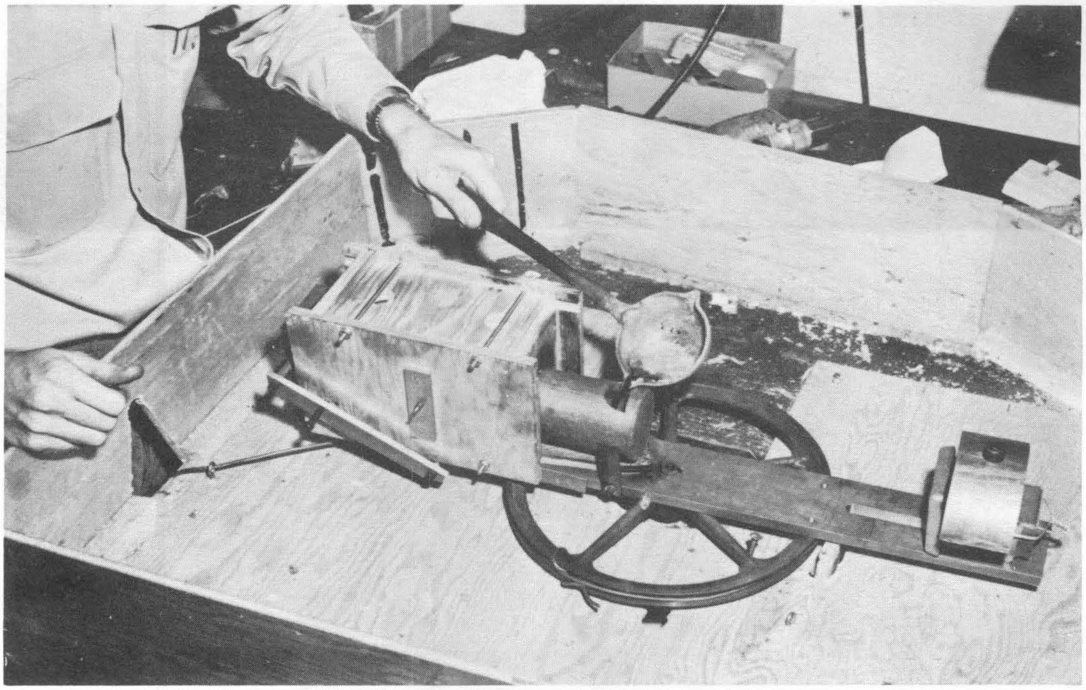

Fig. 20 - Centrifugal casting setup showing metal being poured into crucible before centrifuging into warmed mold.

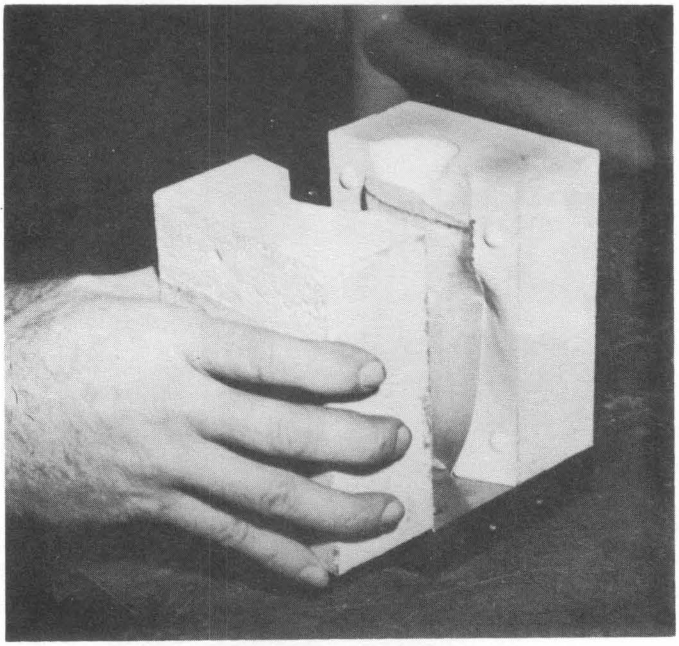

Fig. 21 - Separation of mold halves showing cast blade.

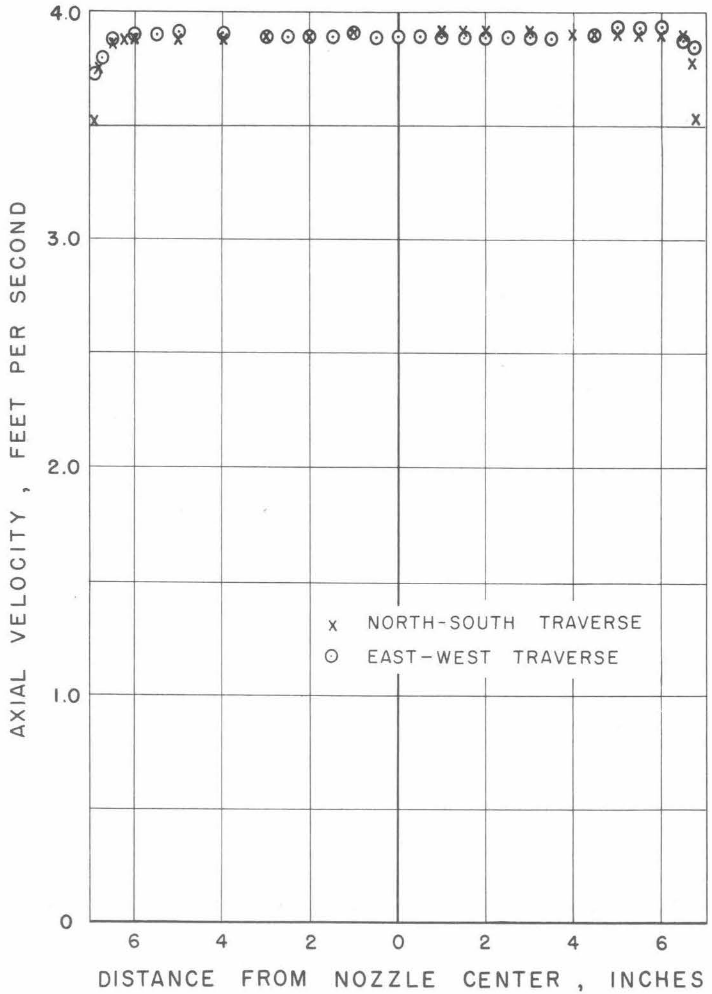

Fig. 22 - Velocity profile at exit section of contraction nozzle.

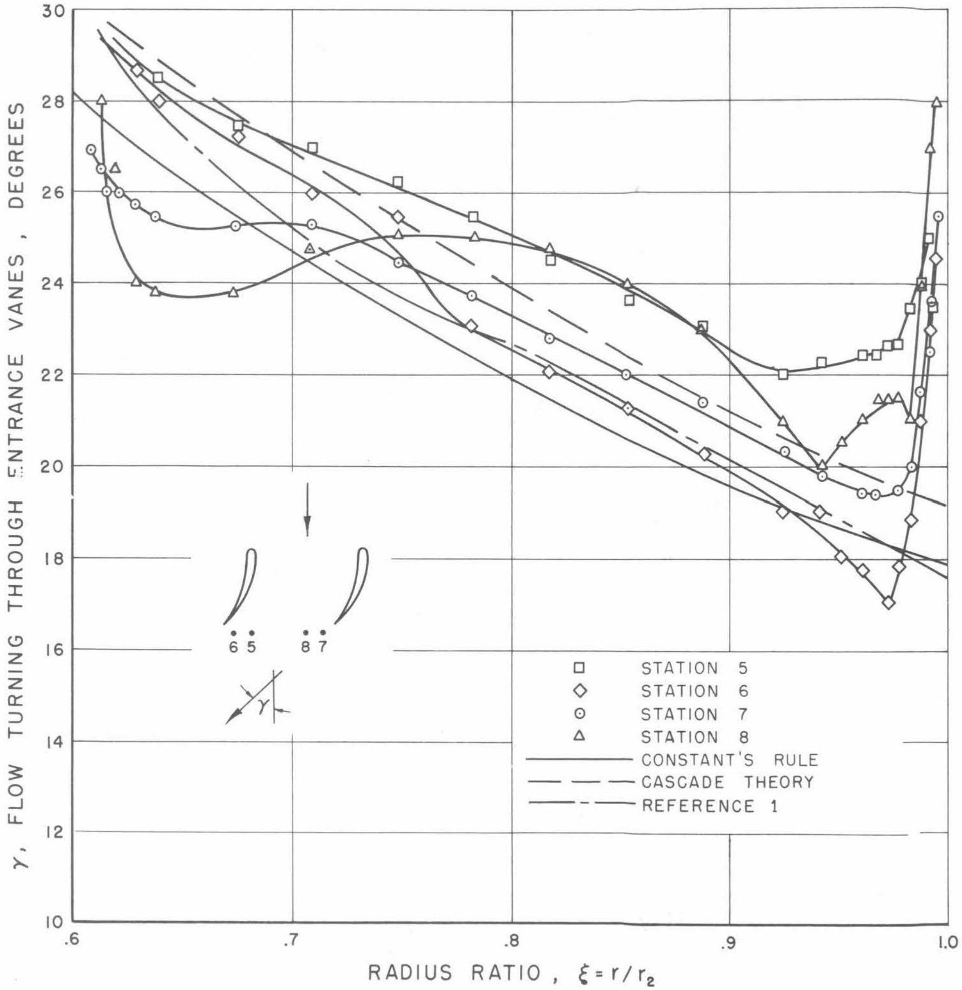

Fig. 23 - Flow angle behind entrance vanes. The solid line is the mean of data in Ref. 1.

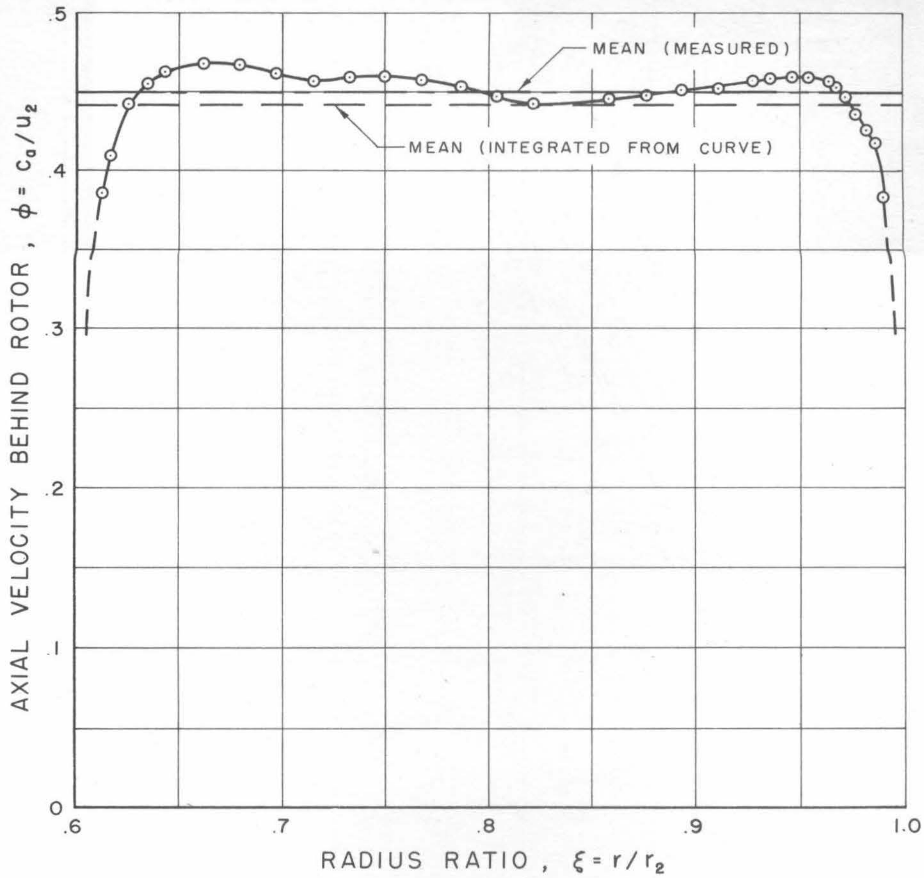

Fig. 24 - Axial velocity profile behind rotor now at design flow rate.

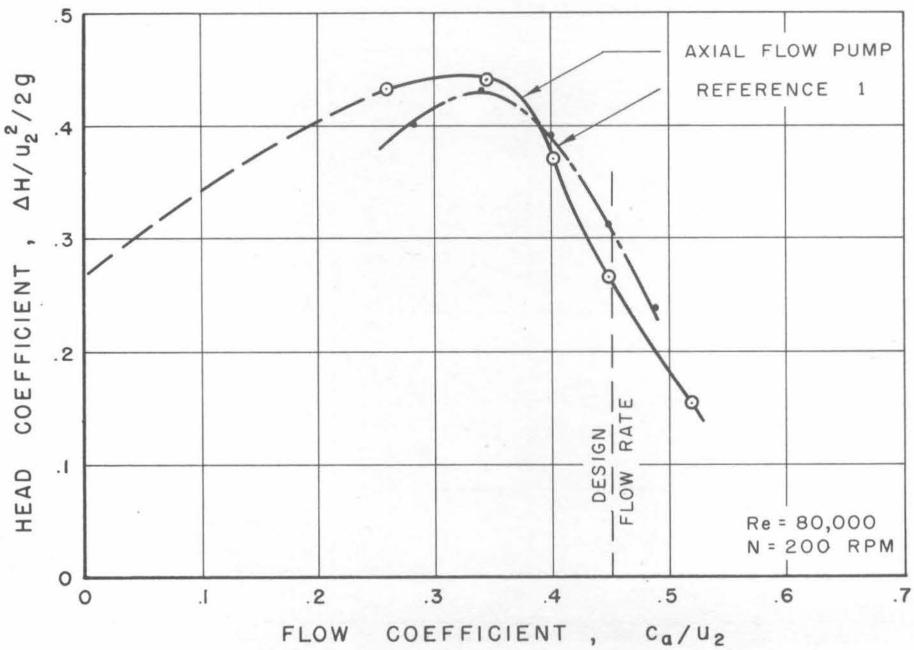

Fig. 25 - Total pressure rise behind rotor row.