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FACILITIES AND TECHNIQUES EMPLOYED AT LEWIS RESEARCH CENTER IN EXPERIMENTAL INVESTIGATIONS OF CAVITATION IN PUMPS

By Staff of Lewis Research Center

Prepared for Symposium on Cavitation Research Facilities and Techniques
Sponsored by the American Society of Mechanical Engineers
Philadelphia, Pa. May 18-21, 1964

TECHNICAL PREPRINT

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ABSTRACT

The Pump Branch of the Fluid Systems Components Division of Lewis Research Center is conducting a study of cavitation as it occurs in the pumping of high-energy propellants (cryogenic liquids) used in chemical and nuclear rocket engines and alkali metals used in space-electric-power generation systems. This paper enumerates the program areas of study and lists and describes the facilities and the techniques utilized to supply experimental input to program studies. Test fluids include water, cryogenic liquids, and alkali metals.

INTRODUCTION

The material contained in this paper covers primarily the experimental research on cavitation in pumps currently being carried out, or projected, by the Pump Branch of the Fluid Systems Components Division, Lewis Research Center. Interest of this group in the cavitation phenomenon stems principally from the application of pumps in flow systems of chemical and nuclear rocket engines utilizing the high-energy (cryogenic) propellants and space-electric-power generation units employing alkali metals.

System Requirements

In a rocket engine system the reduction in weight is realized through the lowering of tank pressures (pump net-positive suction head) and utilizing high pump rotative speeds. The high head rise required to produce a given pressure with a low specific weight fluid such as hydrogen coupled with a trend toward increasing thrust chamber pressures are additional reasons for advocating high blade speeds. The factor that limits the extent to which low system pressures and high rotative speeds may be exploited is generally cavitation through its deleterious effects on pump performance.

Space-power generation systems considered herein include those utilizing high-temperature alkali metals as the working fluid in a Rankine cycle. The primary pump research problem in these systems is that of avoiding or at least controlling cavitation damage to the pump impellers and casings, particularly in the condensate return pump. Subcooling the working-fluid condensate below the saturation temperature to provide a net positive suction head for the pump increases the size of the heat-rejecting radiator and, therefore, the overall weight of the system. A limited amount of subcooling will probably be required, however, and in addition, a pump inducer stage, possibly a jet pump, will probably be required ahead of the main condensate return pump. The degree of cavitation, if any, that can be tolerated in a pump rotor over an extended operating period without undue damage to structural materials must be firmly established, as well as effective means of controlling conditions leading to vapor formation.

Cavitation may also complicate the startup sequence of this type of system, a boot-strap operation begun in space. At the low inlet pressures cavitation at startup will certainly be severe unless auxiliary means are employed to control it.

Research Problem Areas

From considerations of system requirements, the following areas for further study of cavitation in turbomachinery are designated.

Damage to structural parts. - This includes an understanding of the mechanism causing damage, a correlation of damage occurring during pump operation with that induced by accelerated methods such as with magnetostrictive devices, and a definition of the parameters (both hydrodynamic and metallurgical) affecting damage.

Effects on performance characteristics. - Objectives of this phase are a better understanding of the cavitation process, a knowledge of types of cavitation incurred, the effects of various flow and geometry parameters on cavitation performance of inducers, and a better definition of stable operating range.

Scale effects. - Scale effects have been defined as deviations from classical similarity laws. Studies conducted in this phase are directed toward a better understanding of scale effects due to physical properties of fluids, dimensional sizing (including blade tip clearance), and speed.

Unsteady effects. - Under certain combinations of flow and inlet pressure, a highly unsteady form of cavitation has been observed in pump rotor passages. In addition to causing degradation of the pump performance, such cavitation could become a source for triggering instabilities in the system flow. Magnitudes and frequency of pressure and flow perturbations will be observed and correlated with performance and cavitation parameters.

A second phase of this study is concerned with the excitations originating in the system and being imposed upon pump flow. Changes in magnitude and/or phase of these system induced perturbations of flow and pressure occurring from flow across the pump will be observed and correlated with cavitation parameters.

Effects of cavitation on stage matching. - Multistage axial-flow pumps and inducer-centrifugal pump combinations are under study in this area.

FACILITIES AND TECHNIQUES

Insofar as possible, experimental input to meet program objectives is obtained using water as the test fluid. Operation in water is economical, permits extended operating times, allows detailed measurements of all types, and is conducive to visualization techniques.

Considerable evidence, however, has been advanced indicating that cavitation effects as measured in water cannot be accurately related to those occurring in a different fluid by means of similarity laws. Consequently, concurrent investigations are conducted in both cryogenic liquids and alkali metals. The results obtained from investigations in the latter fluids are, in general, limited by the type and number of measurements that can be taken, the difficulty in conducting visualization studies, the hazardous nature of the fluids, the limitations in operating time (for cryogenic fluids), and, at the extreme temperatures experienced, the mechanical operating difficulties encountered.

Summary of Facilities

In order to supply experimental cavitation data, the following facilities are operated:

(1) Test facilities using water

(a) Cold-water-pump test facility

(b) Variable-temperature water-pump test facility

(c) Jet-pump facility

(2) Test facilities using cryogenic fluids

(a) Boiling-fluid liquid-hydrogen-pump test facility

(b) High-flow liquid-hydrogen-pump test facility

(c) High-speed liquid-hydrogen-pump test facility

(d) Liquid-oxygen-pump test facility

(e) Liquid-fluorine-pump test facility

(3) Test facilities utilizing liquid metals

(a) High-pressure sodium-pump test facility

(b) Low-pressure sodium-pump test facility

(4) Miscellaneous facilities - these are test installations operated outside of the Pump Branch but which provide useful input information to the work of the branch.

(a) Venturi test loop utilizing water

(b) Venturi test loop utilizing cryogenic fluids

Facility Description and Techniques

<u>Cold-water-pump test facility</u>. - This facility, usually referred to in the literature as the Lewis water tunnel, was first placed into operation in 1958 and to date has supplied all the Lewis experimental data on cavitation in pumps operating in water. A schematic diagram of the components that compose the system and their location is presented in Fig. 1, and an overall view of the test facility is presented in Fig. 2. The capabilities of the components are enumerated in table I.

The facility serves several purposes. First, with the exception of cavitation damage, basic cavitation information supporting all the objectives is obtained. Second, new or different operational techniques, visualization methods, or instrumentation are developed herein before being applied to operation in cryogenic fluids or alkali metals.

Performance data is obtained by radially surveying flow conditions at the inlet and the outlet of each individual blade row. The types of probes used to record radial distributions of total pressure, static pressure, and angle are shown in Fig. 3. The probes are mounted in actuators that move the sensing elements to a number of preprogramed radial locations. Each sensing element incorporates a null-balancing stream-direction-sensitive element that automatically alines the probe to the direction of flow. All pressures are measured with transducers and are recorded along with angle and radial location on paper tape through a digitizing potentiometer at a rate slightly faster than 1 per second.

Blade performance for various modes of operation, both cavitating and noncavitating, is presented in terms of (1) radial distributions of flow conditions at blade inlet and outlet, (2) performance across a selected number of blade elements, and (3) overall performance, which is obtained by integrating the element performance results. An example of test results from an inducer rotor presented in this form is shown in Fig. 4. A more detailed discussion of this test facility, test procedures, and instrumentation may be found in references 1 to 4.

A significant portion of cavitation research carried on in this facility is devoted to visualization techniques. Visual observations provide the investigator with a physical picture of the flow occurring at various modes of operation and aid in the selection of flow models necessary to obtain analytical expressions for computing flow conditions throughout blade passages.

Cavitation occurring in pump rotor passages is photographed in several fashions.

(1) Cavitation is photographed by means of a high-speed 16 millimeter camera utilizing a continuous light source and a framing rate of 6000 frames per second. This method provides a time history of the cavitation process as well as an opportunity to visualize the cavitation occurring in successive blade passages.

(2) Cavitation is also photographed by utilizing a low-speed 16 millimeter camera with a framing rate of approximately 24 frames per second in conjunction with a stroboscopic light. Blade motion is stopped, and photographs of the same blade passage are obtained after a given number of revolutions.

(3) Cavitation may also be photographed by employing a 70 millimeter camera to take single photographs at particular operating conditions where greater detail of the cavitation zones is desired.

Typical film strips illustrating the methods outlined and the types of cavitation observed are shown in Figs. 5 to 7. Additional examples of this technique are contained in references 1 and 2.

A second method for observing flow patterns is by means of tufts mounted on the casing as well as on the blades and the hub surface of the rotating elements. The direction of the tufts is observed over a range of flow conditions and is recorded on film for correlation with performance results. Illustrations of this visualization technique are shown in Figs. 8 to 10.

Some preliminary attempts at visualization through the injection of dyes such as nigrosive black and acid chrome blue into the flow entering rotating elements have been made. While there is some promise for this method, additional efforts are required before the usefulness can be evaluated.

High-response instrumentation to measure pressure and flow fluctuations is incorporated into all investigations conducted in this facility. The three types of probes considered thus far include the high-response pressure transducer and the barium titanate crystal for measuring pressure fluctuations and the thermistor for observing flow fluctuations. The outputs of these probes are recorded on oscillographs, visicorders, and magnetic tape. Examples of the type of data obtained are presented in Fig. 11.

The study of pump dynamic performance in which flow and pressure perturbations of controlled frequency and magnitude are introduced into the flow at the pump inlet will be conducted in this facility. An attempt will be made to determine what changes in magnitude and phase occur during the flow through the pump.

Variable temperature water-pump test facility. - This test facility is currently under construction, and it is anticipated that operation will begin early in 1964. The test-fluid temperature may be varied from 80° to 450° F with the corresponding variations in the physical properties. Thus, a primary function of this test facility will be to provide data for a study of scaling due to physical properties of liquids. One model for cavitation similarity assumes that, with the vapor and liquid in thermal equilibrium, cavitation conditions are similar when the ratio of volume of vapor formed to volume of mixture of vapor and liquid are the same. This ratio, called the B-factor (Ref. 5), is related to fluid physical properties. Table II lists the values of B-factor of typical test fluids for comparison with water at various temperature.

The technique, the associated instrumentation, and the recording devices used to obtain performance, visual studies, and unsteady flow measurements are similar to those used in the cold-water facility and discussed previously. A schematic diagram of the test facility is contained in Fig. 12 and the capabilities of the test loop and components noted in table I.

Water-jet-pump test facility. - A water-jet-pump program was initiated primarily to support the alkali-metals pump research effort in the area of cavitation control through the injection of high-pressure liquid into the low-pressure inlet stream. In this facility the mixing phenomena both with and without cavitation and general jet-pump performance will be studied. The data generated will be used in the design of configurations to be applied to high-temperature alkali-metal-pump tests.

A schematic diagram of this facility is shown in Fig. 13 and a sketch of a typical test section showing instrumentation locations in Fig. 14. An overall view of the test facility is shown in Fig. 15. In addition to measured performance, considerable emphasis is placed on visualization techniques including the use of dye injection.

Boiling-fluid liquid-hydrogen-pump test rig. - This test facility was designed specifically for the study of cavitation in inducers operating with liquid hydrogen. A cutaway view of the test loop appears in Fig. 16. The pump test section is located at the bottom of the 2500-gallon vacuum-jacketed tank, and piping is designed such that flow from the pump may be recirculated back into the tank or conducted to a receiver tank. Seven 8-inch diameter tubes are used for lighting and viewing the lucite-shrouded test section.

All test operations are conducted manually from a remotely located control center. Running times ranging from 5 to 15 minutes are generally employed. Pump performance is calculated from pressure (total and static) measurements obtained from fixed rakes, temperatures from carbon resistors, and NPSH from vapor bulbs (Ref. 6). Considerable development effort on flow-angle measuring devices immersed in liquid hydrogen is also carried on. Unsteady pressure measurements are made with high-response pressure transducers. Visualization studies utilize the same type cameras as used in water tests plus closed-circuit television. To date, photographs of hydrogen flow have not attained the high quality of those obtained of water flow. Conditions that complicate visualization techniques in this facility include (1) difficulty of getting sufficient light through the long tubes and on the rotor inlet flow being photographed, (2) optical clearness and size of windows used - quartz windows with best optical clearness are extremely expensive, (3) vapor bubbles that form in the bottom of the tank as the tank pressure is lowered and pass in front of the viewing windows, and (4) a cloud formation that appears to form on the pump lucite shroud after a short period of operation and impairs vision of the inducer flow.

To date, the facility has operated as a relatively low-speed, low-power test vehicle. The test data obtained in this facility demonstrate the improved cavitation performance observed during operation in liquid hydrogen. Comparisons of this latter performance with the cavitation performances measured from similar, or the same, rotors operating in water supply input information to study the scaling effects due to physical properties of fluids. Visualization techniques have indicated that cavitation in liquid-hydrogen pumps occurs in a different manner than that commonly observed during operation with water, and these observations have aided in the selection of flow models for use in analytical techniques for calculating two-phase flow patterns in inducer blade passages. Investigations have also been conducted to determine the ability of an inducer to handle a boiling fluid, that is, with no external tank pressurization, both in recirculating and tank pump-out conditions. The latter data serves to determine "boost" pump capability for application in feasibility studies.

Two projects planned for this test facility are installing heaters to simulate heating due to radiation and to study pumping under these conditions and cooling liquid hydrogen down to 20° to 25° R to study the pumping of hydrogen in slush form.

Modifications are currently underway to increase the power, the speed, the flow rate, and the maximum system pressure capabilities of this facility. Accordingly, both the present and the projected capabilities of this test facility are enumerated in table I. A detailed description of this facility is given in reference 7.

High-flow liquid-hydrogen-pump test facility. - This test facility accommodates the high-flow, high-power liquid-hydrogen pumps such as inducer and centrifugal pump combinations and multistage axial-flow pumps. It is an open-loop system, and the present tankage running times are relatively short (flow rate of 5000 gpm gives a running time of approximately 1 min). For this reason a complete test procedure is preprogramed and conducted automatically. Three ramp generators permit simultaneous and independent variation of any three parameters (flow, speed, and NPSH) as desired. Overall performance, unsteady flow measurements, and stage matching comprise the input of this test facility toward obtaining the overall objectives of the program. In addition, thrust-balancing devices and hydrogen-lubricated bearings are mechanical features studied in this facility. A schematic diagram of the test loop is shown in Fig. 17 and an overall view of the facility in Fig. 18.

High-speed liquid-hydrogen-pump test facility. - This high-speed, high-pressure test facility accommodates complete pump units, that is, various combinations of a cavitating inducer and a high-pressure rise producing centrifugal impeller. With present tankage, test runs of 4 to 5 minutes are possible, and all tests are preprogramed and controlled automatically. Three ramp generators permit independent and simultaneous variations of flow, speed, and NPSH (or system pressure) as desired. Some detailed performance of the rotor stages may be obtained. Unsteady flow measurements will also be made.

As with all facilities, the data obtained from this facility will contribute toward eventual realization of more than one of the objectives of the overall program. A primary purpose of investigations conducted in this test loop will be the experimental study of stage matching problems. Because of the speed range capability, scale effects due to speed will be examined, and unsteady flow effects (pressure perturbations) will be observed for a range of speeds and modes of operation. Also, since the pump and turbine employed herein are matched units, startup and acceleration transient characteristics will be studied.

Research projected for this test facility includes the incorporation of a boost pump with its own drive unit in series with the high-speed inducer-centrifugal pump combination.

A schematic diagram of this test facility is shown in Fig. 19 and facility capabilities are listed in table I.

Liquid-oxygen- and liquid-fluorine-pump test facilities. - These two test facilities are discussed together because their designs are similar and the single schematic diagram shown in Fig. 20 will suffice for the two facilities. An overall view of the liquid-fluorine test facility is shown in Fig. 21. Both are closed-loop systems incorporating a heat exchanger to maintain fluid temperature and to permit extensive operating periods. Both test loops employ only fixed instrumentation so that pump overall performance results are the primary output. Capability for visualizing the liquid-oxygen flow in the inlet portion of the pump has been provided.

Several successful tests pumping liquid fluorine, including some under cavitating flow conditions, have been made. This test facility and some performance results are discussed in more detail in reference 8.

High- and low-pressure alkali-metal-pump test facilities. - The primary purpose of these test facilities is to supply experimental results of cavitation damage occurring in pump rotors (including that for long-term operation) and of the effects of cavitation on pump performance. The data obtained will also supply some input toward studies of scale effects and stage matching. Investigations of inducers will be conducted in the low-pressure loop while complete pump units (inducer plus centrifugal impeller) will be tested in the high-pressure loop. Eventually the capability for injecting high-pressure fluid upstream of the inducer inlet will probably be incorporated into both systems.

Both test loops have been operated with liquid sodium at temperatures up to 1500° F for various operating periods up to approximately 40 hours. Operation times experienced thus far have been limited by seal and bearing failures as well as by instrumentation problems (particularly torque measurement accuracy).

The investigation presently being carried out in the low-pressure loop serves as an example of the type of information that will be obtained from these test facilities. An inducer-type blade row with nine blades made of three different materials (three blades of each material) has been installed. The cavitation performance of the rotor will first be determined, and then the rotor will be operated for approximately 100 hours at some selected fluid temperature and inlet pressure in the cavitating range. The rotor will then be removed and examined for cavitation damage. Observed material damage will then be correlated with that induced by accelerated methods (such as with magnetostrictive devices).

Schematic diagrams of these two test facilities are shown in Figs. 22 and 23. Overall views of the two test facilities are shown in Figs. 24 and 25.

Venturi test facility. - This test facility is operated by the Flow Physics Branch in a study of fluid tension observed under dynamic flow conditions. To date a single Venturi section has been operated with water, nitrogen, and Freon 114. Projected research for this facility includes operation with a number of different Venturi sections and possibly with other fluids including liquid hydrogen. Results will be applied to the study of scale effects and to aid in establishing conditions for obtaining equilibrium between vapor and liquid in cavitating regions. A schematic diagram of this facility is presented in Fig. 26. A detailed description of this facility as well as test results are contained in references 9 and 10.

CONCLUDING REMARKS

The deleterious effects of cavitation have long forced compromises in the design and/or operation of flow systems and their components. The responsibility within the NASA Lewis Research Center of studying this flow phenomenon (and its effects) in turbomachinery and, in particular, in the pumping of high-energy propellants (cryogenic liquids) and alkali metals falls to the Pump Branch of the Fluid Systems Components Division. This paper has briefly summarized this group's program objectives, the facilities utilized to supply experimental information, the type of data observed, and how these data apply toward satiating these objectives. To supplement this effort, NASA also maintains extensive contract research effort with various companies and universities. These efforts are coordinated with and supply additional input to the in-house activities but are not discussed in this paper.

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TABLE I. - PUMP TEST FACILITY CAPABILITIES

Parameter		Pump test facility										
		Cold water (fig. 1)	Variable temperature water (fig. 12)	Jet (fig. 13)	Boiling fluid (fig. 16)	High flow (fig. 17)	High speed (fig. 19)	Liquid oxygen (fig. 20)	Liquid fluorine (fig. 20)	High-pressure sodium (fig. 23)	Low-pressure sodium (fig. 22)	Projected boiling fluid
		Test fluid										
		H_2O	H_2O	H_2O	LH_2	LH_2	LH_2	LO_2	LF_2	Na	Na	LH_2
Pump diameter, in.	Axial	5 to 9	5 to 9		5 to $6\frac{1}{2}$	8	$2\frac{1}{2}$	4	$2\frac{1}{2}$	5 to 9	3 to 5	5 (max)
	Centrifugal					12	$4\frac{1}{2}$	9	5			
Fluid temperature, °R		530 to 580 Automatic control	530 to 910 Automatic control	520 to 630	36.5 to 50	36.5 to 50	36.5 to 50	140 to 170	140 to 163	1260 to 1960	1260 to 1960	25 to 75
Drive power, hp		Variable freq. elec. motor 3,000	Variable freq. elec. motor 3,000	----------	Cold-air turbine 50	Hot-gas turbine 10,000	Cold LH_2 gas turbine 1,000	Hot-gas turbine 800	Cold-air turbine 200	Electric motor 250	Electric motor 125	Hot-air turbine 500
Maximum speed, rpm		11,000	15,000	----------	15,000	35,000	60,000	20,000 Direct drive	20,000 Direct drive	35,000	25,000	30,000
Maximum flow, gpm		10,000	4,500	Primary: 100 Secondary: 400	1,800	9,000	1,100	1,200	300	1,500	1,500	3,500
Flow measuring device		Venturi	Venturi	Primary: turbine F.M. Secondary: Venturi	Venturi and turbine flowmeter	Venturi	Venturi	Venturi	Venturi	Electro-magnetic flowmeter	Venturi	Turbine flow-meter
Maximum system pressure, psia		200	600	130	100	1,000	1,500	1,500	1,000	300	150	200
System pressure control		Air pressure on rubber diaphragm in accumulator	N_2 gas pressure on diaphragm in accumulator	Air pressure on diaphragm in accumulator	H_2 cover gas	H_2 cover gas	H_2 cover gas	He cover gas	He cover gas	Argon cover gas	Argon cover gas	H_2 cover gas

TABLE I. - Concluded. PUMP TEST FACILITY CAPABILITIES

Parameter		Pump test facility										
		Cold water (fig. 1)	Variable temperature water (fig. 12)	Jet (fig. 13)	Boiling fluid (fig. 16)	High flow (fig. 17)	High speed (fig. 19)	Liquid oxygen (fig. 20)	Liquid fluorine (fig. 20)	High-pressure sodium (fig. 23)	Low-pressure sodium (fig. 22)	Projected boiling fluid
		Test fluid										
		H_2O	H_2O	H_2O	LH_2	LH_2	LH_2	LO_2	LF_2	Na	Na	LH_2
Pump diameter, in.	Axial	5 to 9	5 to 9		5 to $6\frac{1}{2}$	8	$2\frac{1}{2}$	4	$2\frac{1}{2}$	5 to 9	3 to 5	5 (max)
	Centrifugal					12	$4\frac{1}{2}$	9	5			
Range of system pressure (NPSH) control, ft		5 to 200	Approximate 0 to 100 psi over vapor pressure-automatic	10 to 90	0 to 825	0 to 2500	0 to 2500	0 to 150	0 to 120	0 to 250	0 to 250	0 to 825
Type of flow system		Closed loop	Closed loop	Closed loop	Closed or open loop	Open loop	Open loop	Closed loop	Closed loop	Closed loop	Closed loop	Closed or open loop
Tankage, gal		-----------	-----------	300	2,500	6,000	6,000	3,500 LN_2 dewar	3,500 LN_2 dewar	------	-----------	10,000
Approximate continuous operating time, min		Indefinite	Indefinite	Indefinite	5 to 15	1/2 to 1	3 to 5	60	60	Indefinite	Indefinite	5 to 15
Deaeration system (gas content), ppm by weight		2 to 3	2 to 3	2 to 3	---------	--------	---------	---------	---------	----------	----------	-------
Deionizing system, ohm-centimeters		----------	1,000,000	----------	---------	--------	---------	---------	---------	----------	----------	-------
Filter system (particle size removed), microns		>5	>5	>25	>10	--------	---------	---------	---------	>10	>10	>10
Oxide control system, ppm by weight		----------	----------	----------	---------	--------	---------	---------	---------	Cold trap ≤20 Hot trap <<1	Cold trap ≤20	-------

TABLE II. - CAVITATION SUSCEPTABILITY PARAMETER, B,

FOR VARIOUS FLUIDS

Fluid	Temperature boiling point atmospheric pressure		Test temperature		Cavitation susceptability parameter, B, for Δh = 1 ft
	^{o}R	^{o}F	^{o}R	^{o}F	
Water	672	212	540	80	980
			560	100	320
			660	200	3.7
			760	300	.2
			860	400	.02
			910	450	.007
Liquid nitrogen	139	-321	140	-320	0.35
			160	-300	.05
			180	-280	.01
Liquid oxygen	163	-297	160	-300	0.93
			175	-285	.20
			190	-270	.06
Liquid fluorine	153	-307	150	-310	1.60
			170	-290	.23
			190	-270	.05
Liquid hydrogen	36.5	-423.5	36	-424	0.008
			40	-420	.0035
			44	-416	.0013
Liquid sodium	2078	1618	1400	940	24,000
			1800	1340	40
			2200	1740	.75
			2600	2140	.057
Anhydrous hydrazine	696	236	500	40	32,000
			550	90	1,200
UDMH	606	146	500	40	140
			550	90	11
Nitrotetraoxide	530	70	500	40	7.5
			550	90	.7

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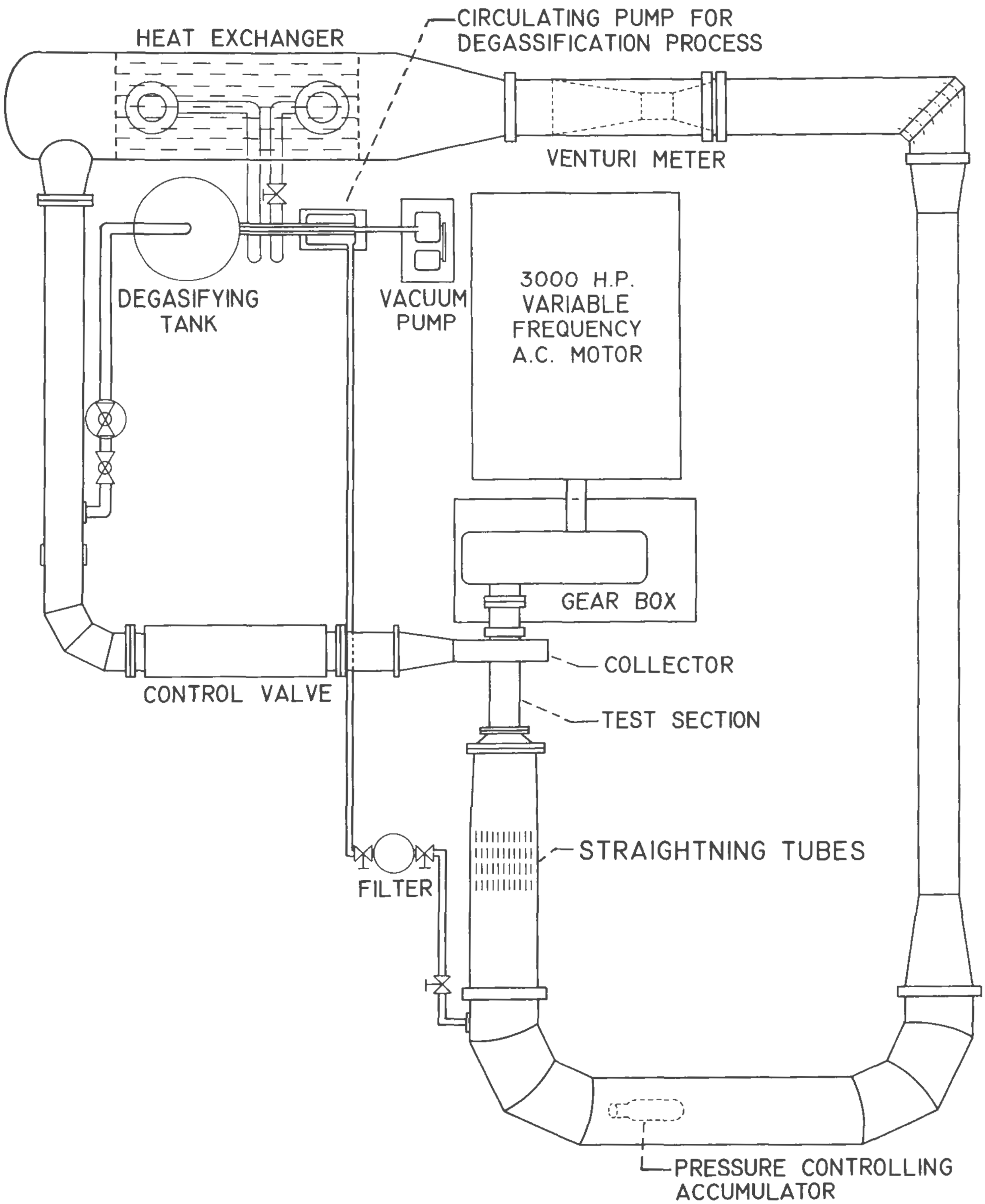

Figure [illegible]. - Schematic diagram of cold-water test facility.

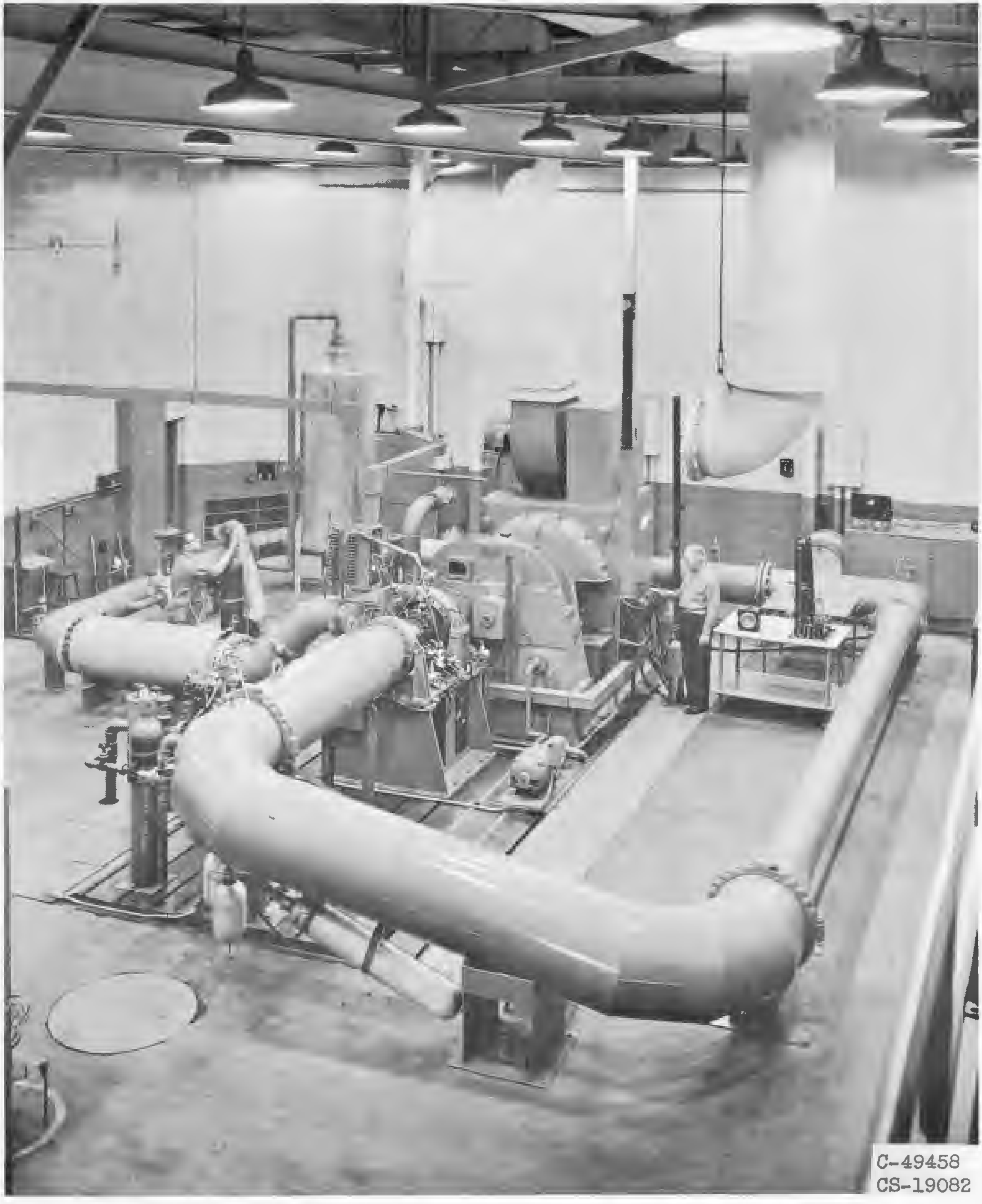

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Figure 2. - Cold-water test facility.

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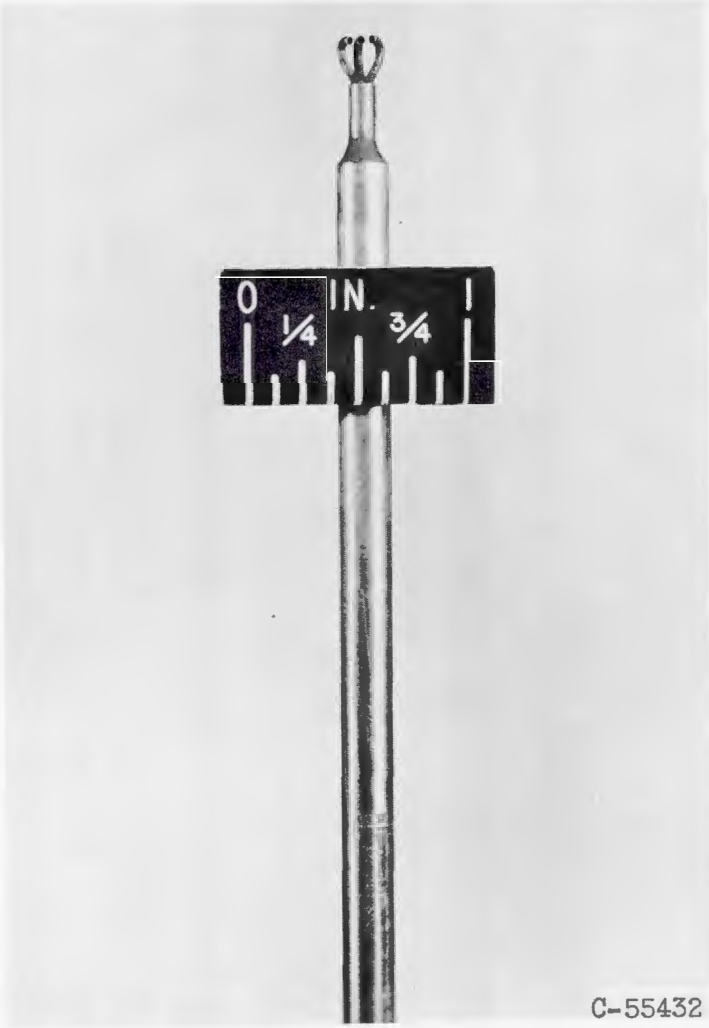
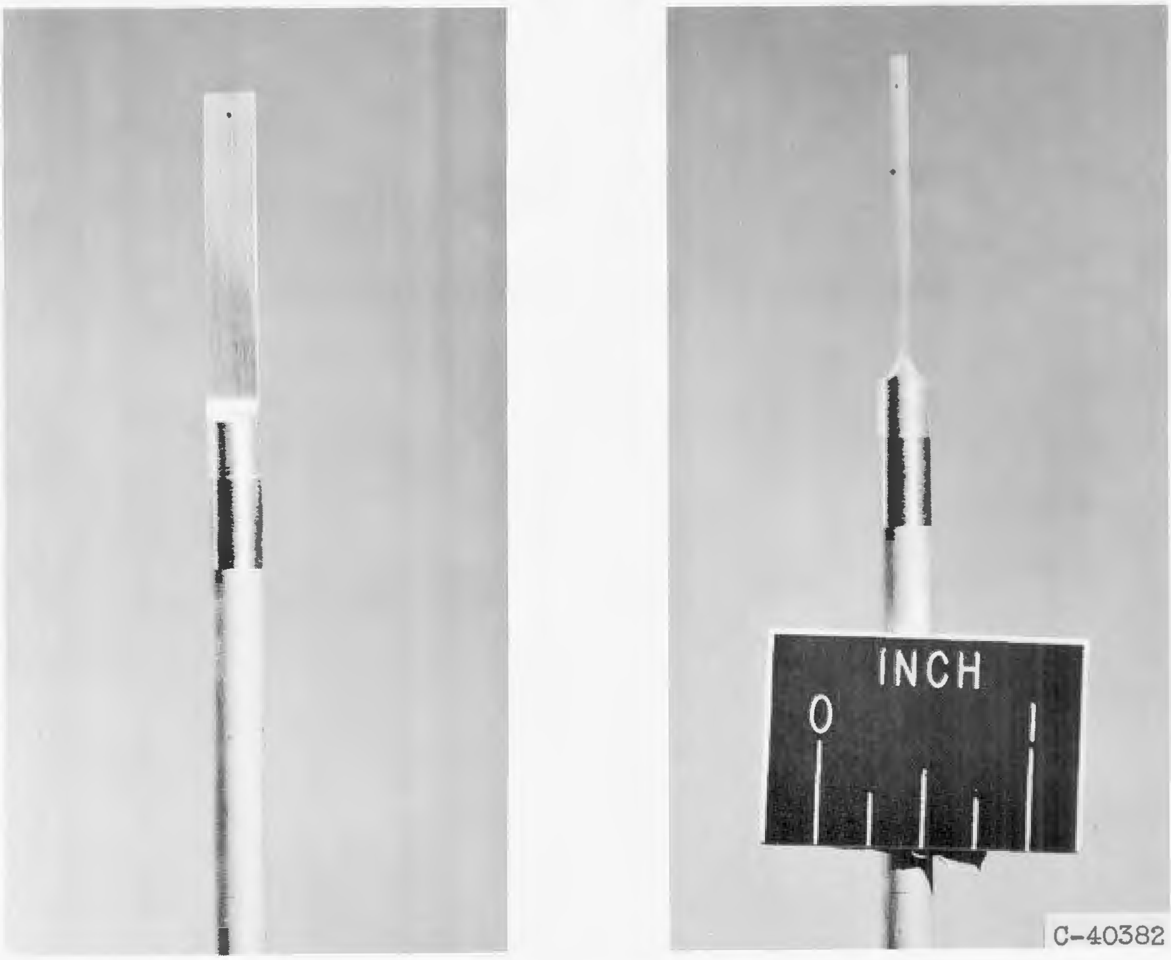


(a) Total pressure claw.

Figure 3. - Pressure measuring instruments.



(b) Static pressure wedge.

Figure 3. - Concluded. Pressure measuring instruments.

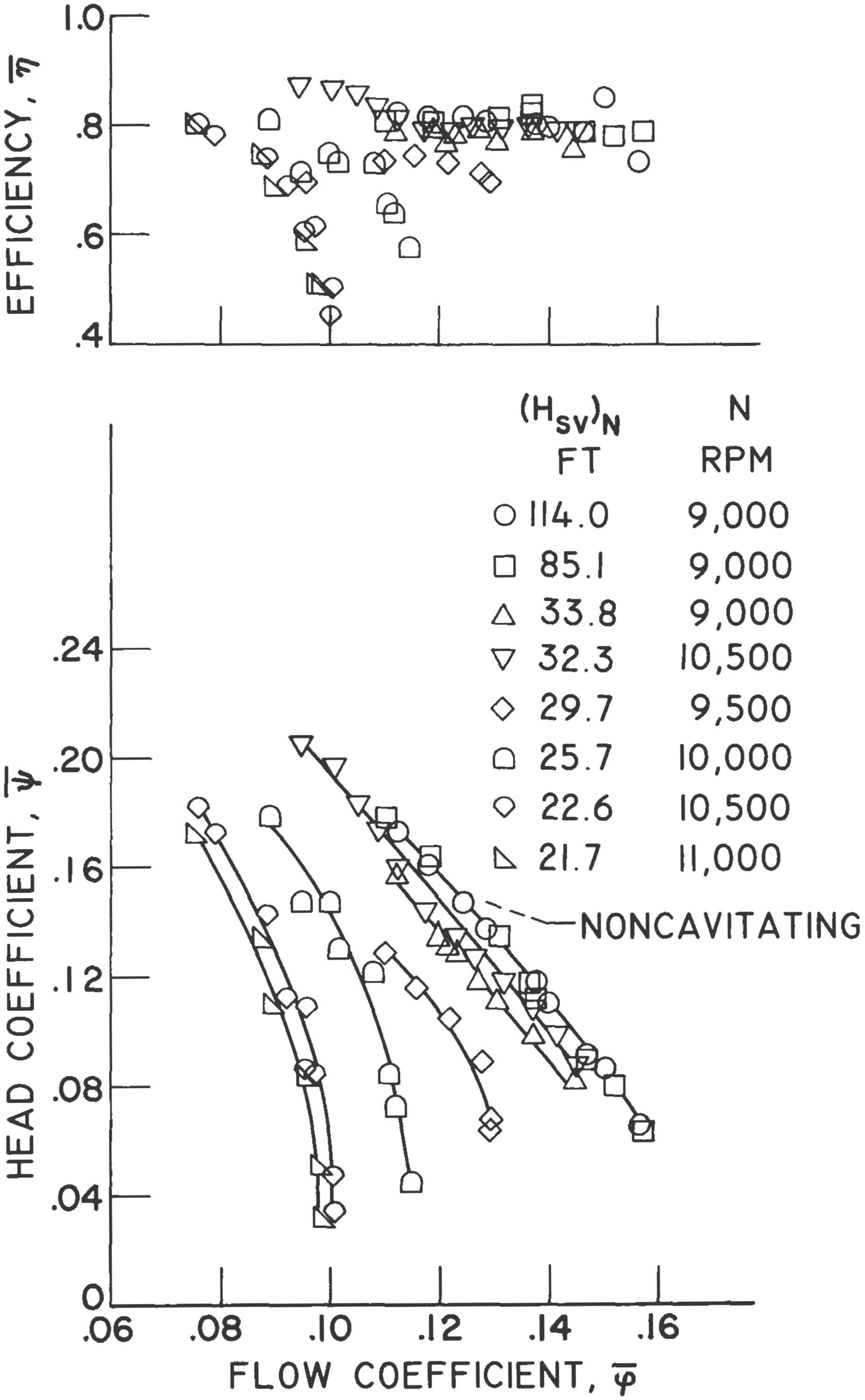


Figure 4a. - Overall performance with cavitating and noncavitating conditions for a 78° flat-plate helical inducer (Ref. 1).

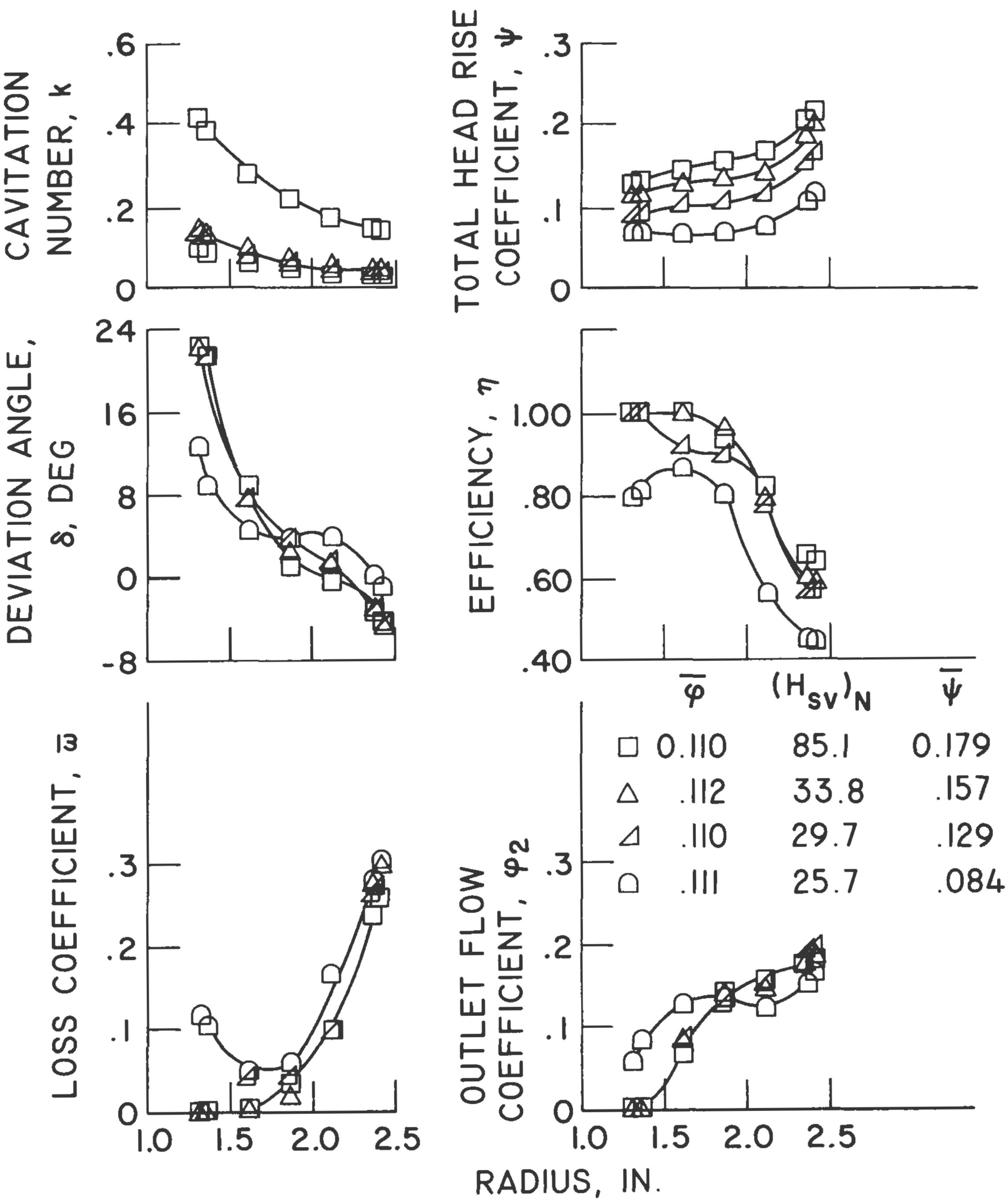


Figure 4b. - Radial distribution of flow conditions and blade-element performance parameters with cavitating and noncavitating conditions for a 78° flat-plate helical inducer (Ref. 1). $\varphi \approx 0.110$.

E-2386

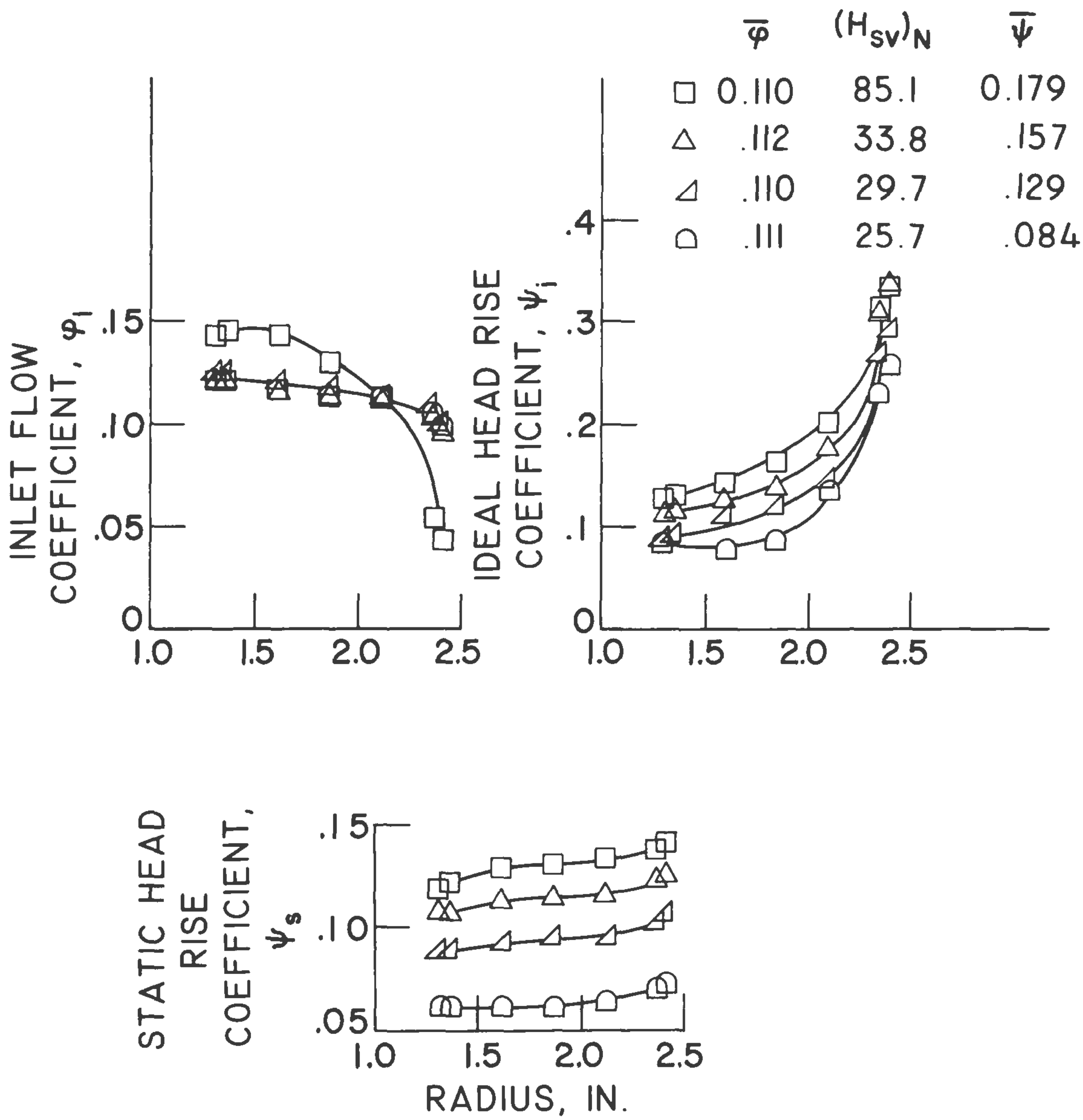


Figure 4b. - Concluded. Radial distribution of flow conditions and blade-element performance parameters with cavitating and noncavitating conditions for a 78° flat-plate helical inducer (Ref. 1). $\varphi \approx 0.110$.

Figure 5. - Cavitation photographed with a 16 millimeter camera at a framing rate of 6000 frames per second utilizing a continuous light source.

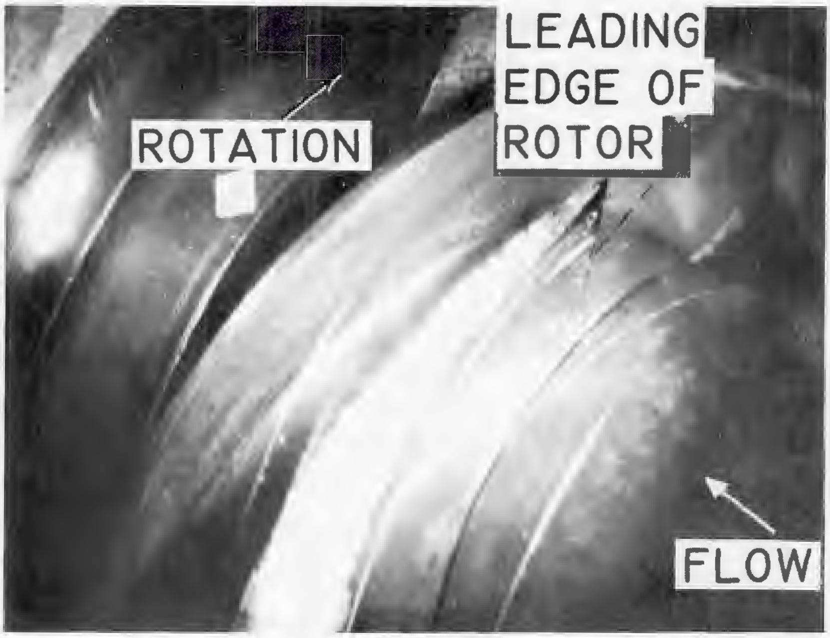
C-58106

Figure 6a. - Film strip sequence showing unsteady type of cavitation for a 78° flat-plate helical inducer (Ref. 1). Film strip was obtained by a 16 millimeter camera at a framing rate of 24 frames per second with a stroboscopic light. $\varphi = 0.1477$.

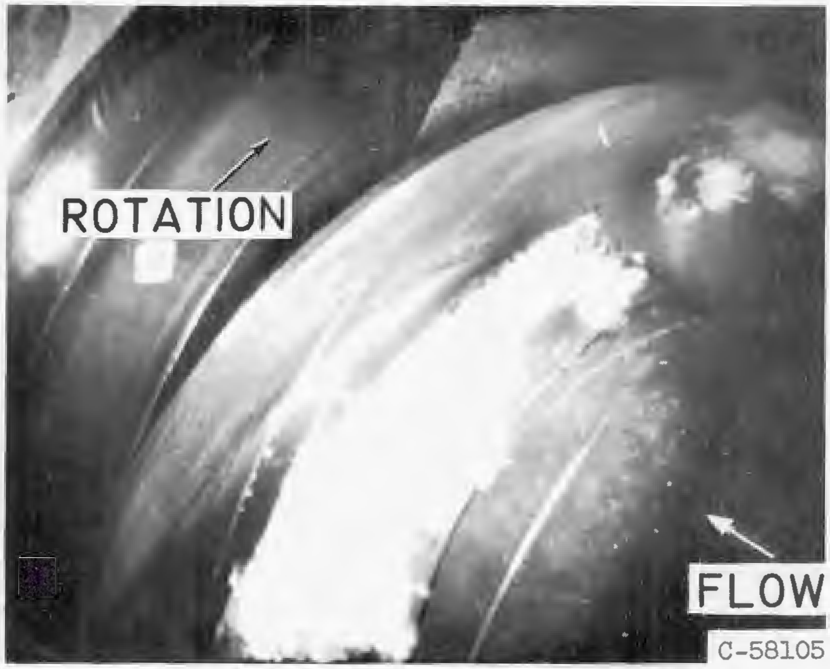
C-58107

Figure 6b. - Concluded. Film-strip sequence showing steady-type cavitation in breakdown region. Q = 0.1162.

E-2386



(a) φ = 0.1477.



(b) φ = 0.1162.

Figure 7. - Tip vortex cavitation at a high value of system inlet pressure (H_{SV}) for a 78° flat-plate helical inducer (Ref. 1). A 70 millimeter camera was utilized with a 1/2 microsecond flash.

(a)

(b)

Figure 8. - Overall views of cavitating inducer illustrating use of tufts mounted in outer casing to aid in describing changes in inlet flow conditions as system inlet pressure is reduced.

C-65415

Figure 9. - Overall view showing location of tufts on hub surface and blade-suction surface of a centrifugal pump operated in cold-water facility (Ref. 1).

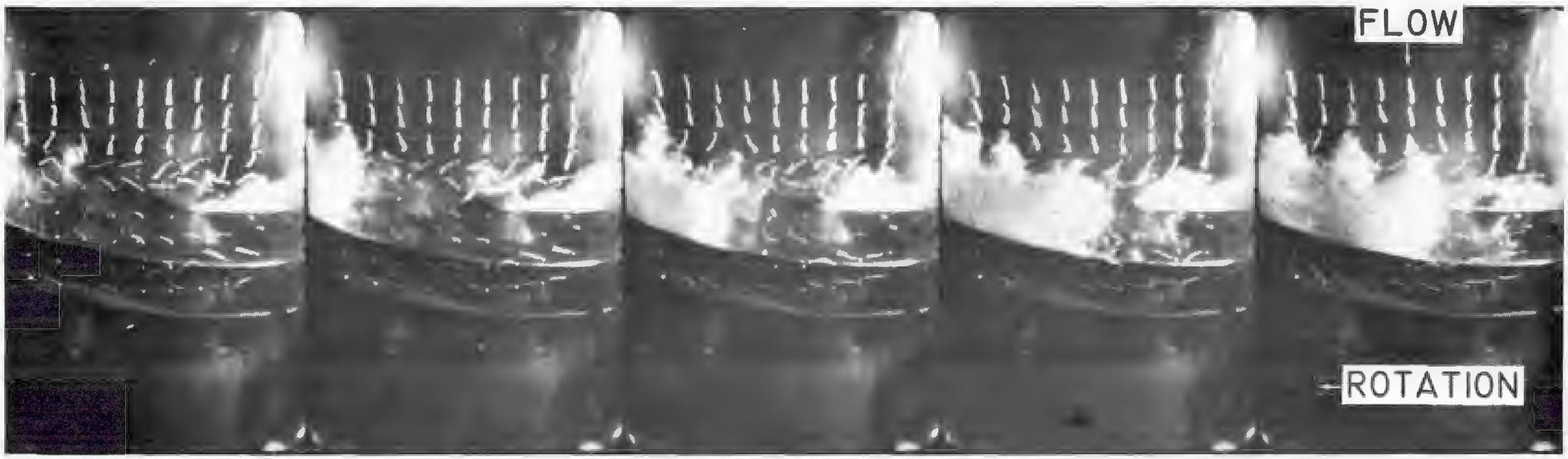


Figure 10. - Cavitating inducer with tufts mounted in outer casing at inlet and across rotor.

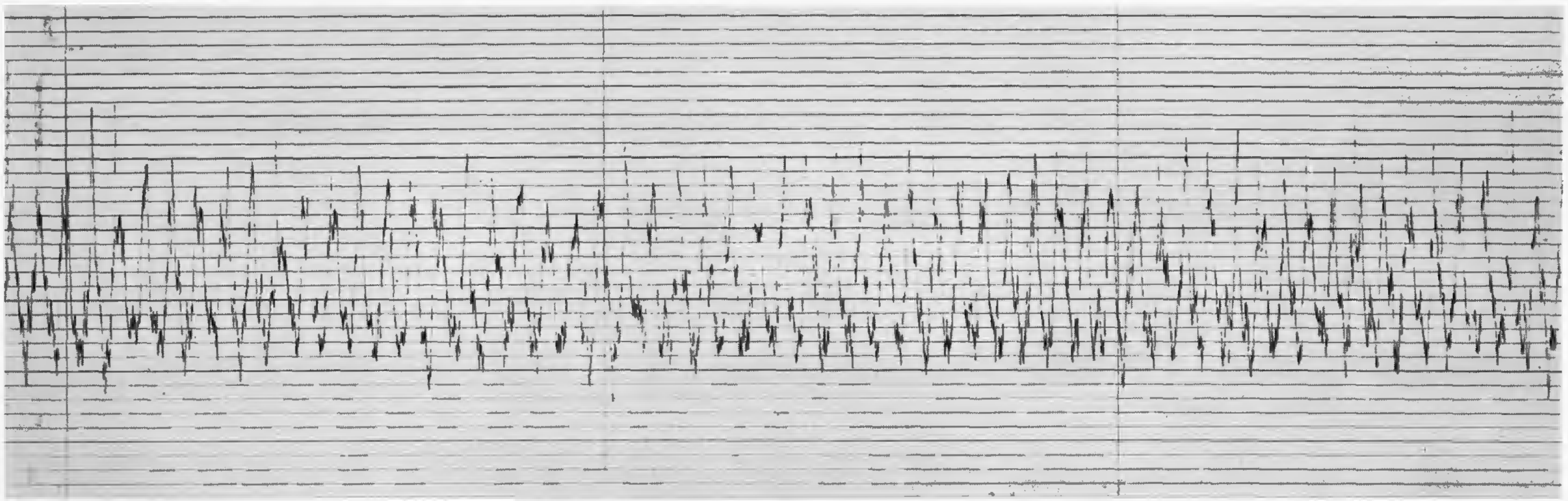


Figure 11. - Visicorder trace of pressure as measured by high-response pressure transducer located in pump housing over leading edge of cavitating inducer.

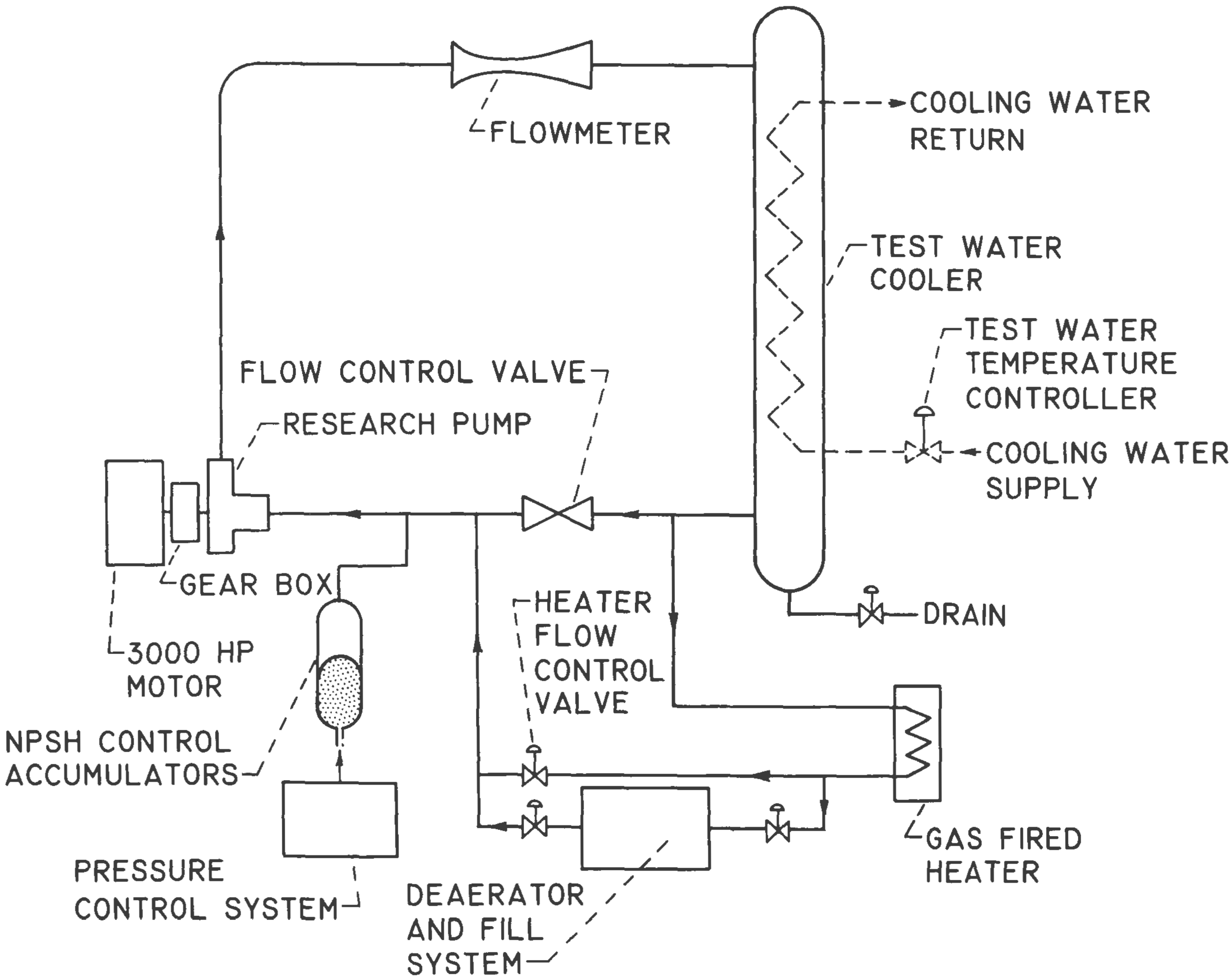


Figure 12. - Schematic diagram of variable temperature water-pump test facility.

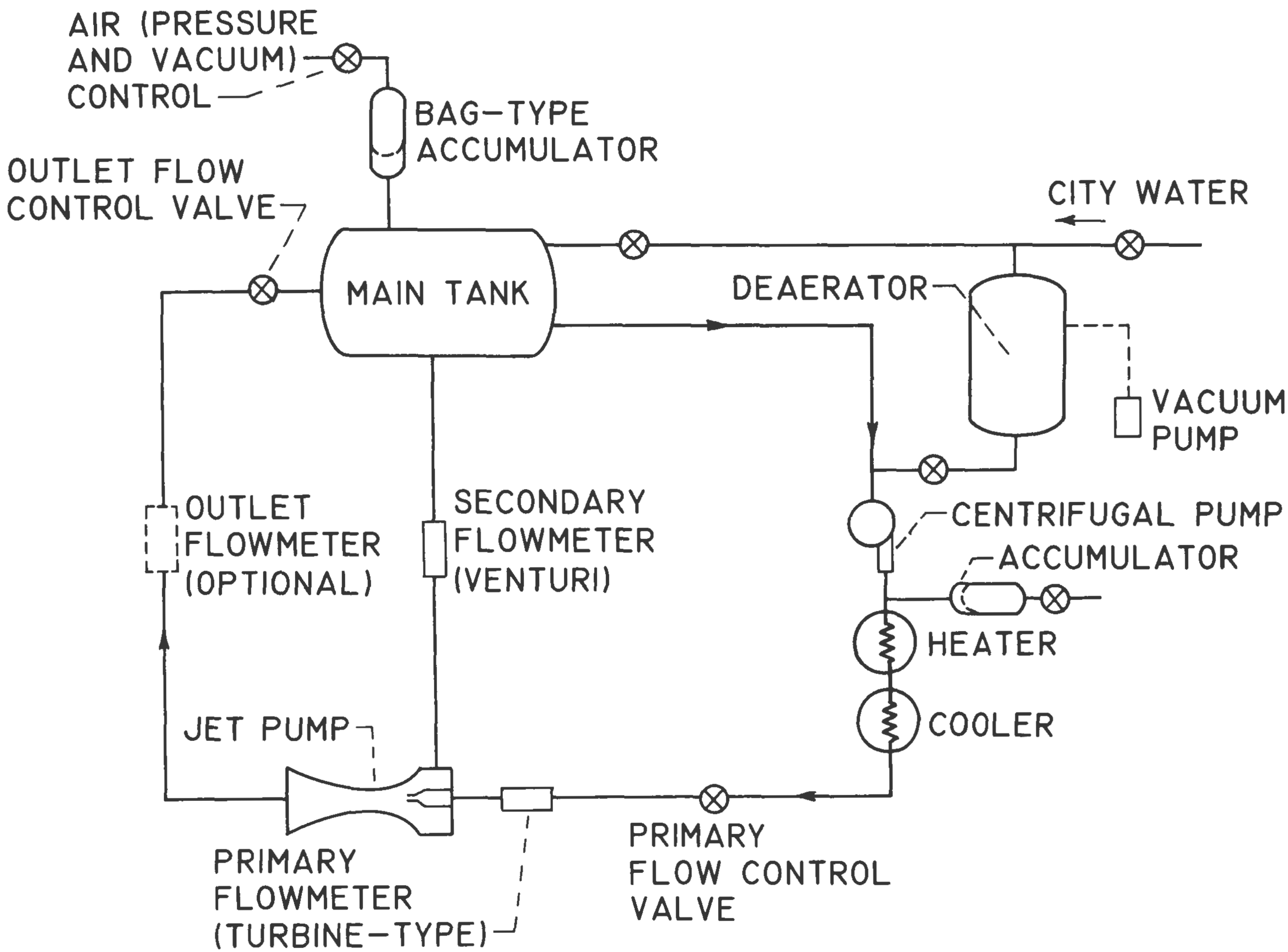


Figure 13. - Schematic diagram of water-jet-pump test facility.

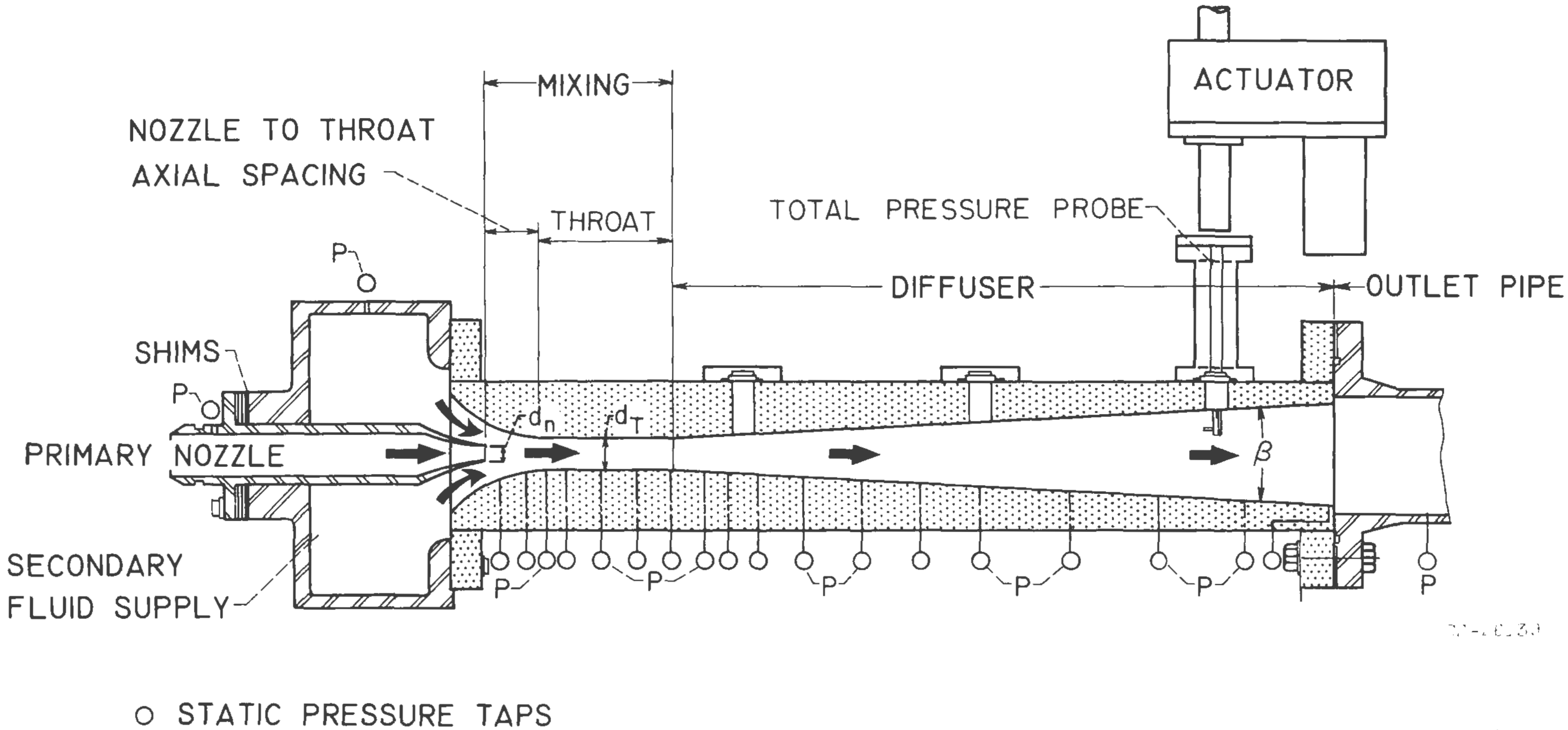
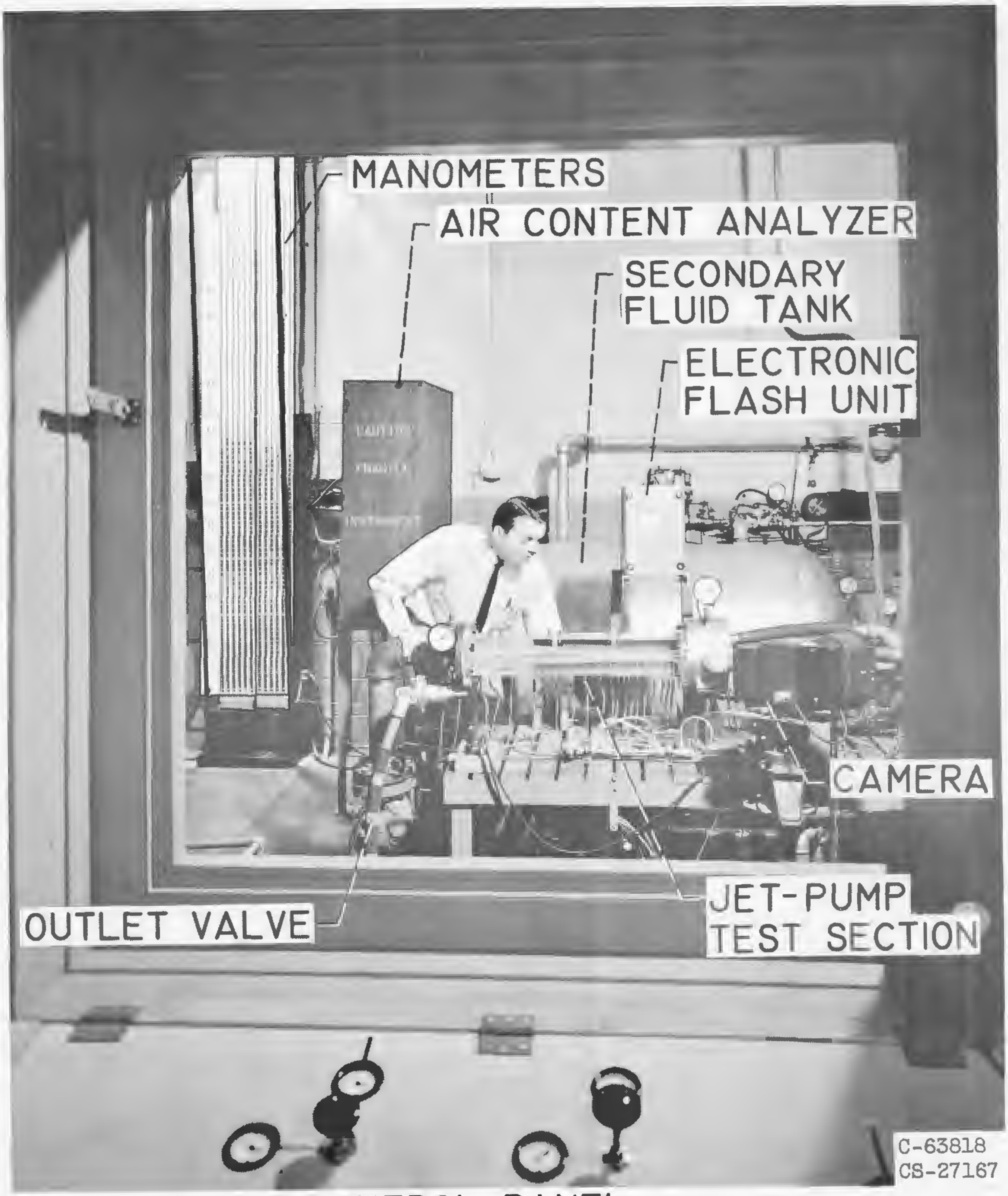


Figure 14. - Water-jet-pump test section showing location of pressure measurements.

E-2386



CONTROL PANEL

Figure 15. - Water-jet-pump test facility.

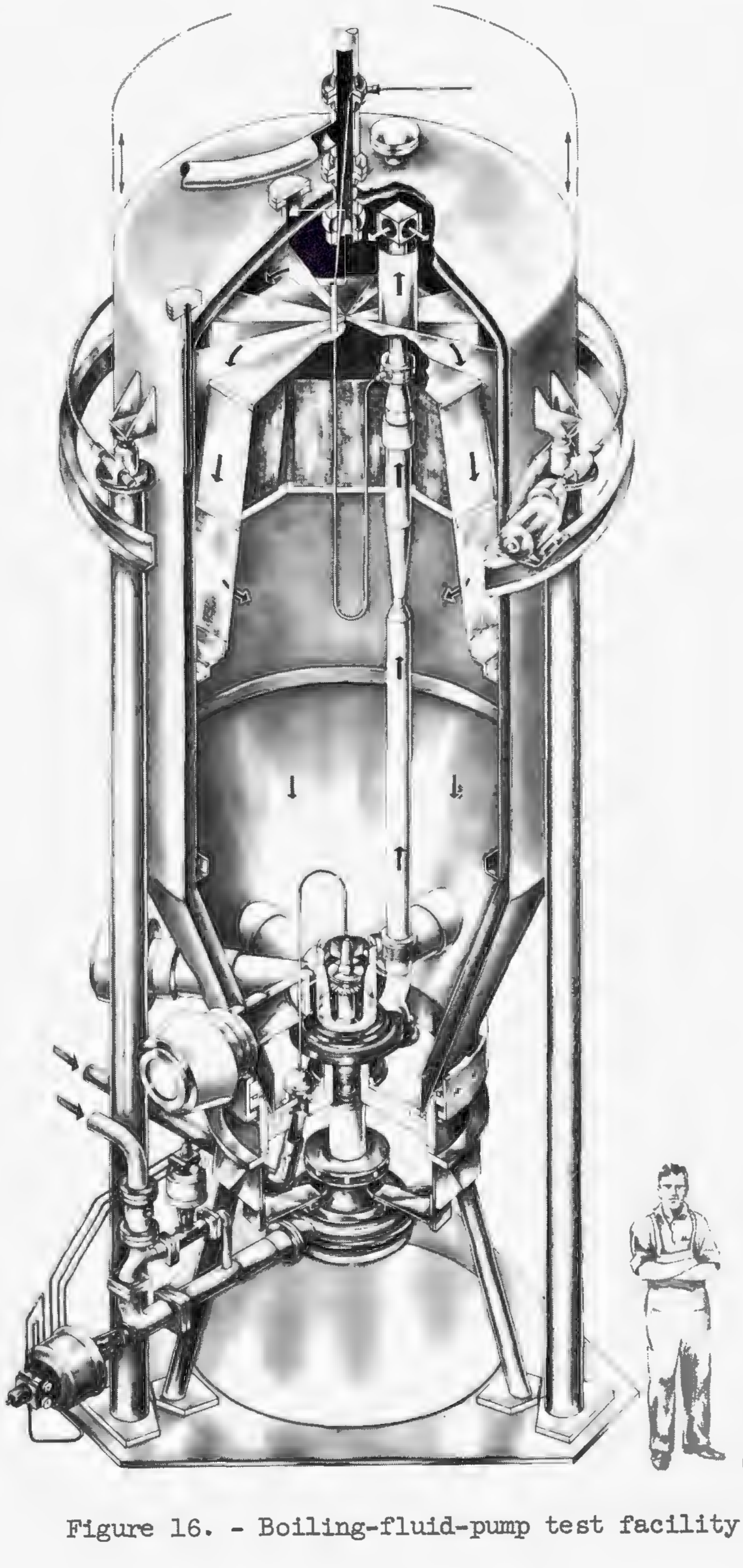


Figure 16. - Boiling-fluid-pump test facility.

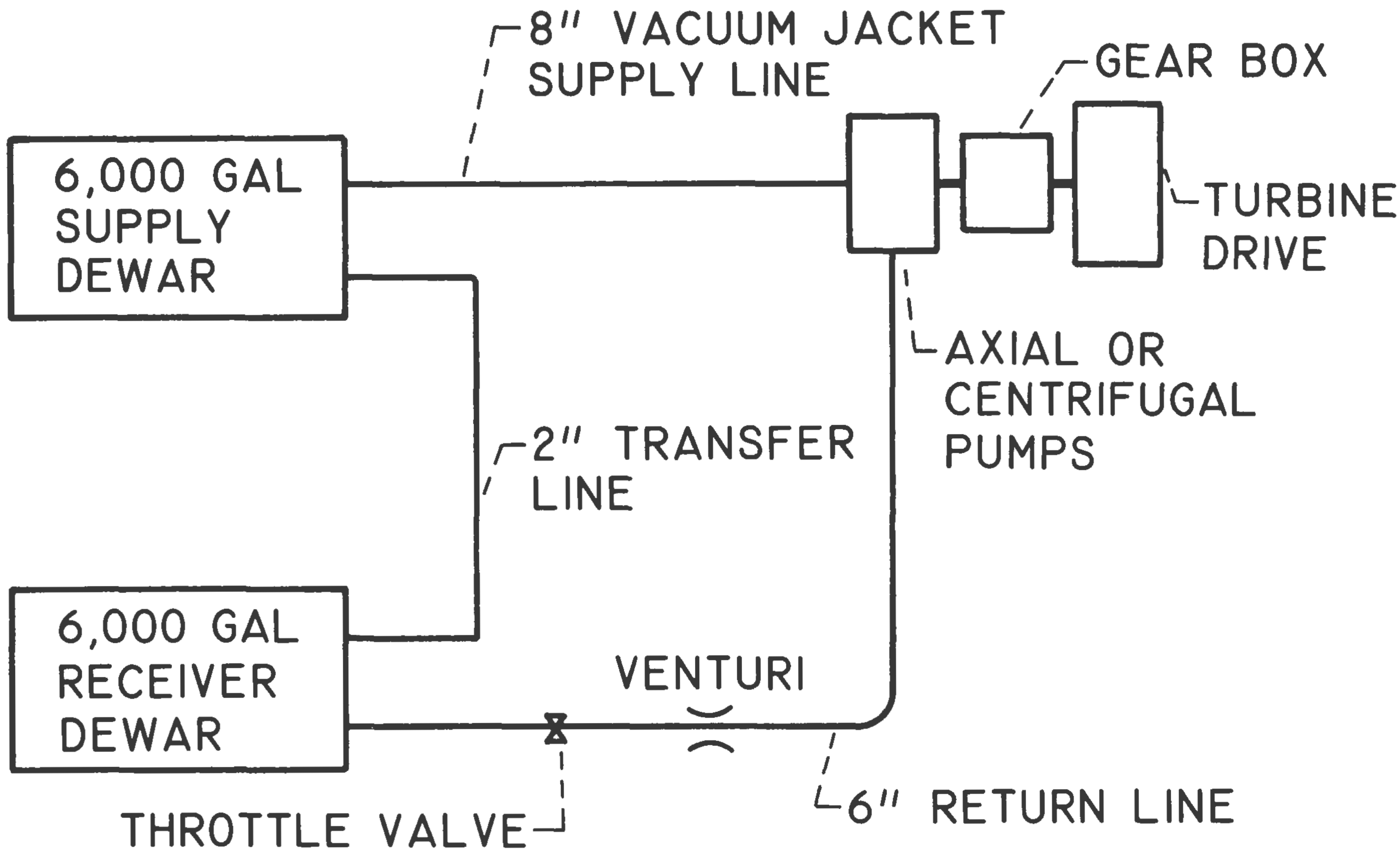


Figure 17. - Schematic diagram of high-flow liquid-hydrogen-pump test facility.

Figure 18a. - Aerial view of high-flow liquid-hydrogen-pump test facility.

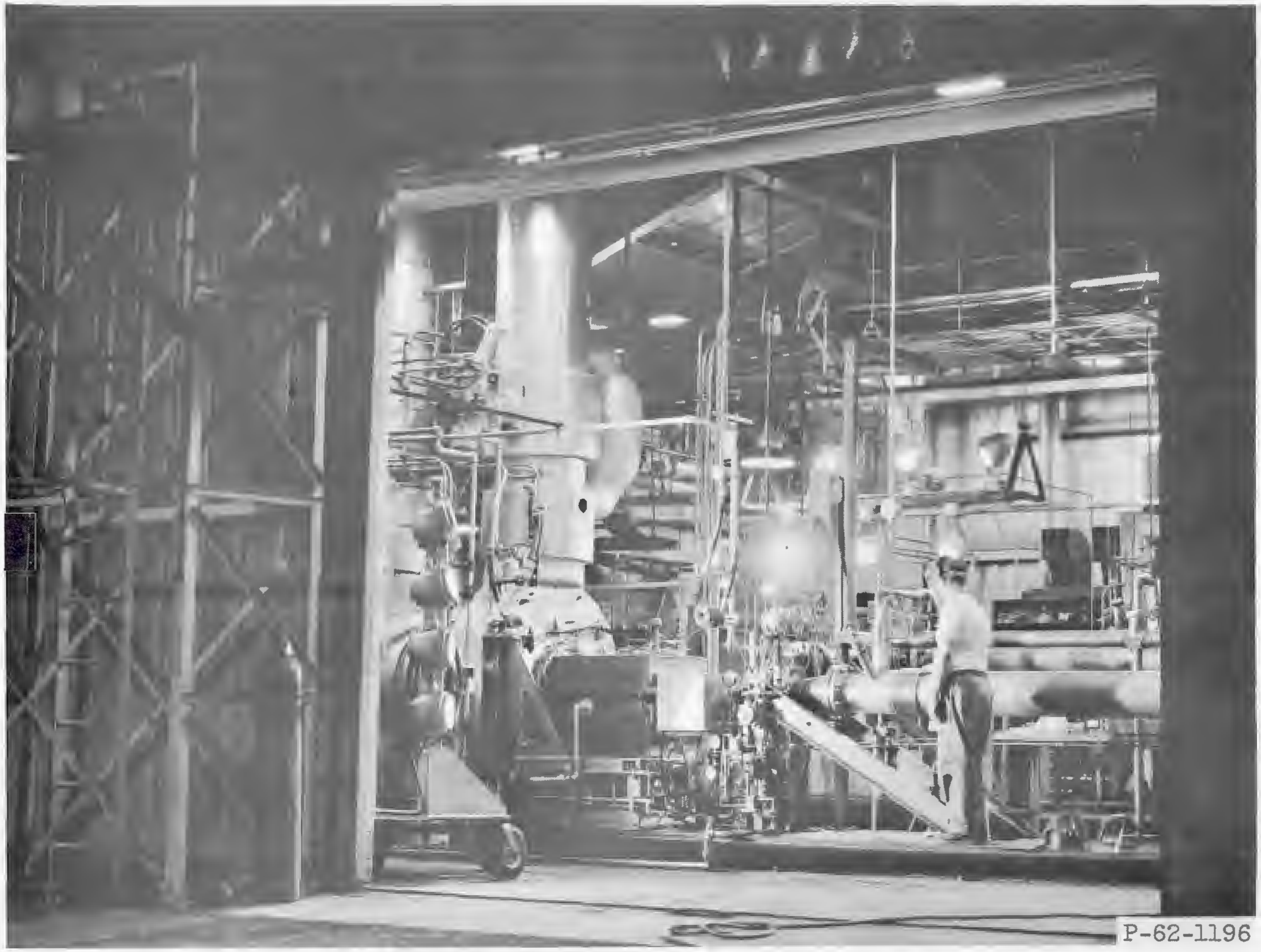


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Figure 18b. - Concluded. Closeup view of piping and running gear of high-flow liquid-hydrogen-pump test facility.

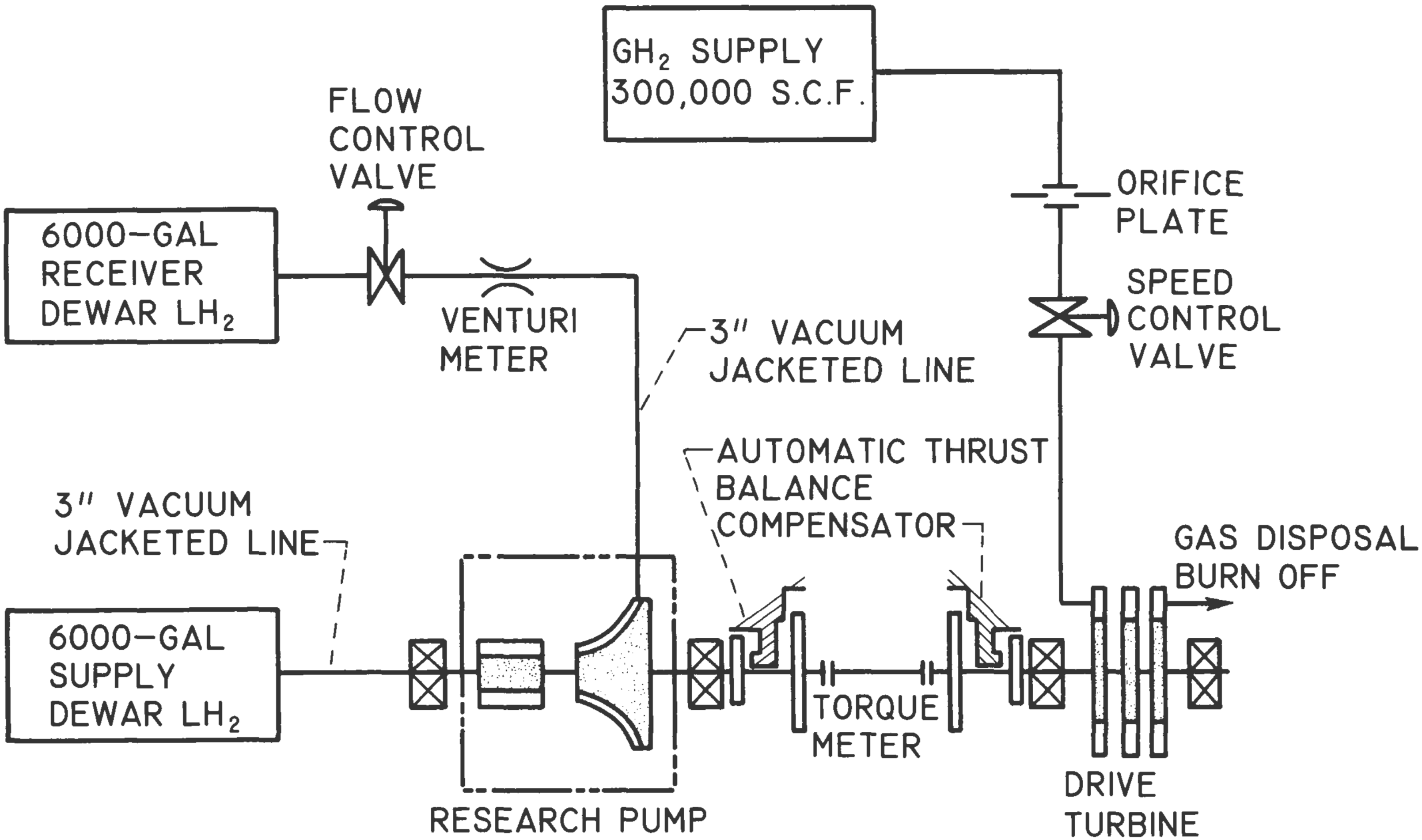


Figure 19. - Schematic diagram of high-speed liquid-hydrogen-pump test facility.

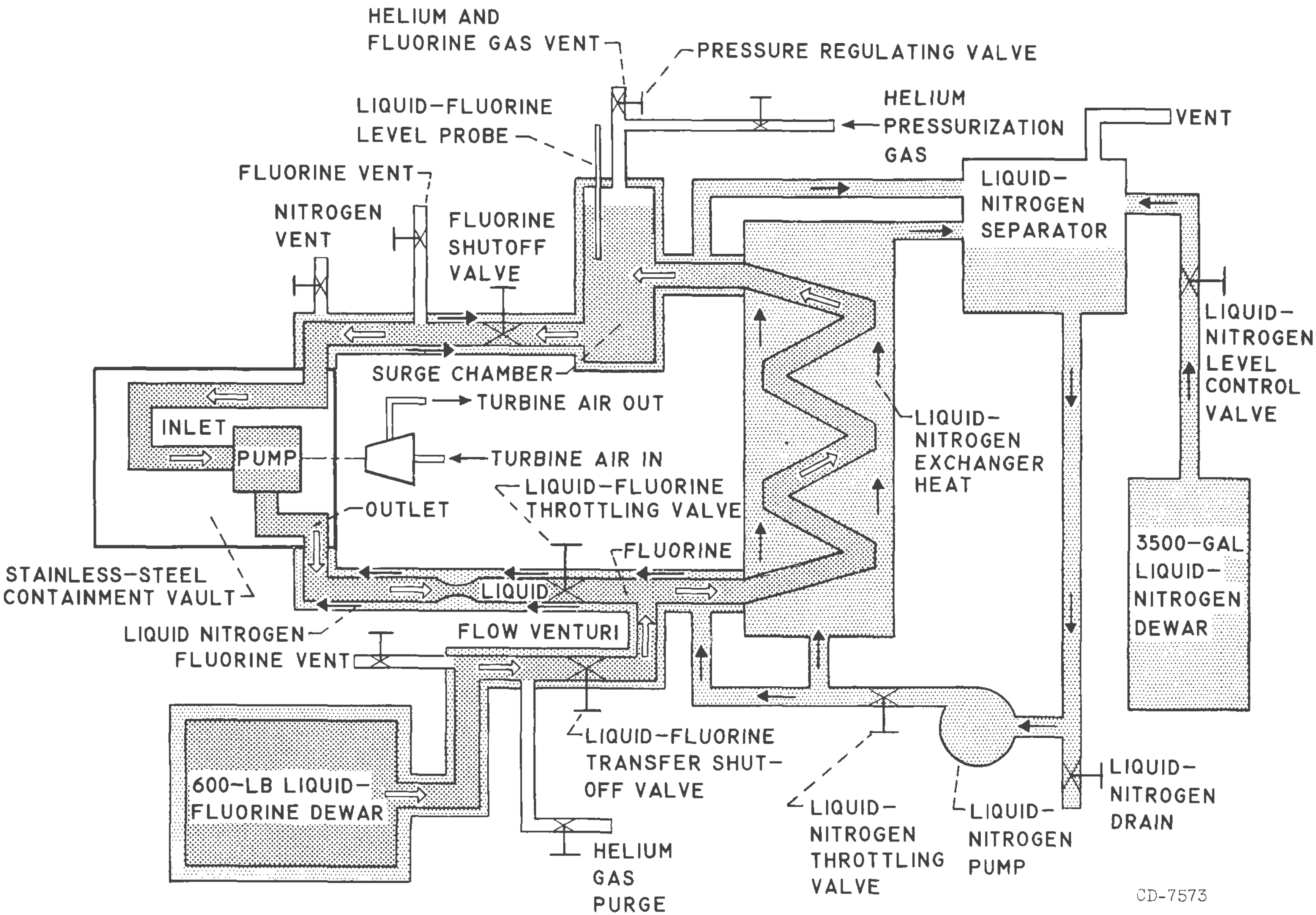


Figure 20. - Schematic diagram of liquid-fluorine/liquid-oxygen-pump test facility.

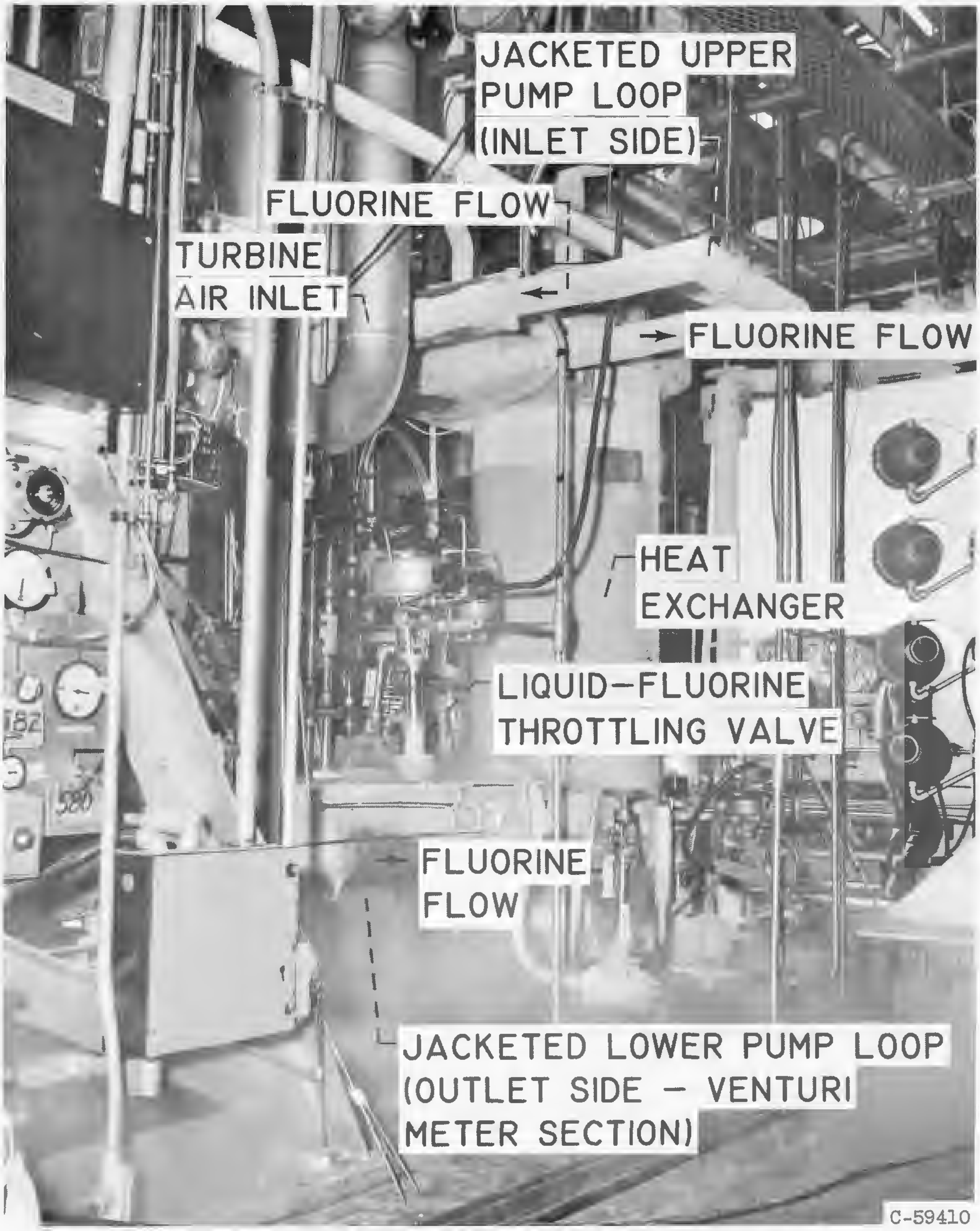


Figure 21. - Liquid-fluorine-pump test facility.

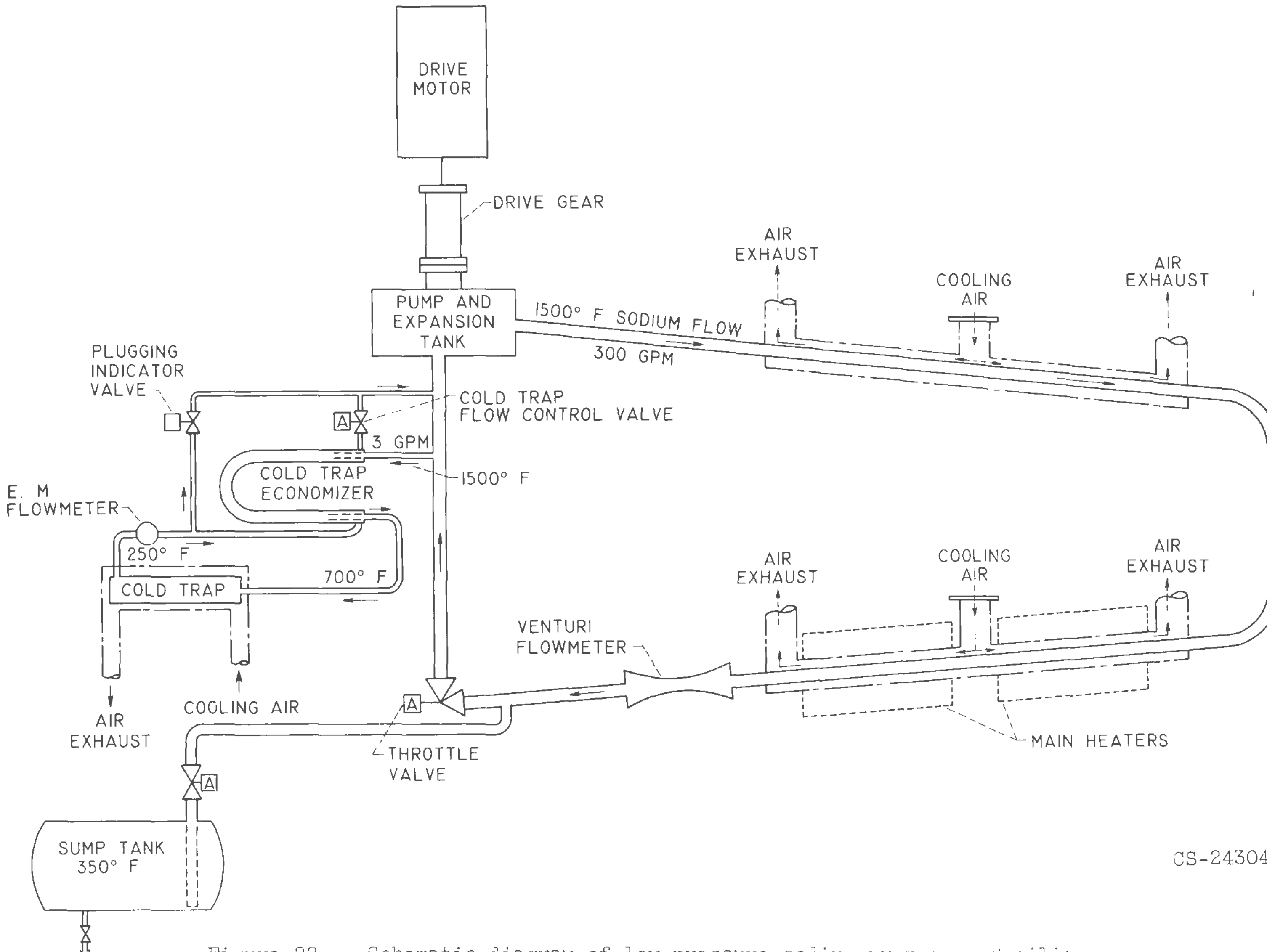
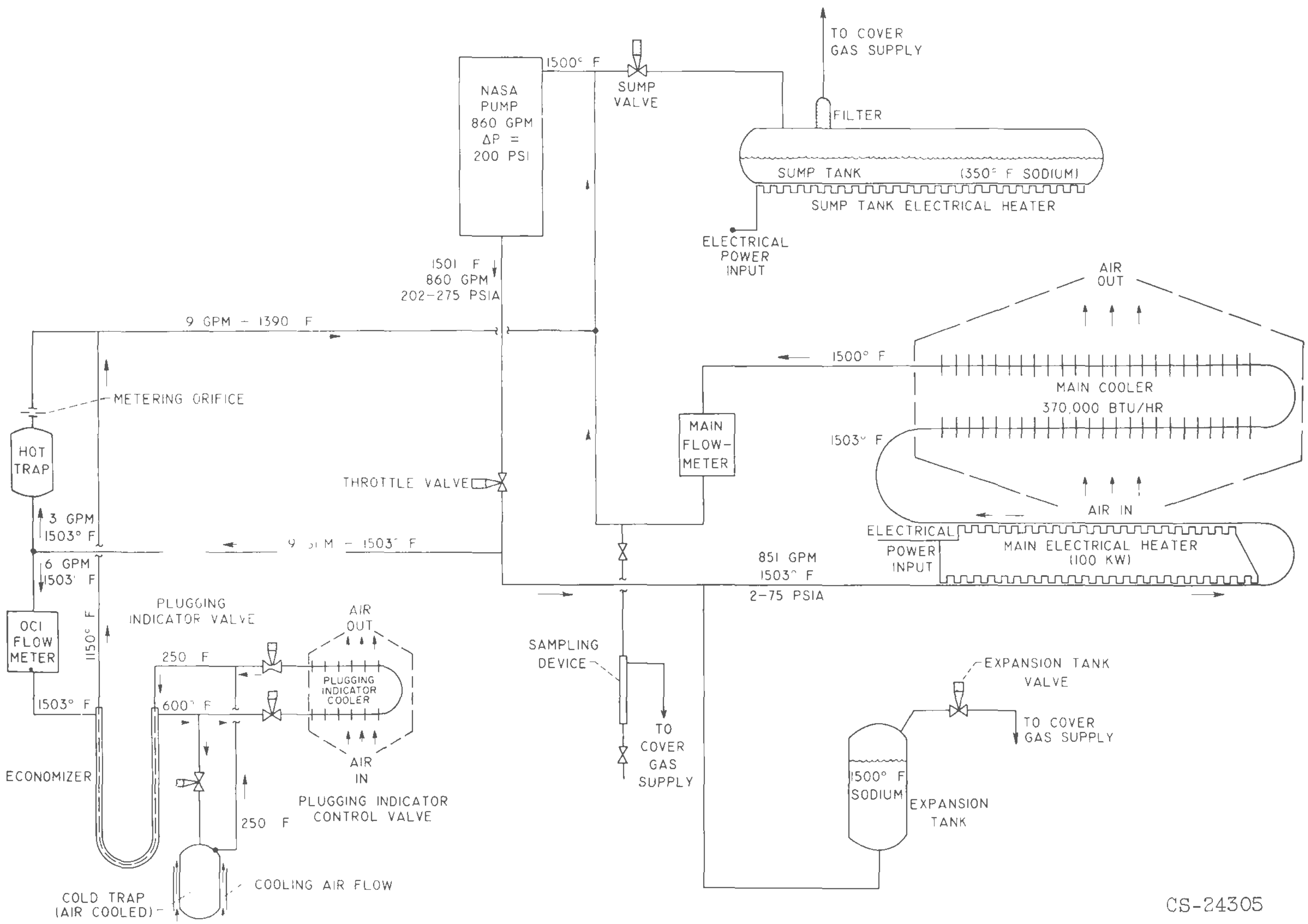


Figure 22. - Schematic diagram of low-pressure sodium-pump test facility.



CS-24305

Figure 23. - Schematic diagram of high-pressure sodium-pump test facility.

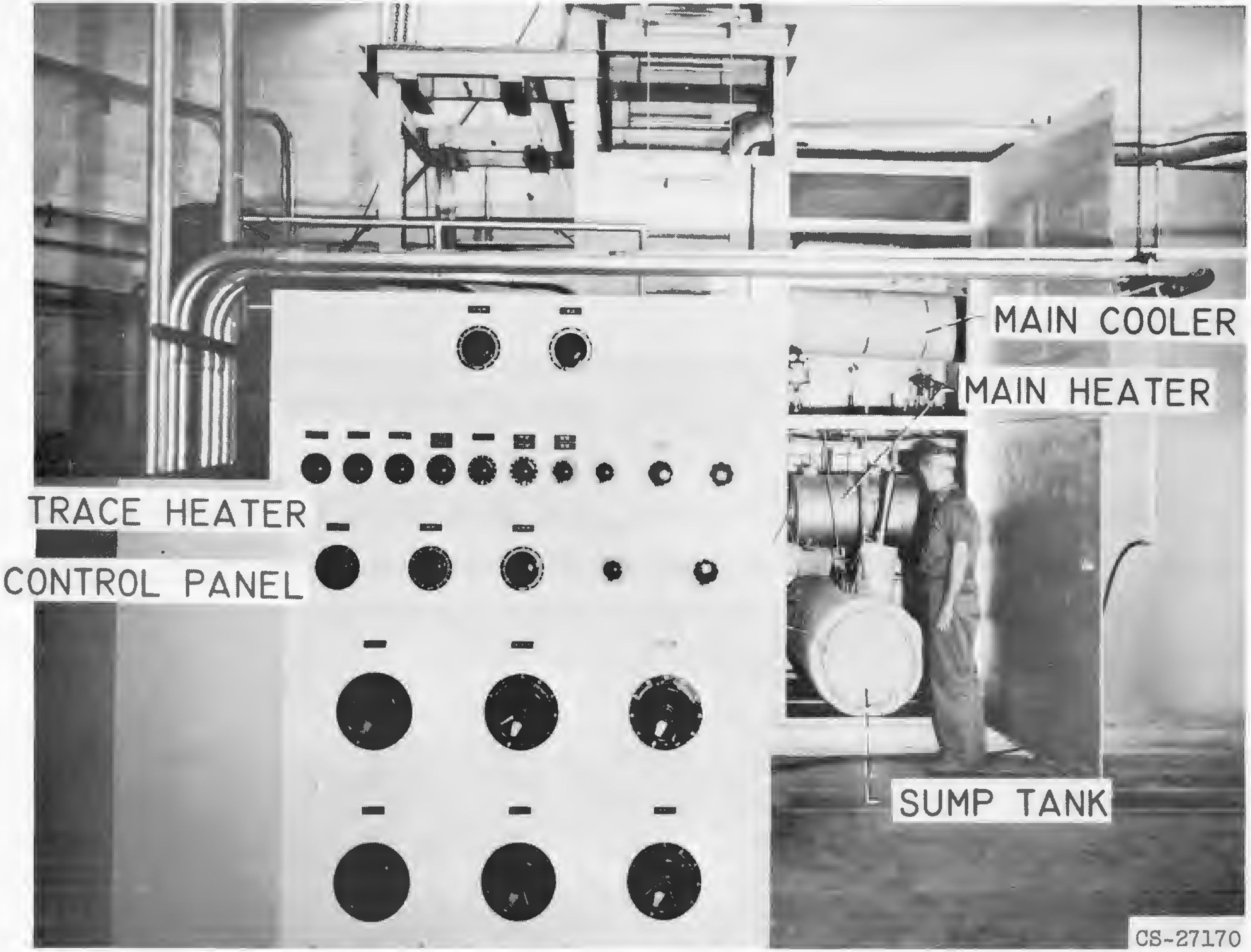


Figure 24. - Low-pressure sodium-pump test facility.

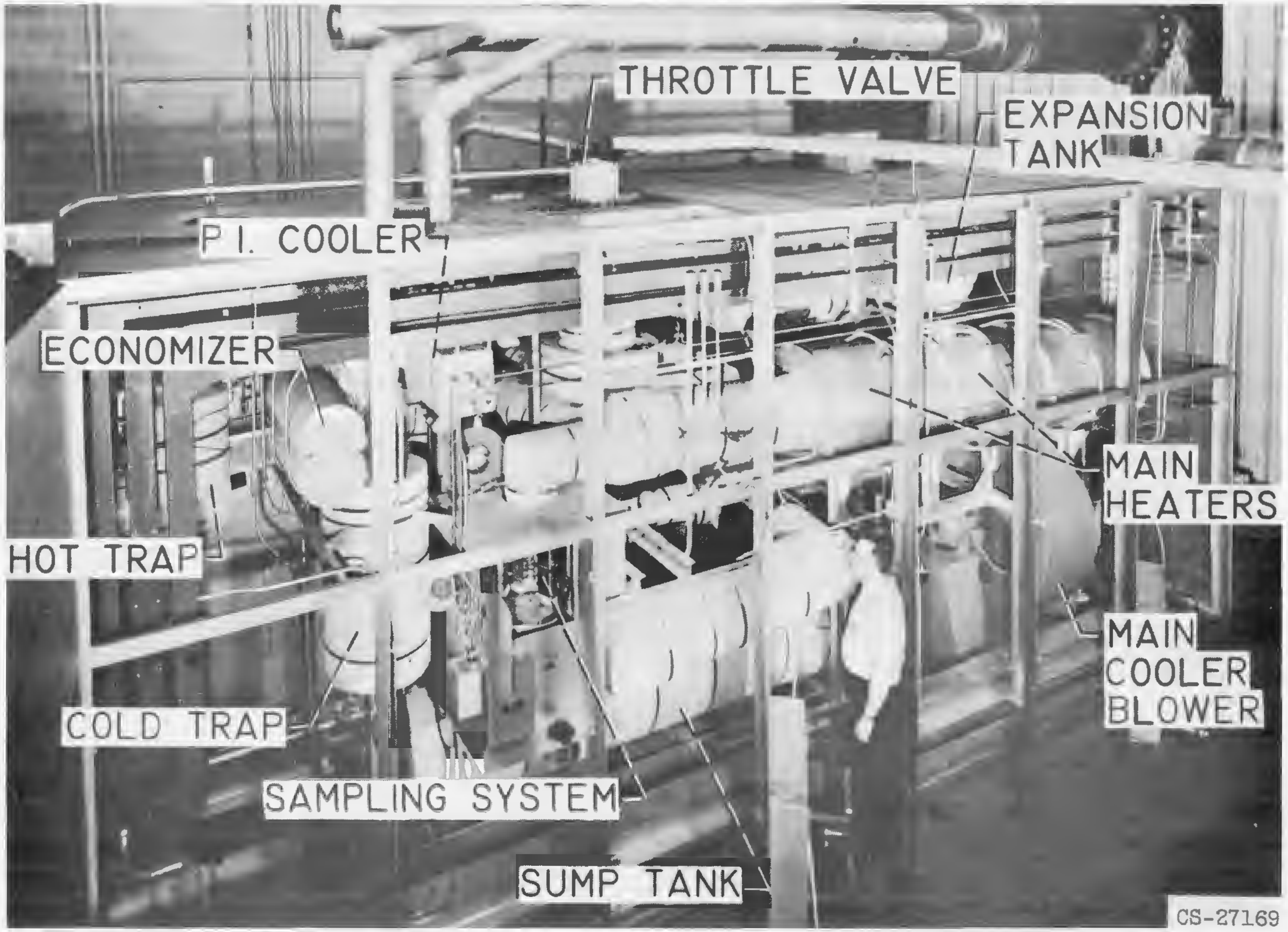


Figure 25. - High-pressure sodium-pump test facility.

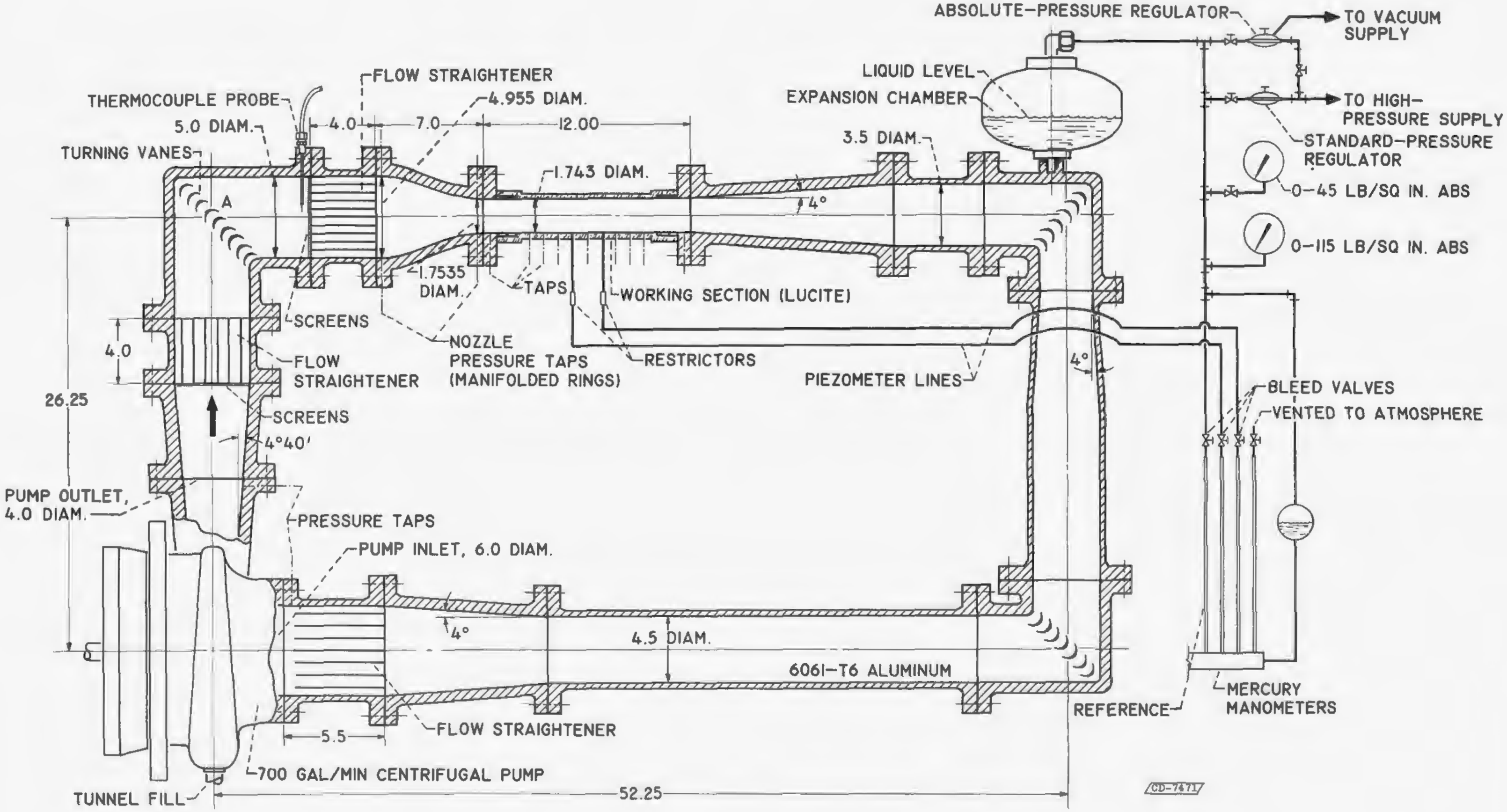


Figure 26. - Schematic diagram of venturi test facility.