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MEMORANDUM

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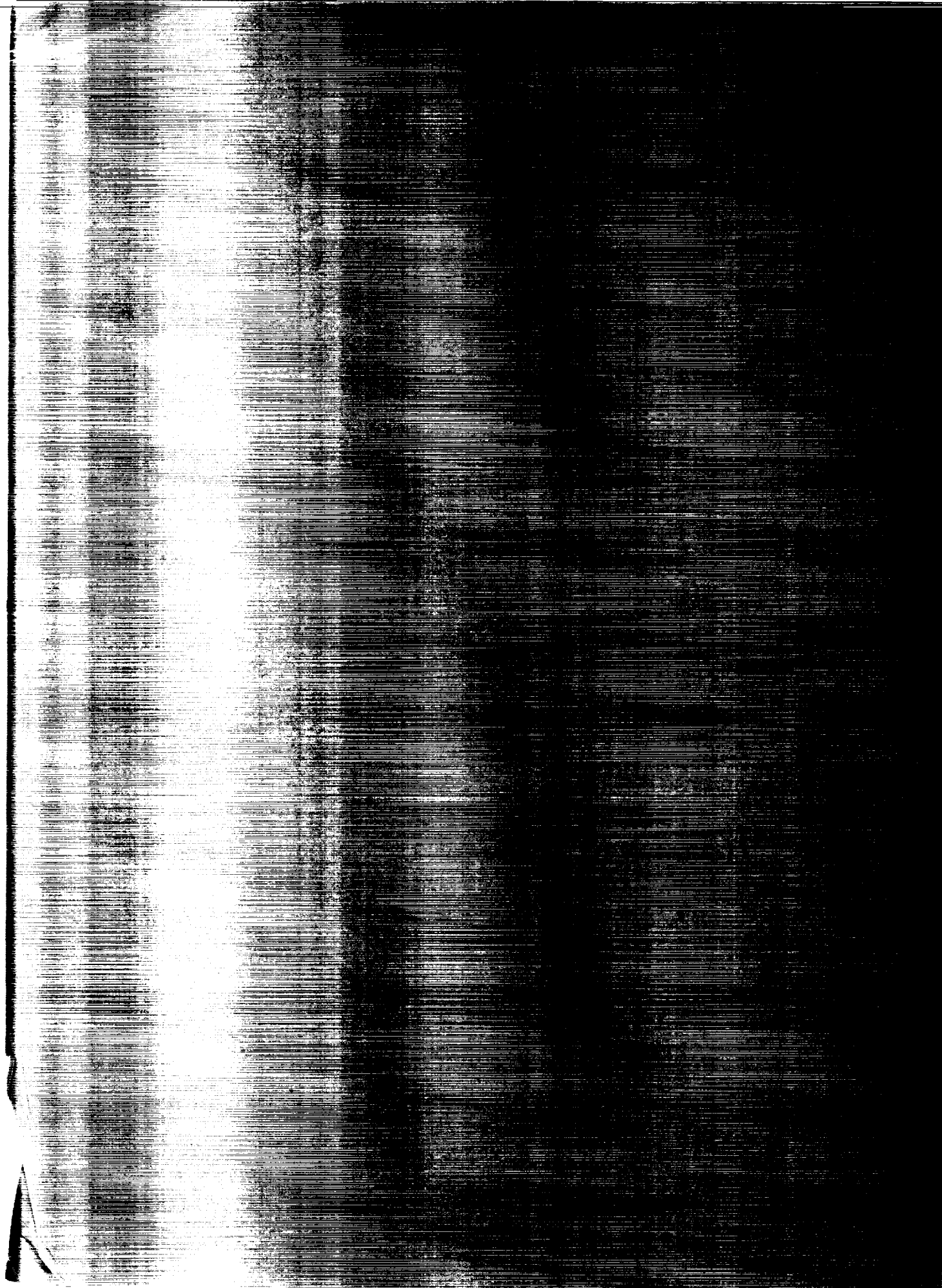
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MEMORANDUM 3-6-59E

PRELIMINARY STUDY OF A PISTON PUMP FOR CRYOGENIC FLUIDS

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SUMMARY

Preliminary data are presented covering the performance of a low-speed, five-cylinder piston pump designed for handling boiling hydrogen. This pump was designed for a flow of 55 gallons per minute at 240 rpm with a discharge pressure of 135 pounds per square inch. Tests were made using JP-4 fuel, liquid nitrogen, and liquid hydrogen. Pump delivery and endurance characteristics were satisfactory for the range of operation covered.

In connection with the foregoing pump development, the cavitation characteristics of a preliminary visual model, glass-cylinder pump and of a simple reciprocating disk were studied. Subcooling of approximately 0.6° F was obtained from the cavitation produced by reciprocating a disk in boiling nitrogen and in boiling water. The subcooling obtained in a similar manner with liquid hydrogen was somewhat less.

INTRODUCTION

In the course of a research program involving liquefied gases, a pump was required for handling liquid hydrogen at pressures up to 135 pounds per square inch gage and flows to 55 gallons per minute. A further requirement stipulated that the pump be capable of handling the boiling fluid and, for reasons of safety and control, that it be driven by a hydraulic motor.

Various types of pumps were considered for this application. The piston-type pump was finally selected because of its favorable pressure-speed characteristics, small leakage areas, low shaft speeds, and low intake velocities.

The design philosophy was to employ sufficiently low bearing loads and speeds in order to permit submerged operation of the entire pump in liquid hydrogen. Submerged operation eliminates the need for a separate pump housing and the accompanying additional heat leak to the fluid. In addition, submerged operation allows vapor to separate from the liquid before the liquid is inducted into the pump inlet.

Pump leakage areas are of particular concern when pumping liquid hydrogen because of the low viscosity involved. Pump leakage is inversely proportional to viscosity of the fluid being pumped. The viscosity of liquid hydrogen is approximately 27 percent less than that of air at room temperature and is 200 times less than that of kerosene. In the piston pump the leakage paths across the piston lie between surfaces as compared with line contact, as found in many rotary pumps. In addition, in the piston pump the circular shape of piston and cylinder provides some freedom from thermal distortion and permits a high degree of accuracy of manufacture.

Preliminary studies covered herein were made to determine the feasibility of a piston pump for handling liquid hydrogen and some preliminary test results from such a pump.

The work reported here was done in two parts. Visual studies of cavitation at various piston speeds were first made with a small model pump having a glass cylinder. In these tests the main objective was to determine by visual and photographic means the maximum piston speed as limited by cavitation. The tests also served to furnish information regarding valve operation, inertia ram, and the effects of cavitation on the fluid temperature. These tests were conducted using water, liquid nitrogen, and liquid hydrogen.

The second part of the work covers preliminary tests of a five-cylinder piston pump. These preliminary tests provide limited information on pump performance for both steady-state and transient operation and pump endurance characteristics. These tests were made using JP-4 fuel, liquid nitrogen, and liquid hydrogen.

Some preliminary data regarding volumetric efficiency and mechanical endurance have been obtained and are presented herein. This report is published prior to complete testing because of the interest shown in this type of pump for ground handling of cryogenic fluids, particularly liquid hydrogen. The work was done at the Lewis Research Center during 1957 and 1958.

APPARATUS AND METHODS

Glass-Cylinder Test Rig

Preliminary cavitation tests were conducted in liquid nitrogen and in water. In these tests a 2-inch-diameter flat disk was reciprocated in open vessels. The disk was reciprocated by a crank mechanism driven by an air motor. The disk was later replaced by a glass-cylinder pump. The use of a glass cylinder permitted visual and photographic observation of the fluid behavior within the pump. The main features of the glass-cylinder-pump test rig are shown in figures 1, 2, and 3. The glass-cylinder pump was installed in a 1-gallon glass Dewar flask which was covered with a lid of foam-type plastic.

Tests with the glass-cylinder pump were made with water, liquid nitrogen, and liquid hydrogen. In the tests with water a glass vessel was used which was heated over an electric hot plate. Heat was thus applied only at the bottom of the vessel. When using liquid hydrogen, means were provided for purging and for pressurizing the Dewar with helium. During test operations the glass Dewar flask was approximately three-fourths full of fluid.

The pump was operated while submerged, and served to circulate the pumped fluid from the pump discharge to the inlet with negligible pressure rise. The piston was reciprocated by the same crank mechanism used in the reciprocating disk tests. The plate valves in the piston and cylinder head were identical and had a ratio of port area to piston area of 0.28. The valves were held in the closed position by very light coil springs.

Instrumentation was provided for measuring fluid temperature and pressure, piston frequency, and time. Data were obtained by photographing the instruments and Dewar with a motion-picture camera. Fluid temperatures were measured with a carbon-resistor-type probe in conjunction with a d-c amplifier. This system gave a galvanometer scale deflection of approximately 2 inches per °F. Dewar pressures were measured in inches of water with an aircraft-type gage.

Five-Cylinder Piston Pump

Design specifications. - A partial section through the five-cylinder piston pump is shown in figure 4; figures 5 to 8 show views of the pump and parts. Figure 9 shows the pump installed in a vacuum-jacketed housing. In this installation the pump is driven by a hydraulic motor through gears located at the top of the housing.

Design specifications of this pump are as follows:

Bore and stroke, in.	3 × 1.5
Total displacement, cu. in.	53.03
Design speed, rpm	240
Displacement at design speed, gal/min	55.1
Design inlet conditions	Saturated liquid with zero head
Discharge pressure, lb/sq in. gage	135
Average piston speed, ft/sec	1.0
Lubrication	Entire pump submerged in pumped fluid
Total piston clearance, diametrical, in.	0.002
Operating temperature, °F	-430

The valves of this pump are similar to those of the glass-cylinder pump, and the piston stroke is the same.

Mechanical Details

The five pistons of this pump are driven by a wobbler - Z-crank mechanism in which the torque reaction on the wobbler is taken by a ball-bearing roller which oscillates in a hardened steel guide.

No attempt was made to balance the pump mechanism because the design speed was low enough to avoid unbalanced forces of noticeable magnitude.

Commercial ball bearings of nonstainless-steel material were used throughout the pump. Corrosion was prevented by spraying the surfaces with a very thin coat of light penetrating oil. The ball portion of the commercial ball joints used on the ends of the connecting rods was fabricated of chrome-plated AISI-440 steel. The outer member was fabricated of AISI-303 steel.

Piston rings were fabricated of Teflon compounded with a glass-fiber filler and were forced to the cylinder wall with stainless-steel inner rings.

The parts of the pump subject to wear were hardened to Rockwell C of approximately 58. The cylinders, pistons, cylinder heads, pins, piston ball joints, and crankshaft were fabricated of AISI-304 stainless steel with commercial nitriding on wearing surfaces. The wobbler, valve plates, and frame were also fabricated of AISI-304 steel; the discharge cover is made of AISI-347. The torque reaction guide is of AISI-440-C hardened to Rockwell C 58.

Thermal distortion was minimized by use of materials having similar thermal expansion characteristics. Welding and brazing were avoided in all parts involving critical clearances.

Pump Test Rigs

JP-4 tests. - Initial tests were made using JP-4 fuel with the pump assembled with the housing shown in figure 9. Conventional instrumentation was provided for determining flow, pressures, and temperatures.

Cryogenic tests. - When using cryogenic fluids, it was very difficult to properly vent the housing in order to maintain the required control of the height of the liquid level above the pump cylinders. Because of the difficulty of controlling liquid level by venting the pump housing, the tests with cryogenic fluids were made with the pump submerged in a large tank.

Figure 10 shows a diagrammatic piping layout of the pump cryogenic test rig. The tank was constructed of stainless steel insulated with 2 inches of polystyrene foam-type plastic insulation encased in a shell of resin-impregnated fiberglass. This tank has a capacity of 443 gallons and is designed to withstand an internal pressure of 50 pounds per square inch. The pump was flange-mounted in a sump at the bottom of the tank. In this installation the pump was driven by a shaft extending through the tank and coupled to a hydraulic motor installed on the top of the tank. The drive shaft was sealed at the top of the tank with a double seal arrangement in which the space between seals was pressurized with helium.

The tank was vented to atmosphere through a relief valve. Liquid level was measured with a capacitor-type instrument. Fluid flow measurements were computed from changes in liquid level. Tank and pump delivery pressures were measured with Bourdon tube gages. Fluid temperatures were measured with carbon-resistor probes. Pump shaft speed was measured with an electronic-type counter.

Prior and subsequent to charging with liquid hydrogen, the tank and piping systems were purged with helium.

A variable displacement, electric-motor-driven pump supplied hydraulic fluid to the hydraulic motor. Basic control of the discharge pressure of the test pump was made by adjusting the hydraulic-supply-system pressure by means of a pressure regulator. Thus, for every hydraulic-supply pressure there was a corresponding pressure rise across the test pump (except for the effects of test-pump friction). This system basically provides constant pressure with variable flow and requires no bypass. It was possible to maintain a preselected discharge pressure with the shutoff valve closed.

RESULTS AND DISCUSSION

Visual Studies of Subcooling by Cavitation

With a Reciprocating Disk

Initial tests were made to determine the cavitation characteristics at the design piston speed. These tests were made by reciprocating a 2-inch-diameter disk in an open vessel. Because this work revealed a phenomenon of subcooling by cavitation which might have an effect on pump performance, these tests will be described first.

In these experiments a fluid such as liquid nitrogen was first brought to the boiling state in an open vessel. A disk was then reciprocated in this boiling liquid sufficiently fast to cause cavitation. This operation caused the fluid temperature in the Dewar flask to fall. The phenomenon is apparently caused by cavitation created by the low pressure regions accompanying the disk motion. During cavitation the heat of vaporization required to produce the gas bubbles is removed from the residual fluid. The gas bubbles from cavitation rise through the liquid to the gas above the liquid and the liquid is subcooled. The process is one of cooling by evaporation through reduction of pressure. It should be noted that a small amount of subcooling is equivalent to a large amount of effective head. Due to the relation between temperature and vapor pressure in hydrogen, subcooling of 0.1°R is approximately equivalent to a head of 110 inches of liquid hydrogen or 5 inches of liquid nitrogen.

Typical subcooling results obtained by cavitation of liquid nitrogen are shown in figure 11. The results with boiling water were similar. A reduced amount of subcooling was obtained, however, with liquid hydrogen. The comparative results obtained with hydrogen and nitrogen, however, may have been partially obscured by the increased heat leak into the vessel during the tests with liquid hydrogen.

Attempts to increase the amount of subcooling over that shown in figure 11 by increasing the disk frequency were unsuccessful. In addition, various mechanical stirring and agitating devices were used in an attempt to increase the subcooling over that obtained with the simple disk; practically no improvement, however, was obtained with the devices tested.

Subcooling by cavitation, as described previously, may prove of significance in the operation of a submerged bucket-type piston pump inasmuch as cavitation is produced on the suction side of the piston and a substantial proportion of the cavitation bubbles are dispersed in the tank without entering the pump.

Visual Studies with Glass-Cylinder Pump

Piston speed limited by cavitation. - The reduction in pressure during the inlet or suction stroke of a piston pump handling boiling fluids may generate vapor which by displacement reduces the amount of liquid inducted and, as a result, the volumetric efficiency. The pressure reduction at the intake is a function of piston speed. In order to determine a suitable piston speed for the pump design, information was desired regarding the cavitation associated with various piston speeds as a function of inlet pressure. Tests were made in the glass-cylinder pump rig in which liquid nitrogen or liquid hydrogen was brought to the boiling point at atmospheric pressure and the pump was brought up to a preselected speed. This procedure produced violent cavitation throughout the fluid in the glass Dewar vessel. Because of the low delivery pressure, in the glass-cylinder test apparatus, the cavitation bubbles generally persisted throughout the cycle into the pump discharge. The pressure in the vessel was then raised until the cavitation bubbles disappeared. Portions of motion-picture film comparing the pump operation in liquid nitrogen under cavitating and noncavitating conditions are presented in figure 12. The pump speed and the Dewar pressure in inches of water above atmospheric are shown on the gages appearing in each photograph. The sequences begin at the top of figure 12 and show one complete pump stroke. It can be seen from the films that a net positive suction head of 10 inches of water (12.1 in. of liquid nitrogen) is sufficient to eliminate cavitation.

Figure 13 shows the increase in Dewar pressure required to reduce the cavitation obtained at saturation conditions at the initial temperature and pressure to incipient cavitation. Although these curves indicate that a greater pressure is required to suppress cavitation in hydrogen than in nitrogen, a direct comparison of the data does not consider the effect of additional heat leak in tests with liquid hydrogen.

In the foregoing experiments the collapse or creation of cavitation bubbles appeared to follow pressure changes very rapidly in terms of the period of the pumping cycle.

In practice it may be necessary to accept some cavitation if maximum pump capacity is to be obtained. However, in the performance of a pump, a point of maximum capacity will be reached beyond which any further increase in piston speed will be offset by lowered volumetric efficiency resulting from cavitation. Consequently, from a design standpoint it is desirable to know the volume of gas produced by cavitation. This information was not directly obtainable from the glass-cylinder tests. A rough idea of the maximum possible cavitation volume (volume of gas resulting from cavitation) was obtained, however, through calculations based on the assumption that the local pressure in the region of the cavitation bubbles may be determined from the experimentally derived

increase in pressure (see fig. 13) required to suppress cavitation. On this basis it was possible to approximate the volume of gas in the fluid by knowing its quality. The fluid quality was calculated using the T-S diagram for the test fluid. In the calculations saturated liquid was taken as the initial condition. By reducing the pressure an amount equal to that shown in figure 13 and by assuming a constant enthalpy process in the liquid-vapor phase of the diagram, a value of quality was obtained. The volume of gas resulting from cavitation at the pump intake was assumed to remain constant throughout the entire piston stroke and the piston speed was assumed to be constant at the maximum instantaneous (mid-stroke) value. Figure 14 then indicates a minimum volumetric efficiency for hydrogen that would result if piston speed were constant throughout the stroke at midstroke velocity and if the low pressure, which produces cavitation, extended throughout the cylinder volume. It is apparent that these assumptions are pessimistic and that the pump volumetric efficiency should be considerably better than indicated by figure 14.

In general, the estimated cavitation volume (fig. 14) based on tests with the glass-cylinder pump indicated that the loss of capacity resulting from cavitation at piston speeds of less than 1 foot per second under saturation conditions at the pump inlet would be acceptable. In the most pessimistic case (fig. 14) this loss would amount to about 15 percent.

Valve operation. - The inlet valve was operated by a combination of inertia, fluid pressure, and spring forces. In order to avoid excessive pressure drop, the spring force was just sufficient to close the valve plate under static conditions. At the beginning of the inlet stroke the inertia of the valve plate serves to open the valve port as the piston is accelerated. After midstroke, the piston decelerates and the valve plate tends to continue at midstroke velocity. Under these conditions alone, the valve would close before the piston reaches the end of the stroke, and a loss in capacity would result. In this respect the design philosophy was to rely on the inertia ram of the incoming fluid to hold the valve open during the latter part of the stroke. Figure 15 shows that such was the case and that the observed intake-valve operation was satisfactory, however, a more rapid closure of the discharge valve is required. A stronger discharge valve spring is indicated.

Pressure drop during the charging process. - The pressure reduction in the cylinder during the suction stroke of the conventional plunger-type pump is caused by the force required to accelerate the fluid column as well as that required to move the fluid through the inlet valve. This process differs from that of the bucket-type pump (reported herein) because in the latter the fluid acceleration process is accomplished during the discharge stroke. The only force required during the suction stroke is that required to move the fluid through the inlet valve. Thus, for comparable valve areas the pressure reduction in the cylinder of the bucket-type pump will be less.

In the bucket-type pump the fluid is essentially at rest in the cylinder during the suction stroke and the piston merely moves through the fluid. Any velocity change in the fluid is caused by the difference in flow area of the cylinder section and that of the inlet valve. During the suction stroke the pressure in the cylinder is thus determined by the pressure drop across the inlet valve alone.

Intake ram in a bucket-type pump. - During the discharge stroke of a bucket-type pump, the piston movement causes a column of fluid to follow the inlet side of the piston. This general flow toward the piston tends to persist after the discharge stroke and into the suction stroke. Whether the wave motion toward the piston persists long enough to effectively charge the cylinder is, of course, a function of the frequency of the wave motion with respect to the frequency of the pumping cycle. It is apparent that this inertia ram can also be detrimental to charging if out of phase with the filling stroke.

The natural frequency of the wave motion accompanying the charging process is a function of vessel size, depth of liquid, and so forth. For the conditions of these experiments and within the limits of observation it appeared that inertia ram was substantially in phase with the suction stroke.

Pump Performance

The performance characteristics of a displacement pump will be satisfactory if the volumetric and mechanical efficiencies are reasonably high. Cavitation, slip losses, pressure development, and power required are all reflected in these efficiencies.

Volumetric efficiency. - Figure 16 shows the approximate volumetric efficiencies obtained while pumping JP-4 fuel, liquid nitrogen, and liquid hydrogen. The volumetric efficiency was above 80 percent for all of the liquids pumped. There were no distinguishable differences in the efficiencies with the different fluids.

Both cavitation and leakage or slip losses act to reduce volumetric efficiency. Slip losses at a given delivery pressure were obtained in an approximate manner by closing the pump discharge and measuring the speed of rotation. With JP-4 fuel the slip speed was 0.052 rpm at a delivery pressure of 70 pounds per square inch. The slip loss with any of the cryogenic fluids was less than 2 rpm. This method of determining slip with cryogenic fluids is probably very approximate because of the amount of gas in the pump during stalled operation.

Pressure developed at vapor-lock conditions. - The maximum pressure developed by a vapor-locked piston pump is the pressure developed by the

pump acting as a gas compressor. The maximum pressure developed by a piston-type compressor occurs, of course, when the expanded volume of gas from the clearance volume equals the displacement volume. As long as the pressure developed by a liquid pump while pumping a gas is higher than the required delivery pressure, the pump will not vapor-lock completely.

In these tests the maximum pressure rise across the pump when pumping hydrogen gas was approximately 40 pounds per square inch. Higher pressures as limited by vapor-lock can, of course, be obtained by decreasing piston clearance volume; however, in order to achieve simplicity of construction, little effort was made to obtain a minimum clearance volume. There is no indication that complete breakdown of pumping was imminent with any of the fluids tested. While pumping liquid hydrogen, the pump was stopped repeatedly by closing the outlet shutoff valve. Because of heat leak into the system, this procedure caused the cryogenic fluids to vaporize and fill the pump with gas. No difficulty or delay was experienced in resuming normal pumping operation after such stops.

Intake head requirements. - Within the accuracy of the measurements, there was no observable effect on pump performance of variation in fluid head while pumping liquids at saturated conditions. On several occasions the tank of liquid hydrogen at saturated conditions was pumped dry. During these tests the pump speed and delivery pressure remained practically constant as head was reduced.

Pressure fluctuations. - During the tests with cryogenic fluids the pump was operated without a surge chamber in the discharge line. In general, the entrained gas in the cryogenic fluids smoothed out the pressure fluctuations and made the pump less harsh and less noisy than with JP-4 fuel. In this respect, hydrogen was superior to nitrogen. Pressure fluctuations decreased as volume of gas in the fluid increased.

Flow fluctuations. - The use of a ball-bearing roller oscillating in a hardened steel guide to restrain the wobbler causes a somewhat non-uniform cylinder-to-cylinder variation of cylinder delivery as shown in figure 17. The data for figure 17 were taken from field measurements and include the effects of bearing clearances. A uniform variation of displacement can be obtained by restraining the wobbler with gears or with a constant-velocity-type universal joint. However, the advantages did not compensate for the additional complications of these constructions.

Transient performance. - For some applications considerable interest is attached to the response of a pumping system to sudden changes in demand. A number of tests were made to demonstrate pump response while suddenly opening and closing the discharge throttle. These tests showed that pump discharge pressure followed hydraulic pressure closely and that the pump responded almost immediately to discharge-valve opening position.

Rapid response to flow and pressure requirements was obtained with little instability. The overshoot in discharge pressure upon suddenly closing the discharge valve was roughly 50 percent of the initial discharge pressure.

Pump wear. - After $4\frac{1}{2}$ hours of operation with JP-4 fuel, 1 hour with nitrogen, and approximately $13\frac{1}{4}$ hours with hydrogen the wear of bearings, pistons, and rings was found insignificant. Tool marks were yet visible on piston ring surfaces. There was no evidence of scuffing or of distortion of parts.

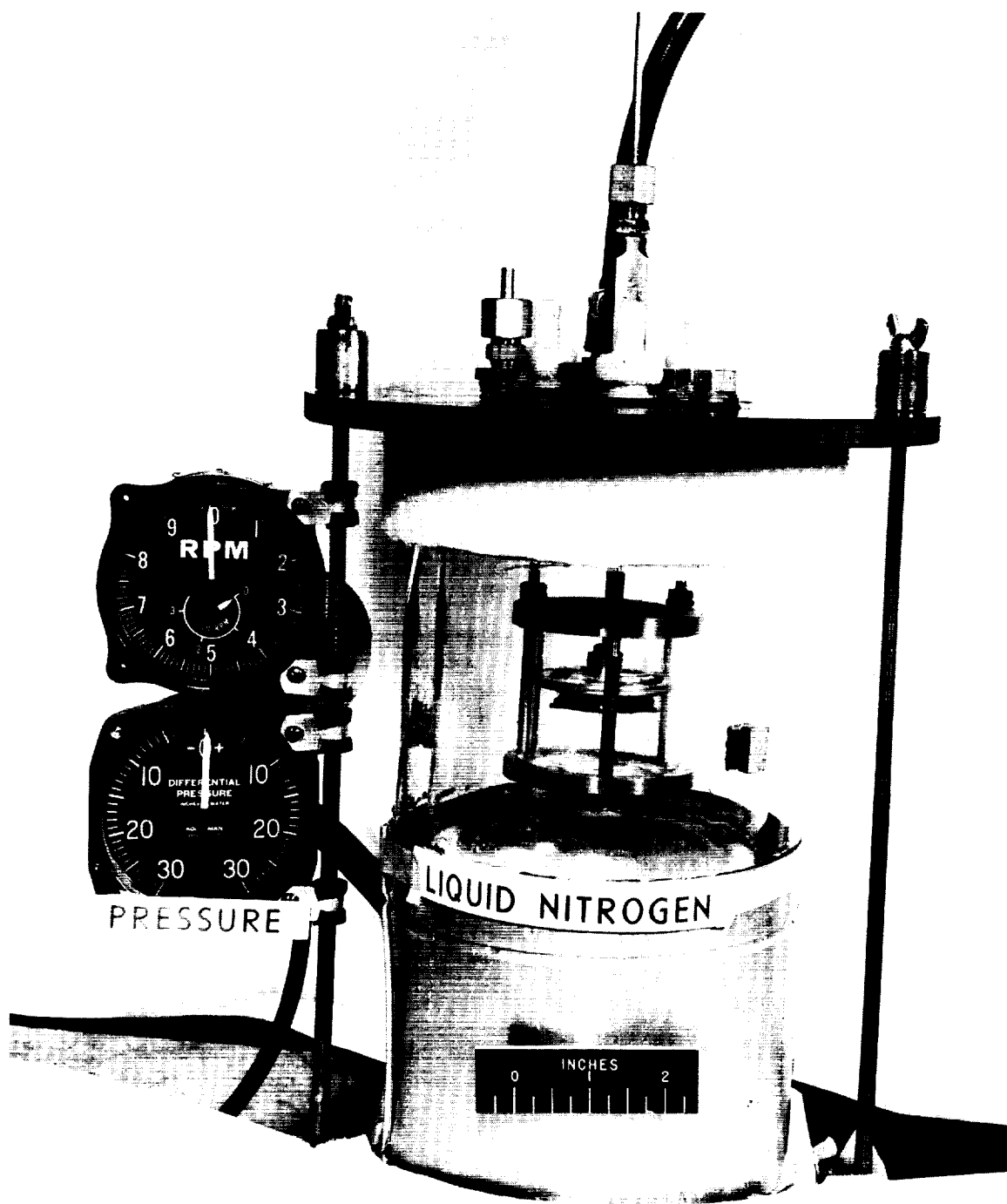
CONCLUDING REMARKS

On the basis of preliminary tests of a five-cylinder, piston-type liquid-hydrogen pump, the following concluding remarks are submitted:

1. Subcooling of approximately 0.6° F was obtained from the cavitation produced by reciprocating a disk in boiling nitrogen and boiling water. The subcooling obtained in a similar manner with hydrogen was less.
2. The collapse or creation of cavitation bubbles appeared to follow pressure changes very rapidly in terms of the period of the pumping cycle. In this respect, there were no discernible differences in the liquids tested.
3. Satisfactory pumping, under boiling conditions, was obtained with all fluids tested. No observable difference in pump performance was noticed between liquid nitrogen and liquid hydrogen.
4. The timing and operation of the pump inlet valve appeared satisfactory; the discharge valves were late in closing.
5. The pump and hydraulic drive responded almost immediately to flow and pressure requirements with little instability.
6. The mechanical functioning of the pump was satisfactory. The wear of bearings and piston was insignificant after approximately 13 hours of operation in liquid hydrogen.

Lewis Research Center

National Aeronautics and Space Administration
Cleveland, Ohio, December 15, 1958

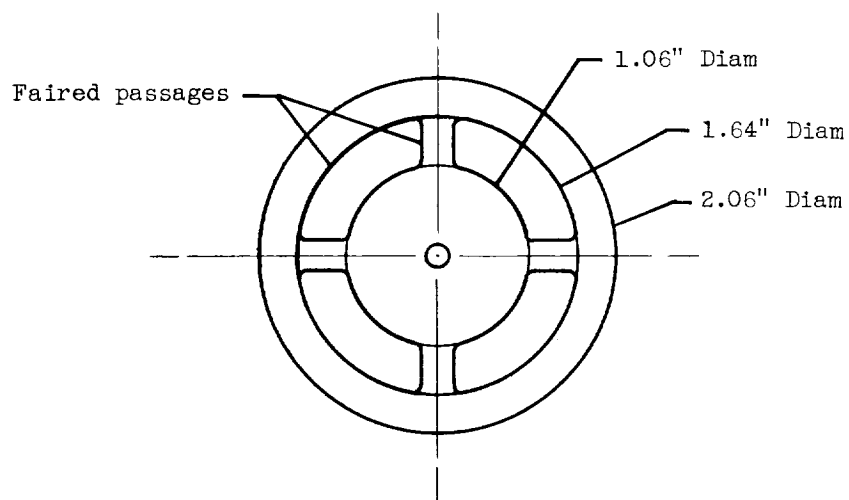
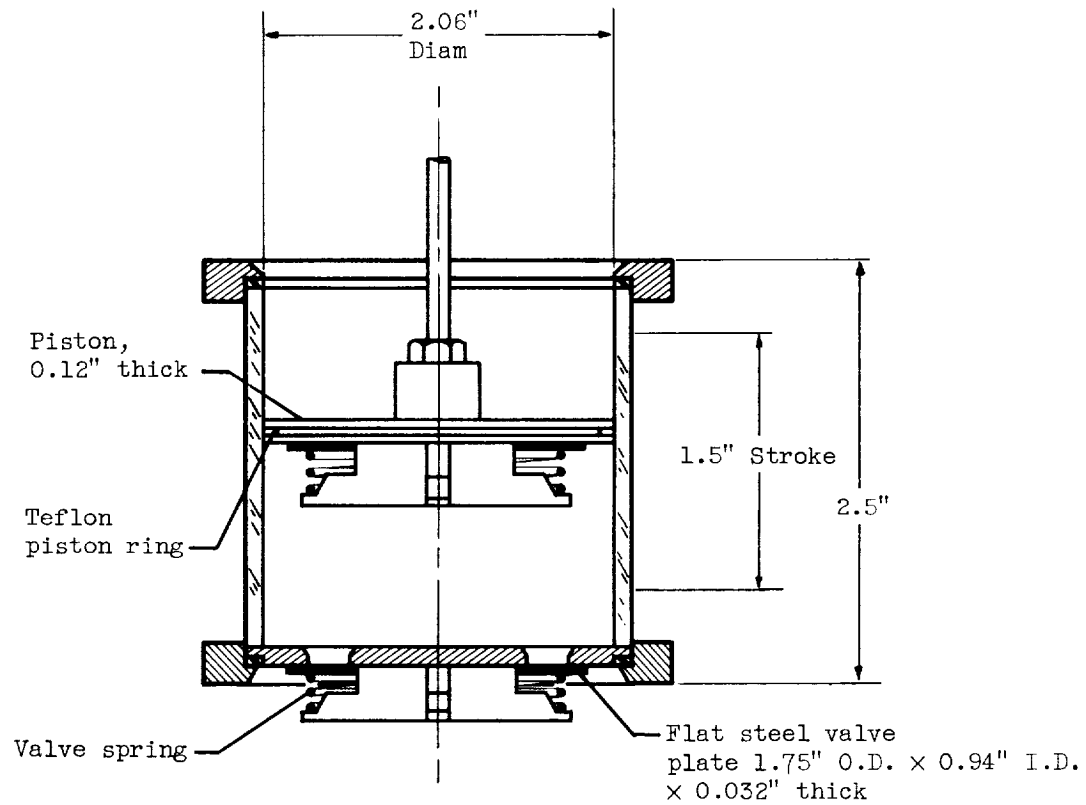


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Figure 1. - Glass-cylinder pump installed in a glass Dewar vessel.



Figure 2. - Glass-cylinder pump setup for liquid hydrogen.



Valve seat for inlet
in piston and discharge
in cylinder head

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Figure 3. - Diagrammatic sketch showing principle dimensions of the glass-cylinder pump.

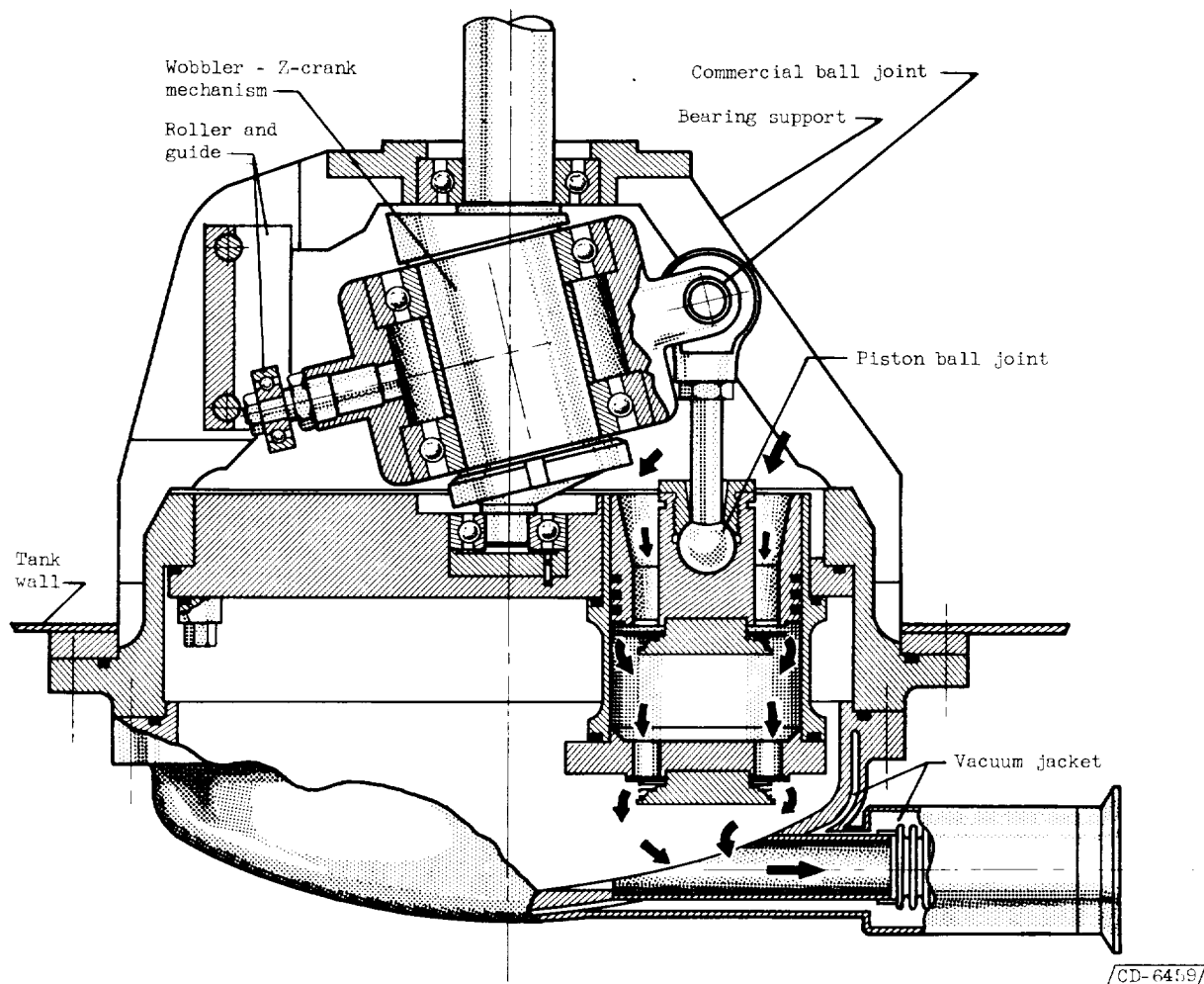
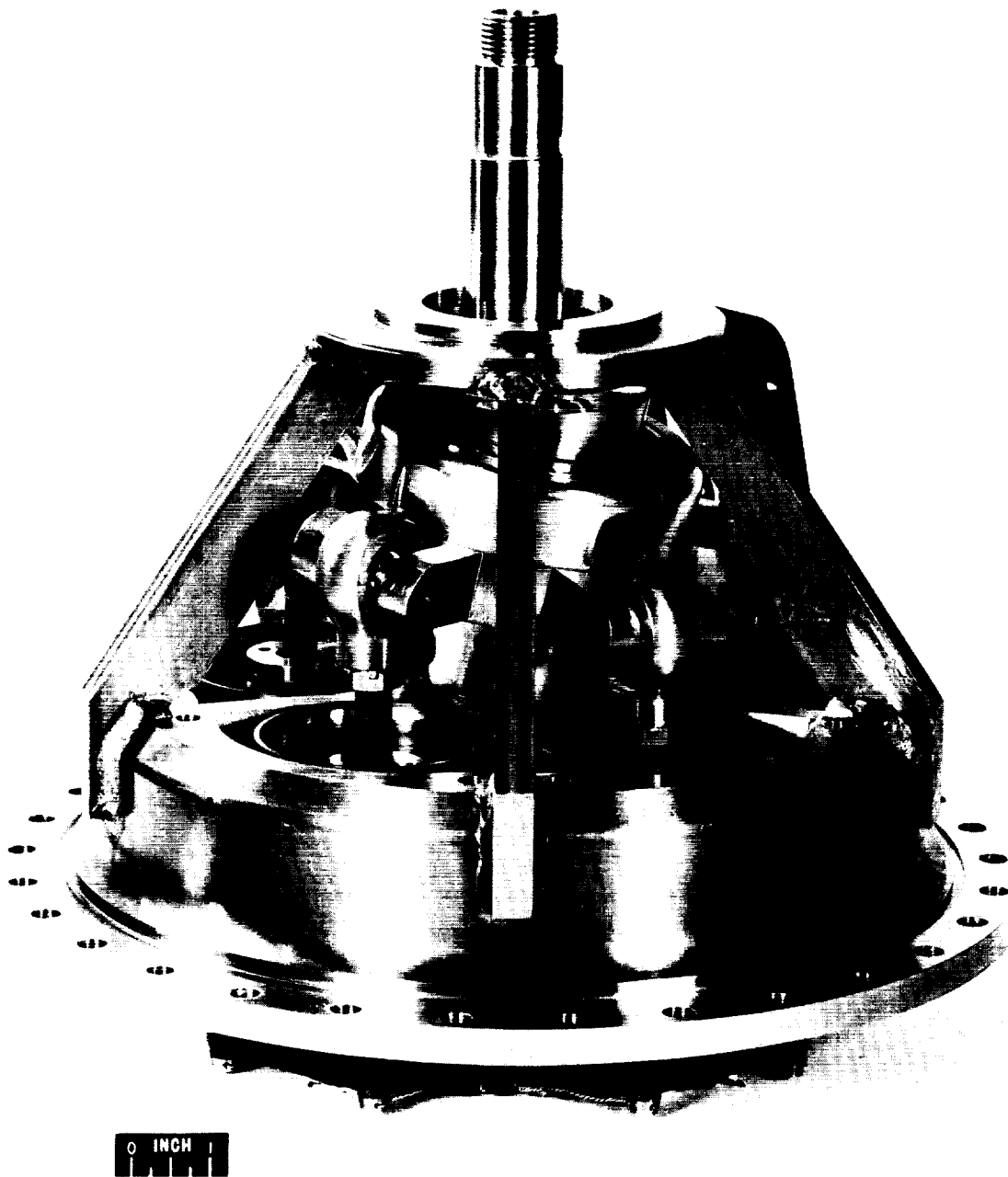
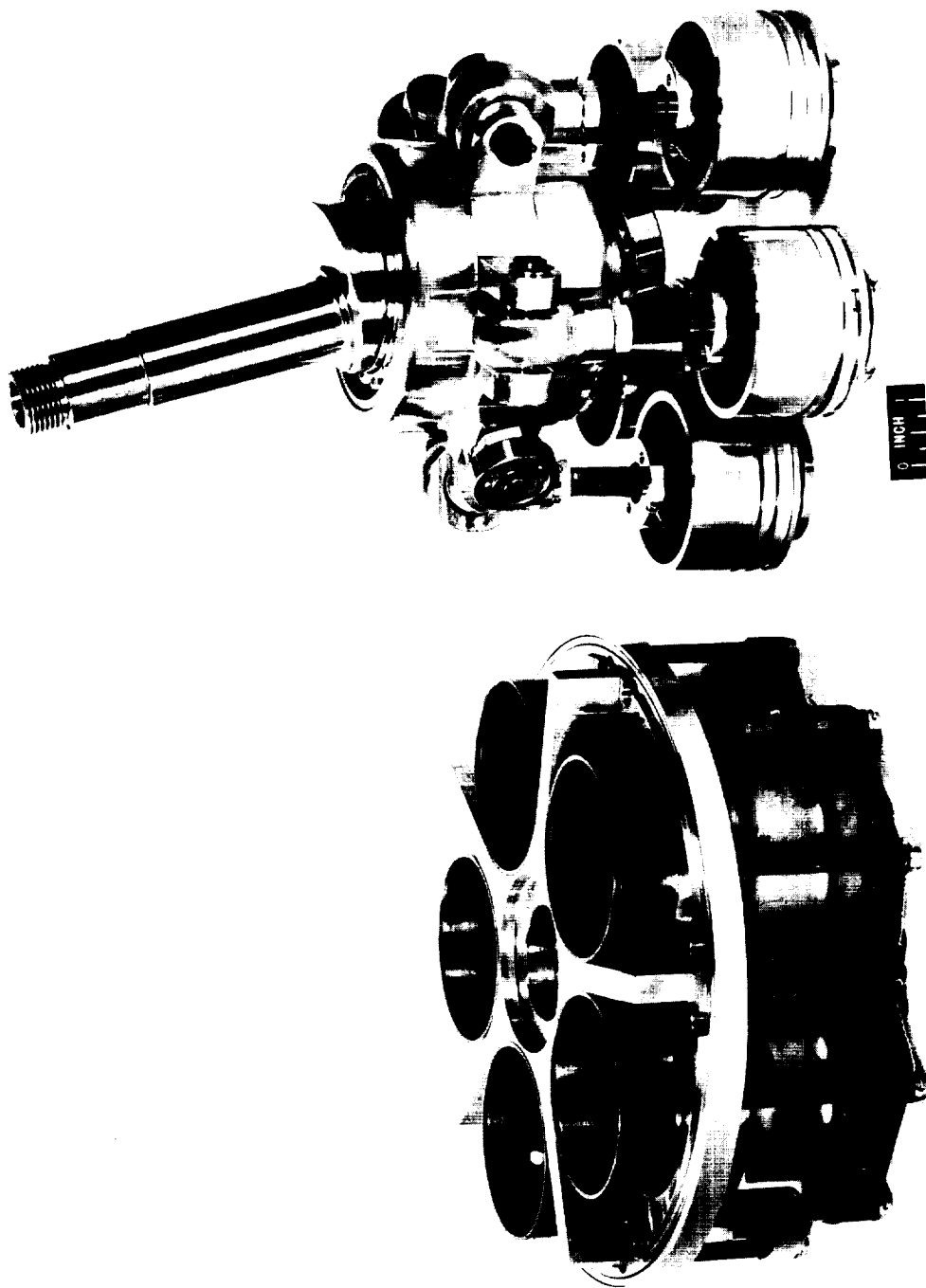


Figure 4. - Section through five-cylinder pump as constructed for flange mounting in the bottom of a tank.



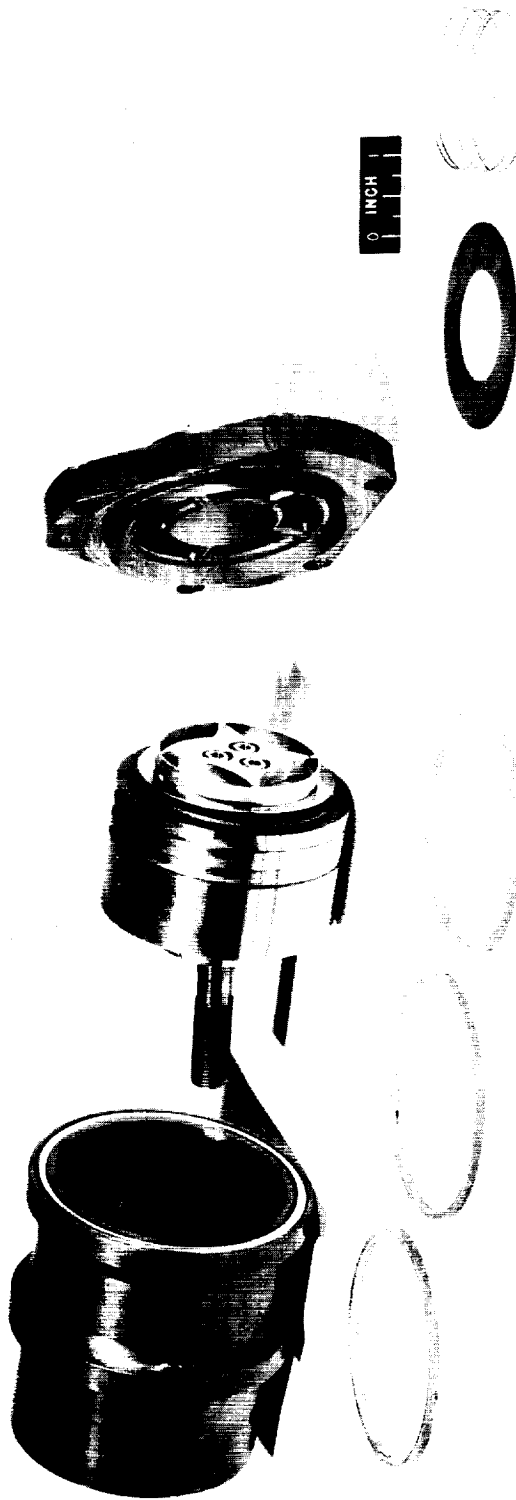
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Figure 5. - Pump assembly with discharge cover removed as constructed for submerged operation in the bottom of a tank.



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Figure 6. - Cylinder and piston assemblies.



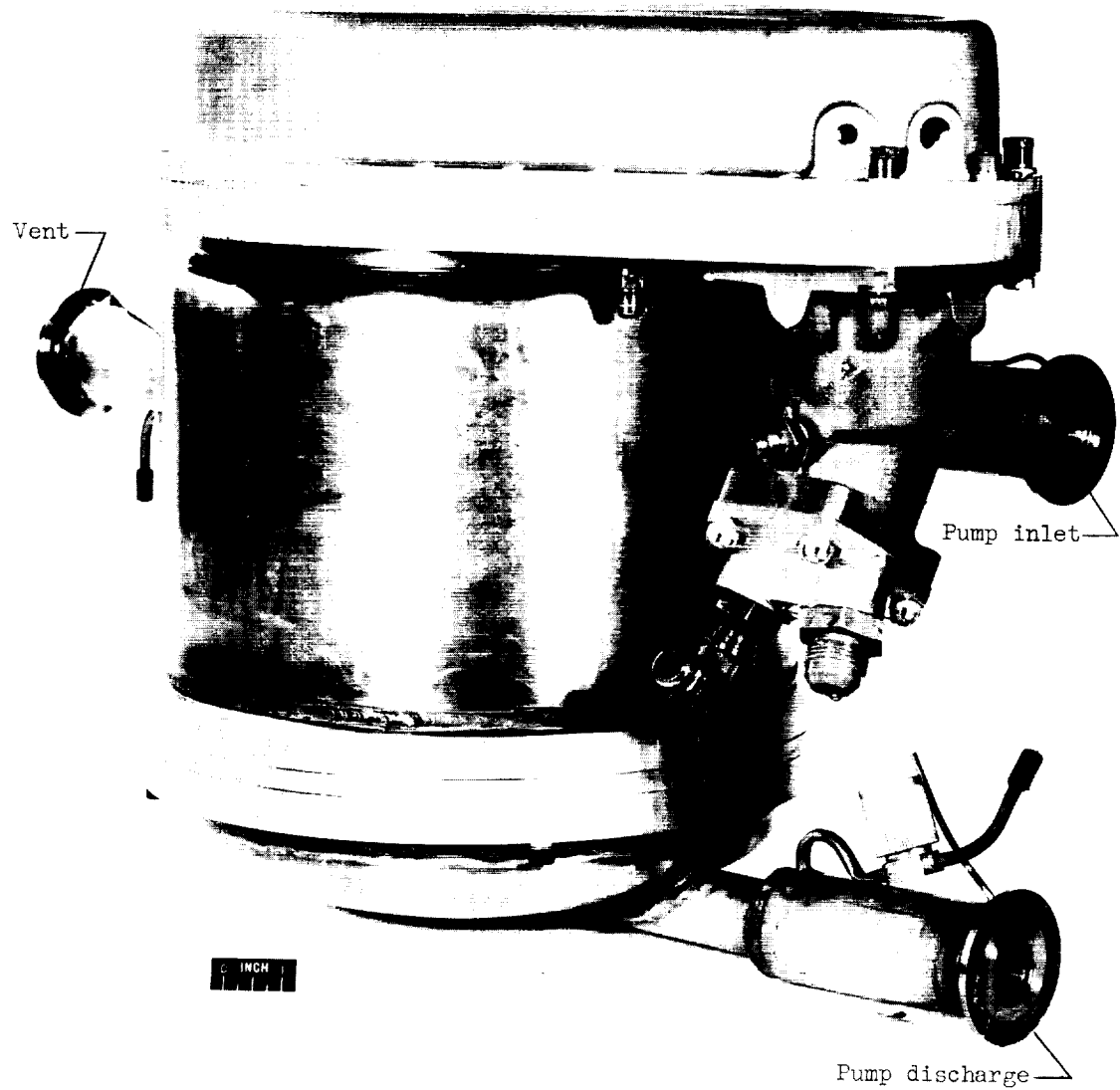
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Figure 7. - Cylinder and piston parts.



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Figure 8. - View showing discharge valves at bottom of cylinder assembly.



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Figure 9. - Pump installed in a vacuum jacketed housing with hydraulic motor drive through a gear train.

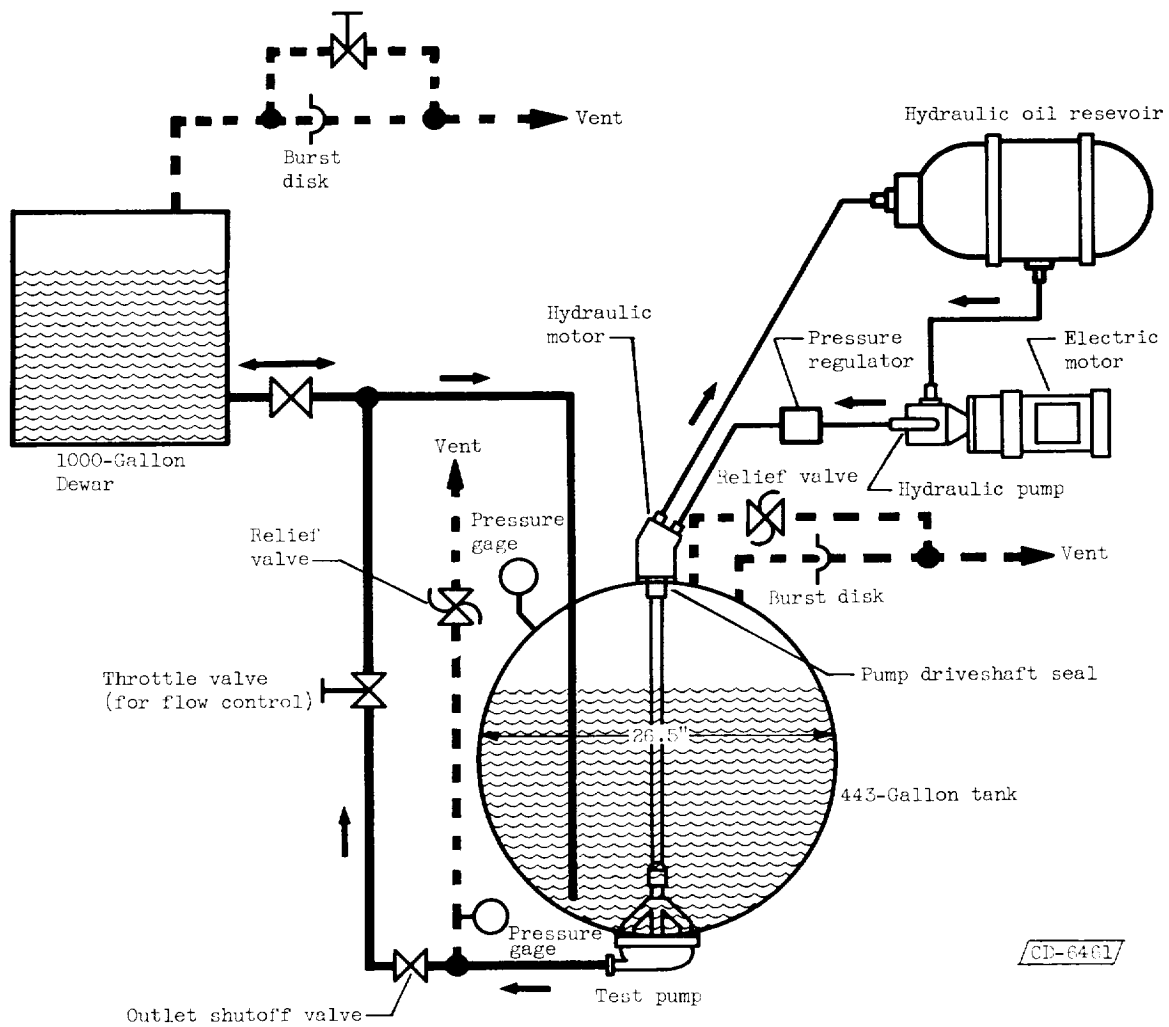


Figure 10. - Schematic diagram of pump test rig for cryogenic fluids.

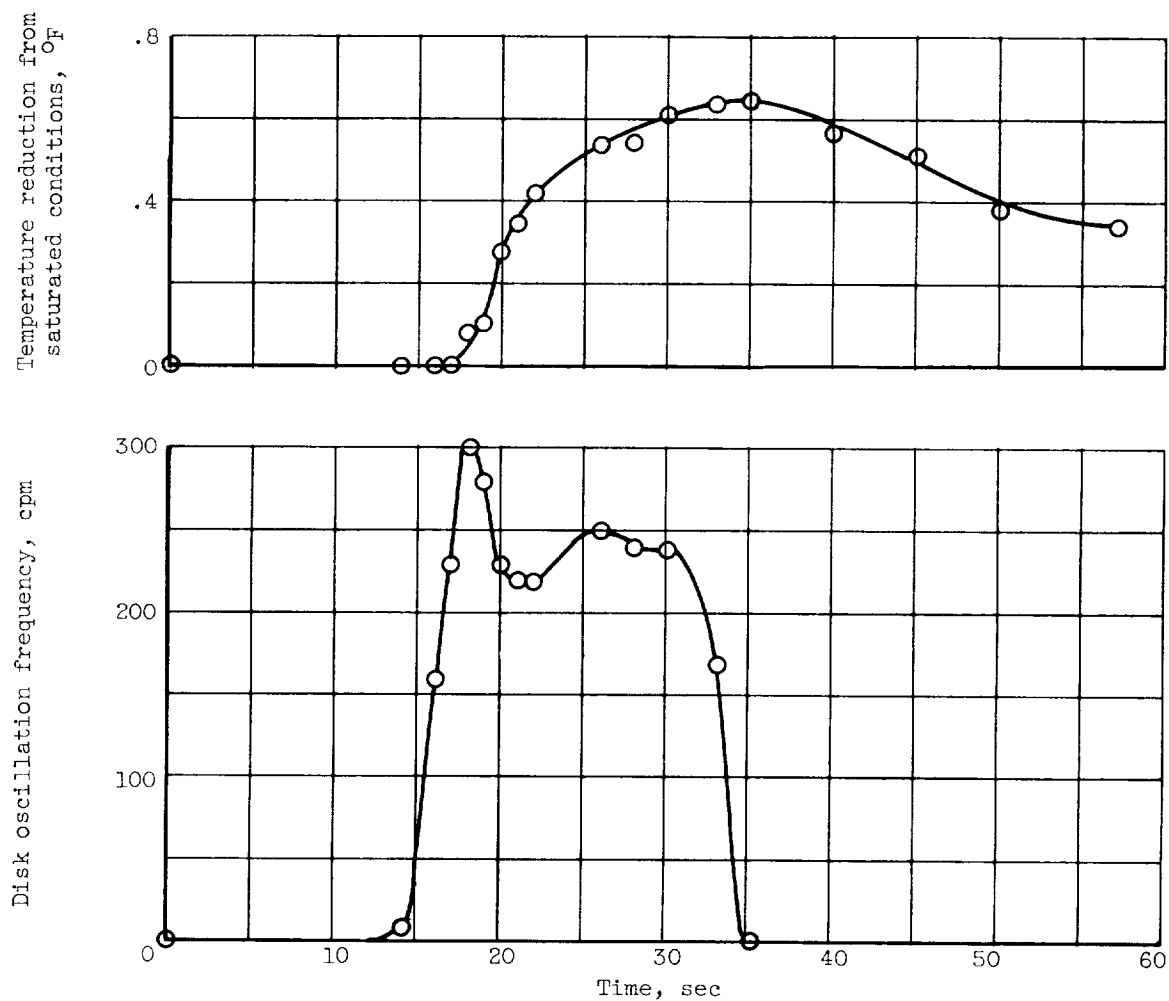


Figure 11. - Subcooling of liquid nitrogen by cavitation from a 2-inch-diameter reciprocating disk.

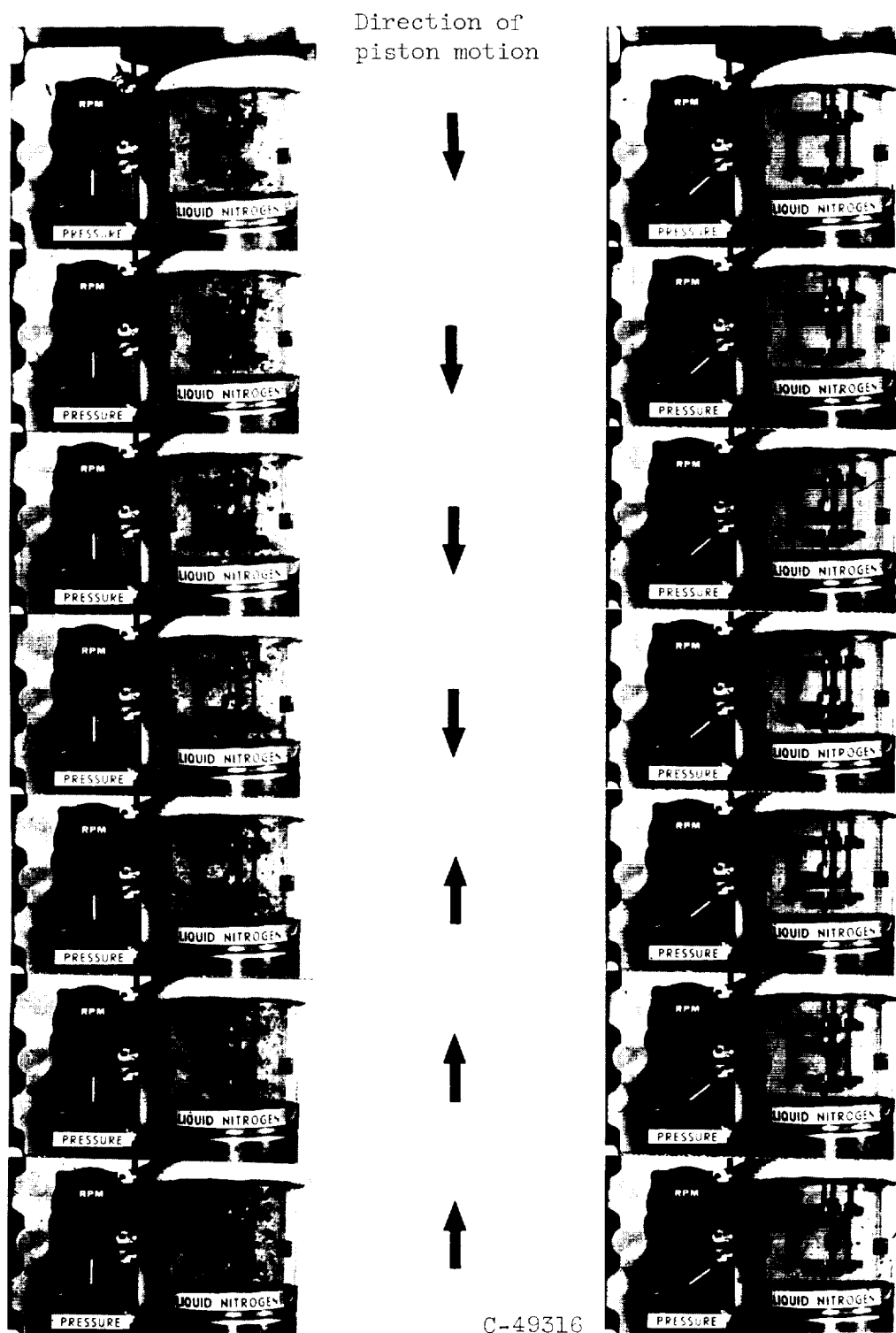


Figure 12. - Picture sequences showing one pump cycle in liquid nitrogen cavitating and noncavitating conditions; cavitation shown in left column was eliminated, as shown in right column by raising the Dewar pressure to approximately 10 inches of water.

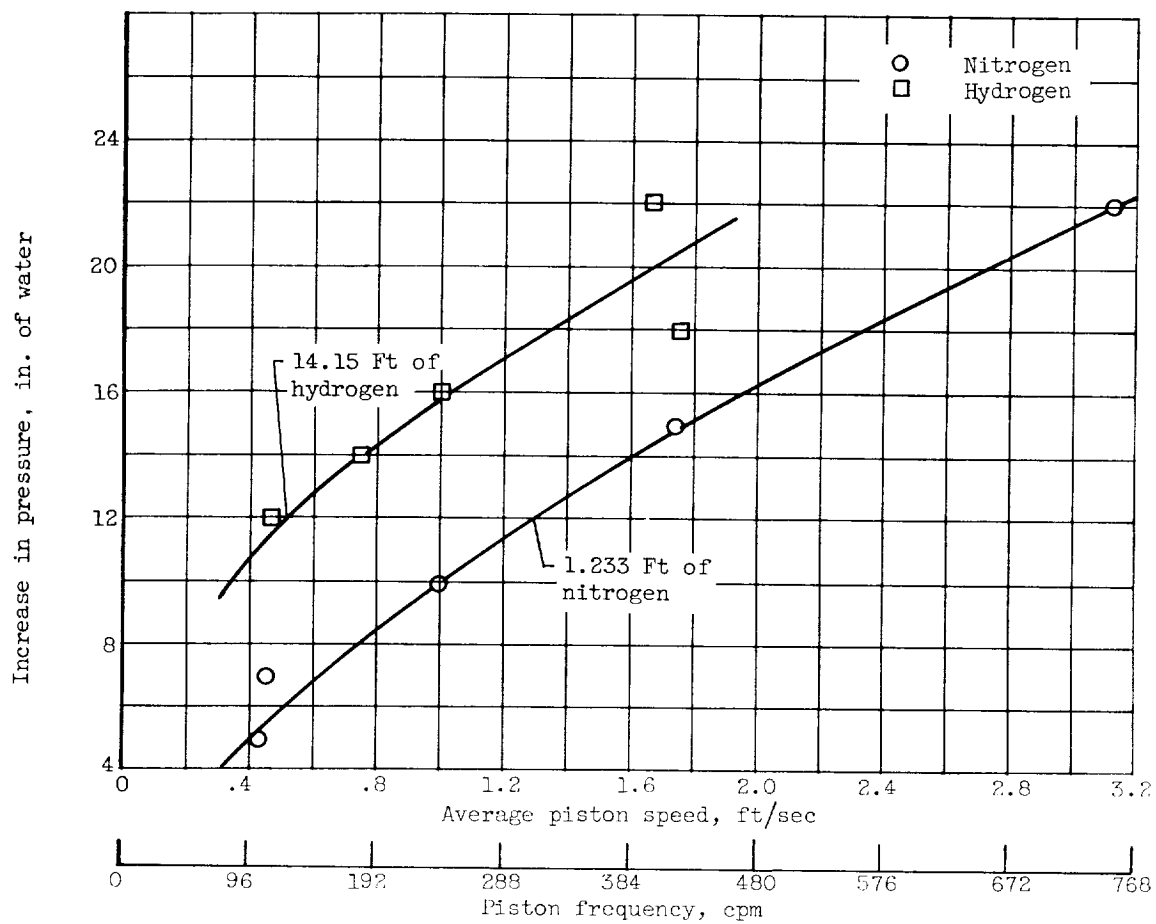


Figure 13. - Increase in pressure required to reduce cavitation obtained at boiling conditions to incipient cavitation.

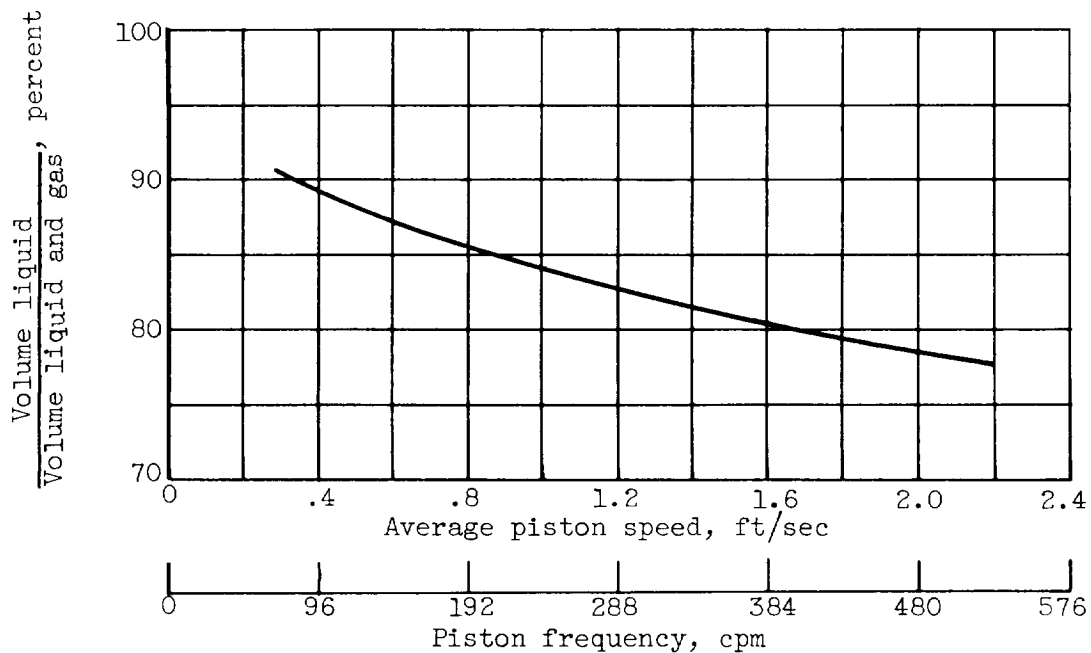


Figure 14. - Estimated cavitation volume from glass-cylinder cavitation tests with hydrogen.

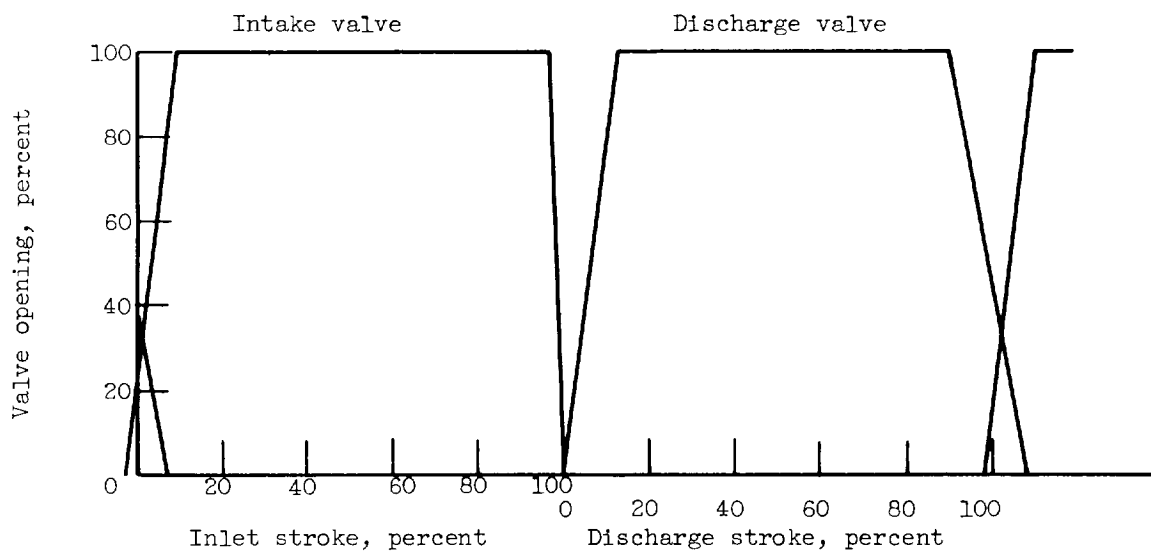


Figure 15. - Observed operation of valves at 240 rpm with negligible pressure rise across the pump.

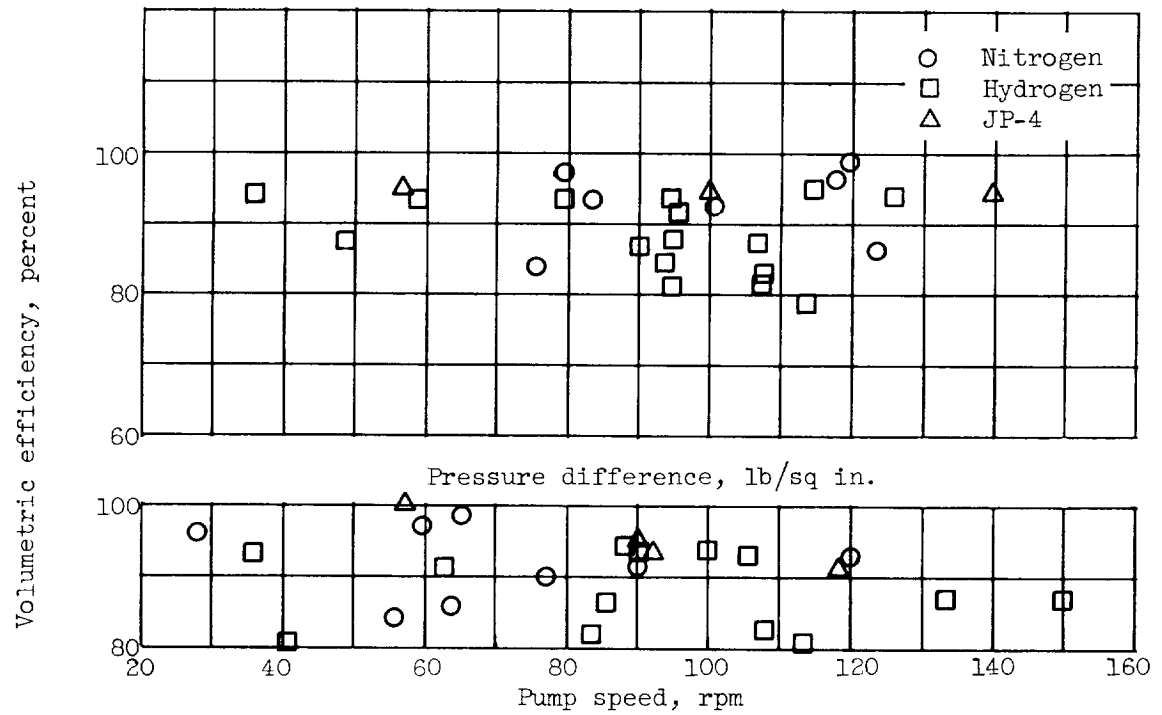


Figure 16. - Volumetric efficiency of the piston pump. Hydrogen and nitrogen pumped as boiling liquid.

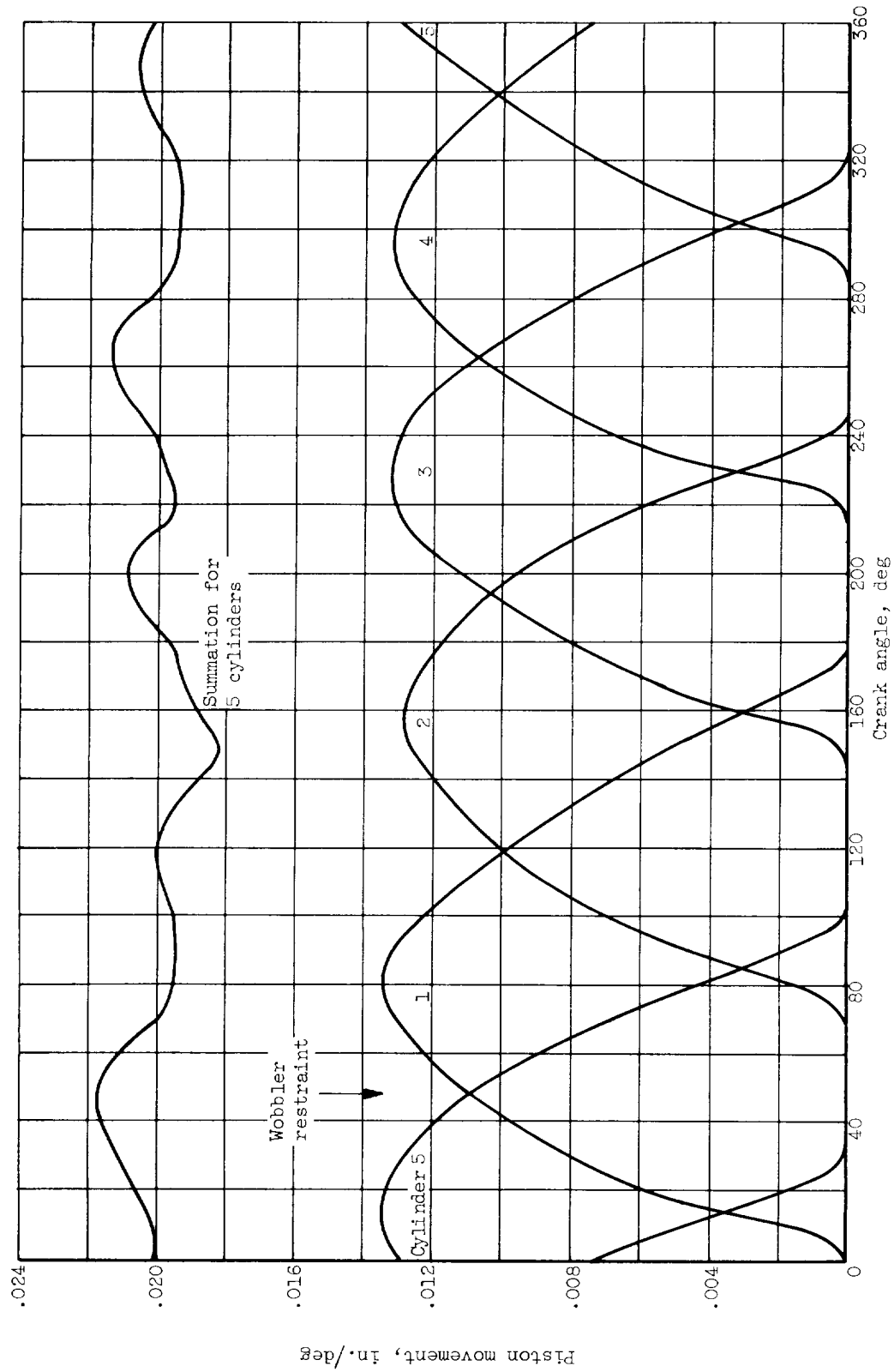


Figure 17. - Variation of piston movement with angle of rotation.

<p>NASA MEMO 3-6-59E National Aeronautics and Space Administration. PRELIMINARY STUDY OF A PISTON PUMP FOR CRYOGENIC FLUIDS. Arnold E. Biermann and Robert C. Kohl. March 1959. 27p. diags., photos. (NASA MEMORANDUM 3-6-59E)</p> <p>Preliminary performance data are presented for a low-speed, five-cylinder piston pump designed to handle boiling hydrogen. The pump is designed to deliver 55 gallons per minute at a discharge pressure of 135 pounds per square inch. The design pump speed is 240 rpm. The report also describes associated cavitation experiments in which liquid nitrogen and water were subcooled as much as 0.6° F by reciprocating a disk in an open vessel containing the test fluids. This method produced a lesser amount of subcooling with liquid hydrogen.</p>	<ol style="list-style-type: none"> 1. Cylinder and Piston Mechanisms (3.8.2.2) 2. Accessories and Accessory Functions (3.12) 3. Fuel Systems (3.12.1) 4. Research Equipment and Techniques (9) <ol style="list-style-type: none"> I. Biermann, Arnold Ernest II. Kohl, Robert C. III. NASA MEMO 3-6-59E 	<p>NASA MEMO 3-6-59E National Aeronautics and Space Administration. PRELIMINARY STUDY OF A PISTON PUMP FOR CRYOGENIC FLUIDS. Arnold E. Biermann and Robert C. Kohl. March 1959. 27p. diags., photos. (NASA MEMORANDUM 3-6-59E)</p> <p>Preliminary performance data are presented for a low-speed, five-cylinder piston pump designed to handle boiling hydrogen. The pump is designed to deliver 55 gallons per minute at a discharge pressure of 135 pounds per square inch. The design pump speed is 240 rpm. The report also describes associated cavitation experiments in which liquid nitrogen and water were subcooled as much as 0.6° F by reciprocating a disk in an open vessel containing the test fluids. This method produced a lesser amount of subcooling with liquid hydrogen.</p>	<ol style="list-style-type: none"> 1. Cylinder and Piston Mechanisms (3.8.2.2) 2. Accessories and Accessory Functions (3.12) 3. Fuel Systems (3.12.1) 4. Research Equipment and Techniques (9) <ol style="list-style-type: none"> I. Biermann, Arnold Ernest II. Kohl, Robert C. III. NASA MEMO 3-6-59E 	<p>Copies obtainable from NASA, Washington</p> <p>NASA</p>	<p>NASA</p>
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