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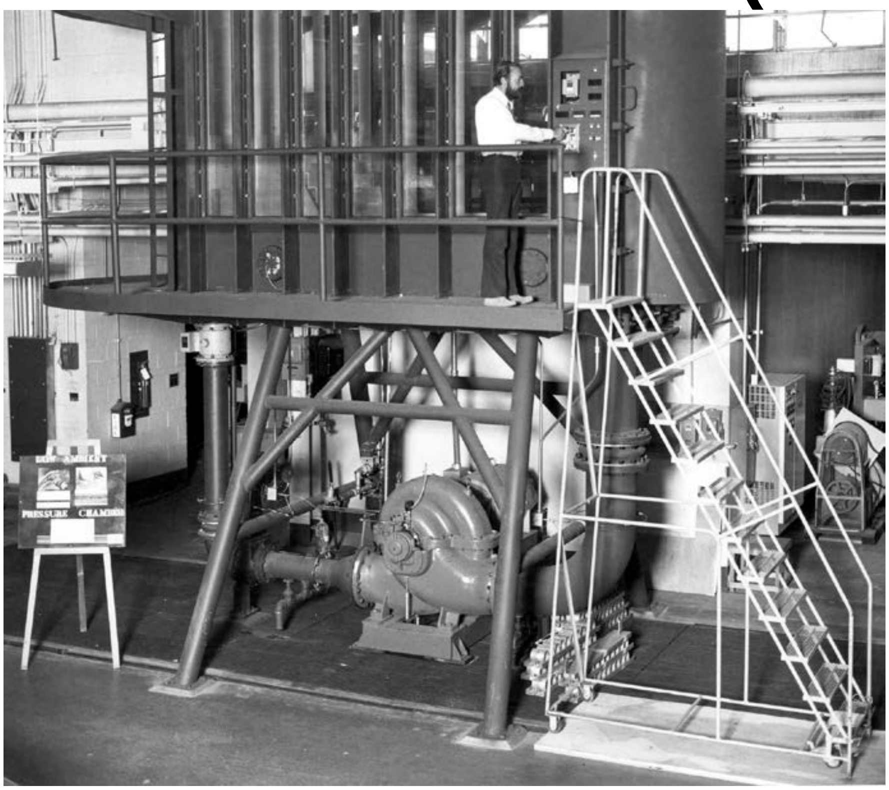
Hydraulic Laboratory Report HL-2016-02

Theory of Use and Operation of Reclamation's Low Ambient Pressure Chamber (LAPC)



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

April 2016

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
04-20-2016	HL	2015

4. TITLE AND SUBTITLE
Theory of Use and Operation of Reclamation's Low Ambient Pressure Chamber (LAPC)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Bureau of Reclamation

8. PERFORMING ORGANIZATION REPORT NUMBER
HL-2016-02

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Bureau of Reclamation

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This document describes the theory, use and operation of Reclamation's Low Ambient Pressure Chamber (LAPC), located in the hydraulics laboratory in Building 56 at the Denver Federal Center in Denver, CO. As a result of the sporadic use that the LAPC has received over the years, the current laboratory staff have limited knowledge of how to operate the facility. This guide, while not all inclusive, should provide those wishing to perform experiments using the LAPC a start in understanding basic setup and operation.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Robert F. Einhellig
a. REPORT	**b. ABSTRACT**	**a. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
UL	UL	UL	UL	24	303-445-2142

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Theory of Use and Operation of Reclamation's Low Ambient Pressure Chamber (LAPC)

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Date: 2016.04.20 15:33:05 -06'00'

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Date: 2016.04.20 13:49:41 -06'00'

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Acknowledgments

The LAPC was formulated through many discussions among former Hydraulics Laboratory personnel and came to fruition in the early 1970s. Perhaps the two people most vital to the planning and completion of the LAPC were Henry Falvey and Donald Colgate. It remains one of the only such facilities in the world capable of testing larger three-dimensional scale models at reduced ambient pressures to evaluate the cavitation potential associated with either open-channel or closed-conduit flows.

Hydraulic Laboratory Reports

The Hydraulic Laboratory Report series is produced by the Bureau of Reclamation's Hydraulic Investigations and Laboratory Services Group (Mail Code 86-68560), PO Box 25007, Denver, Colorado 80225-0007.

Disclaimer

Cover Photo: The Low Ambient Pressure Chamber with Henry Falvey at the controls.

Funding for this document was provided by Reclamation's Manual and Standards Program

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FIGURES

GLOSSARY OF SYMBOLS

$(C_p)_{min}$	Minimum pressure coefficient
P_o	Reference pressure
P_v	vapor pressure of water
V_o	Reference velocity
ρ	Density of water
σ	cavitation parameter – referred to as sigma

Background

In the early 1970s, engineers in Reclamation's hydraulics laboratory proposed, planned, and designed a facility to aid in the study of cavitation. This facility was called the Low Ambient Pressure Chamber or LAPC due to its ability to reduce the ambient pressure within the chamber to levels approaching zero pressure, absolute. Scale models could be placed within the sealed chamber which featured a recirculating pump, allowing flow through structures or past geometries of interest. The size of the chamber would allow modeling of closed conduit (pressurized flow) or open channel (free surface flow) conditions.

Prior to having this tool, research had concentrated on scale models or specific geometries known to produce cavitation and resulting damage under certain flow conditions. These geometries were typically those found in gate slots and frames (gaps and offsets). Models were tested at ambient (normal) atmospheric pressure conditions, and model pressures were measured using traditional techniques and scaled to appropriate full scale (prototype) values. Problems arise with this methodology when scaled up pressures reach the threshold of the vapor pressure of water, where cavitation would form in the prototype flow, but does not form in the model. In addition, shear flow properties and intensity are difficult to measure and evaluate even with today's instrumentation technology.

Ground-breaking research had been performed at the laboratory in the 1950s regarding cavitation damage reduction when free air was introduced locally into the cavitating zone. These discoveries led to the design and construction of aeration ramps and slots at many of Reclamation's facilities, primarily at outlet works and spillways, yet visualization of exact cavitation location, strength, and extent was still not possible in the scale models typically used for study in the laboratory.

Cavitation in hydraulic structures is a result of localized pressures reaching the vapor pressure of water, causing the formation of vapor bubbles and cavities. Typically these low pressures are the result of a separated, high velocity flow, of such magnitudes that they are not easily reproduced in the laboratory. In addition, free and wall-bounded shear flows can be responsible for cavitation formation. In the 1970s, reduced pressure facilities were not new, although all documented prior work had been carried out in closed conduit water tunnel circuits with the capability to reduce the pressure within the tunnel to levels near absolute zero. Facilities such as this had been constructed all around the world and used to study cavitation that occurs on propellers of water vessels, internal parts of pumps and turbines, and specific shapes of bodies used in underwater high-speed applications. The large size of the test chamber in Reclamation's LAPC made it uniquely suited to studies of open channel flows and relatively large three-dimensional models.

Description of the Facility

The LAPC's designers envisioned a facility that would be:

- Versatile – it should readily accommodate models designed for a variety of purposes and fabricated in many different sizes and shapes,

- Accessible – models inside the chamber must be accessible so that changes can be readily made. It should be visually accessible while in operation to allow observation and photography

- Easy to Construct – the chamber should be relatively simple since the type of studies proposed would be a new approach with little known about the controls and instrumentation required. The facility should allow for upgrades and updating of major components and instrumentation. As many of the "results" would be visual, adequate viewing windows and lighting would be major issues. Internal pressure would generally be below atmospheric and approach zero (absolute). Joints and corners should take advantage of this and use the external pressure to aid in sealing.

With these basic requirements, the LAPC was designed in-house, fabricated externally, and then erected in its permanent location along the east side of the Hydraulics Laboratory in Bldg. 56 at the Denver Federal Center (Figure 1).

Figure 1: Low Ambient Pressure Chamber, Bureau of Reclamation Hydraulics Laboratory

The basic chamber that holds the study models is roughly 12 ft long by 4 ft wide by 10 ft tall and is elevated 10 ft above the laboratory floor (Figure 2). Treated, municipal water is supplied to the chamber to fill it to an appropriate level. A 0-10 ft^3/s variable speed split-volute pump is located at floor level to drive the recirculating system. A separate vacuum pump located on the top of the chamber is used to evacuate and maintain the reduced ambient pressure within the chamber, approaching absolute zero. Seven large windows are located on each long side of the chamber with 6 smaller windows in the top of the chamber. The windows are single sheets of 1.25-inch thick Lexan polycarbonate, providing better strength and flexibility than many other glass or acrylic products. Lighting is provided by temporary means with internal or external options available.

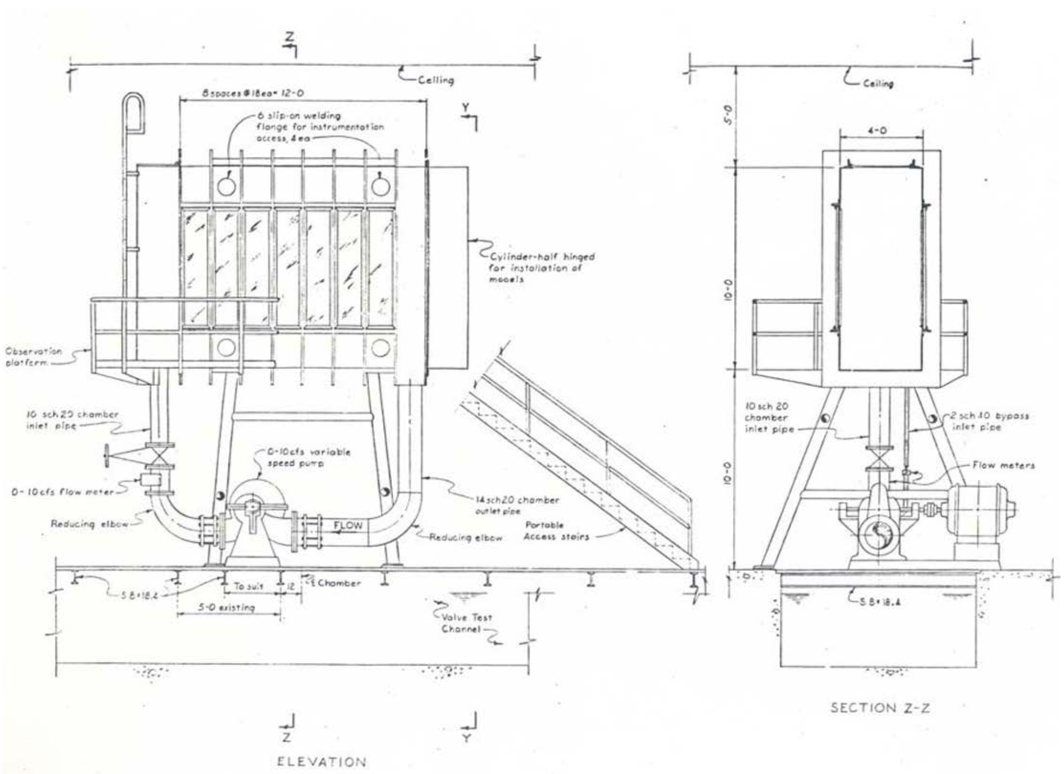

Figure 2: Elevation and section of the LAPC as constructed in the Bureau of Reclamation Hydraulics Laboratory.

Theory of Use

The formation of cavitation and the associated damage caused by it has continued to be an issue affecting many areas of fluid flow, including hydraulic machinery such as turbines and pumps, hydraulic equipment and structures such as gates, valves, chutes and spillways, and underwater features of ships, such as propellers, hydrofoils, and other high speed submerged bodies. The study of cavitation using pressure controlled facilities dates back to the late 1800s when Parsons used a pressure-controlled water tunnel to investigate cavitation on a ship's propeller. Investigations into what appeared to be a limitation on the ship's maximum speed eventually showed that the cause was a loss of thrust due to cavitation on the propeller. This first small water tunnel led to the construction of larger water tunnels at locations all over the world in order to study this phenomenon known as "cavitation." The LAPC is essentially a water tunnel, but in addition to being configured as a closed conduit (pressurized) circuit, it can also feature a test section with a free water surface. This allows for the study of cavitation that may occur in hydraulic structures such as spillways and stilling basins.

Cavitation is defined as the phenomenon of transforming a flowing fluid from the liquid phase to a vapor phase by a reduction in pressure while keeping temperature relatively constant. Boiling describes a similar phase change, but with the pressure kept constant while the temperature is increased. Just as a fluid may transform from liquid to vapor due to a momentary pressure reduction (e.g., turbulent fluctuation of pressure), vapor bubbles may transform back to a liquid when pressure increases again. The collapse, or implosion, of vapor bubbles leads to large pressure spikes at the center of the collapsing bubble; when this happens near a flow boundary, damage to even very durable materials (e.g., steel or concrete) can occur quickly.

A special subset of cavitation is "gaseous" cavitation which involves a reduction in pressure causing supersaturated gas (a different compound from the fluid itself, e.g., air dissolved in water) to diffuse from the liquid before the pressure has dropped to the liquid's vapor pressure. Since these diffused bubbles do not reabsorb into the fluid at the rapid rate at which water vapor changes phase back to a liquid, gaseous cavitation is generally not damaging. However, gaseous cavitation can create a two-phase flow of liquid water and gas bubbles that interferes with true cavitation processes. To avoid having excess gaseous cavitation distort model performance with respect to true cavitation, it is important to degas the fluid in the LAPC prior to performing experiments to ensure that the water is not supersaturated.

The most important non-dimensional parameter to describe cavitation is a minimum pressure coefficient formulated with the minimum pressure set to vapor pressure. For flow around a streamlined body (Figure 3), a pressure coefficient (also called the Euler number) describing the pressure variation over the surface of the body can be defined as

$$C_p = \frac{P - P_o}{\rho\, V_o^2/2}$$

where P is the pressure at a point on the surface, P_o is the free-stream pressure upstream from the area of interest, V_o is the free-stream velocity, and $\rho V_o^2/2$ is the dynamic pressure of the flow. At points on the body that experience pressure reduction, the value of C_p is negative. Reversing signs, we can write

$$-C_p = \frac{P_o - P}{\rho V_o^2/2}$$

If we now presume that the minimum pressure on the surface of the body reaches vapor pressure (the threshold for cavitation to develop), we can write that the minimum pressure coefficient is

$$-(C_p)_{min} = \sigma = \frac{P_o - P_v}{\rho V_o^2/2}$$

We call this minimum pressure coefficient the cavitation index of the flow, σ. In a given flow, the free-stream pressure exceeds the vapor pressure by some multiple of the dynamic pressure, and the streamlined body will experience a pressure reduction that is a fixed multiple of the dynamic pressure, depending on the shape. If the pressure reduction equals or exceeds P_o-P_v, then cavitation will occur. (Pressure will not actually reduce below P_v, since the transformation to vapor prevents further pressure reduction.) Considered nondimensionally, if the minimum pressure coefficient for the shape is less than $-\sigma$, then cavitation will occur. For a non-streamlined body where separation occurs, the most negative pressure occurs in the fluid stream rather than on the surface of the body, but the concept for identifying the cavitation threshold is similar.

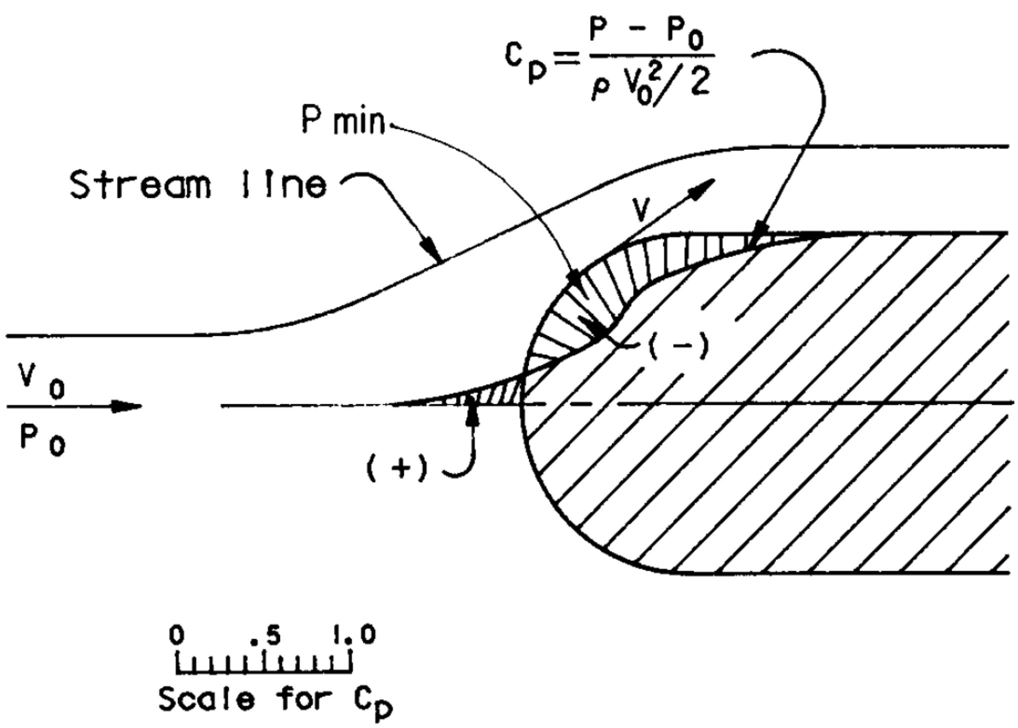

Figure 3: Pressure distribution on a hemispherical rod (from Falvey 1990, Engineering Monograph 42).

Scale models of hydraulic structures are often based on Froude scaling, which maintains an equal ratio of gravitational and inertial forces when the Froude number of the model and prototype are equal. To also study cavitation in such a model, the values of σ must be equal in the model and the prototype, so the reference pressure P_o must be reduced below atmospheric pressure. This is where the pressure reduction possible in the LAPC becomes important. As an example, for a geometric scale of 1:10 the velocity (V_o) in the Froude-scaled model would be reduced by the square root of 10 or a factor of 3.162, and the value of V_o^2 would be reduced by a factor of 10. To have equivalent cavitation behavior in the model, the ambient pressure would need to be reduced so that the model value of P_o-P_v is 1/10 th of the prototype value of P_o-P_v. Note that P_v does not change, since water is used as the working fluid in both model and prototype.

Strict model scales are not always used. For instance, if you wish to know the critical cavitation parameter for inception of a specific shape, you may reduce the ambient pressure as low as possible and vary the velocity until cavitation is detected. Detection is typically accomplished with a hydrophone or acoustic emission sensor. Generally, cavitation can be sensed acoustically long before visual identification is possible.

Operation

Preparing for Start Up

Basic operation of the LAPC begins with filling the chamber with water to an appropriate level. The first step is to open the two drain valves on each side and below the pump (Figure 4), then close the chamber drain valve (Figure 5). Next, open the bypass valve to the pump bearings (Figure 6).

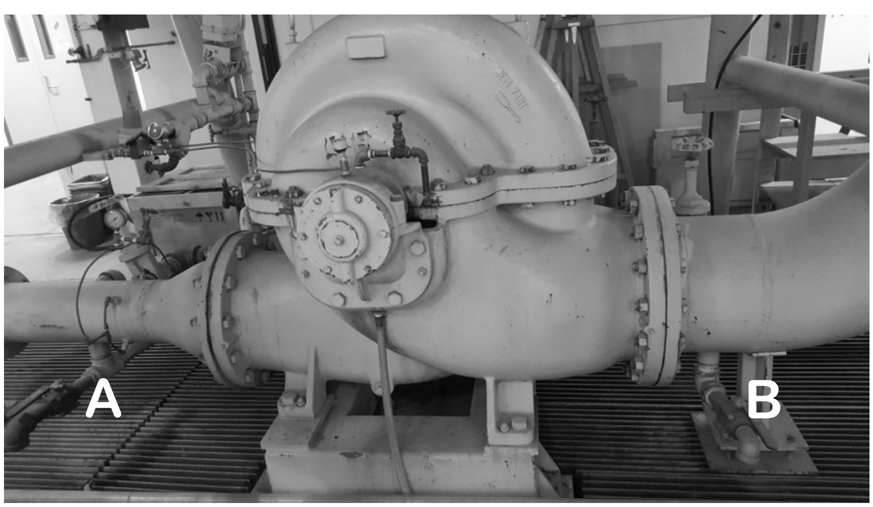

Figure 4: Main water pump, A) left drain, B) right drain.

Figure 5: North end of LAPC, chamber drain piping, A) drain valve.

Figure 6: Bypass to pump bearings, A) valve. This line tees off the city water line.

Open bearing supply valves, (Figure 7, A&B). Pressure gauges should read 20 lb/in^2. If not, adjust the valves (Figure 7, C&D) downstream from the gages until pressures on both gages read 20 lb/in^2. Note that valves should be open similar amounts.

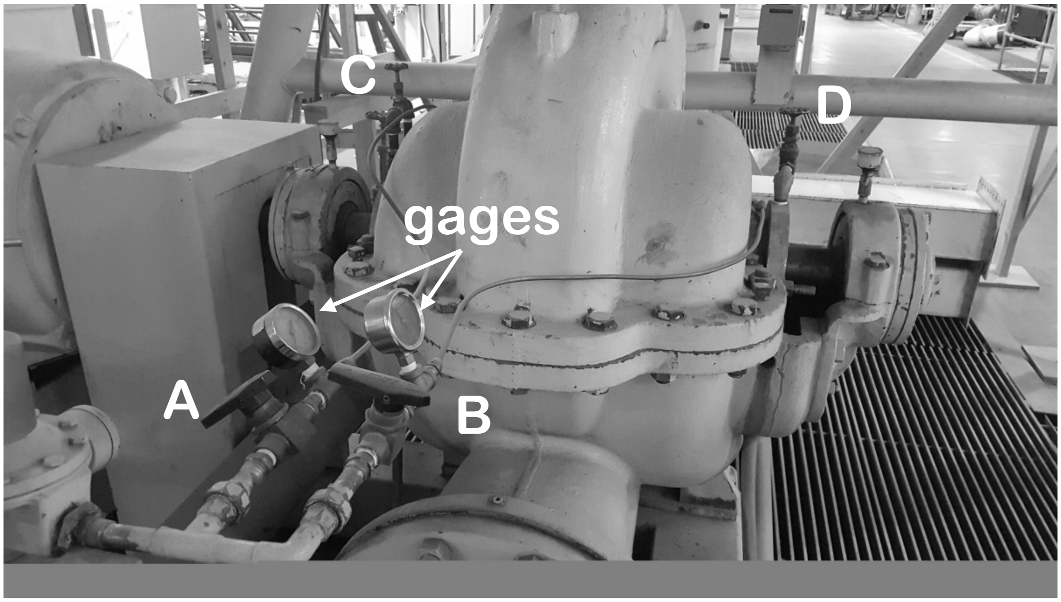

Figure 7: Bearing water supply lines. Shaft on each side of the split volute pump has a water lubricated bearing.

Once the bearing supply lines are balanced, close the bypass valve (Figure 6, A).

Inspect the main door (south end of LAPC) to ensure that all of the clamping dogs are properly tightened. Figure 8 shows the clamping dog locations. All dogs should be perpendicular to the joint they cross and in contact with the door. They may need to be adjusted once a vacuum is attained within the chamber due to compression of the seating material.

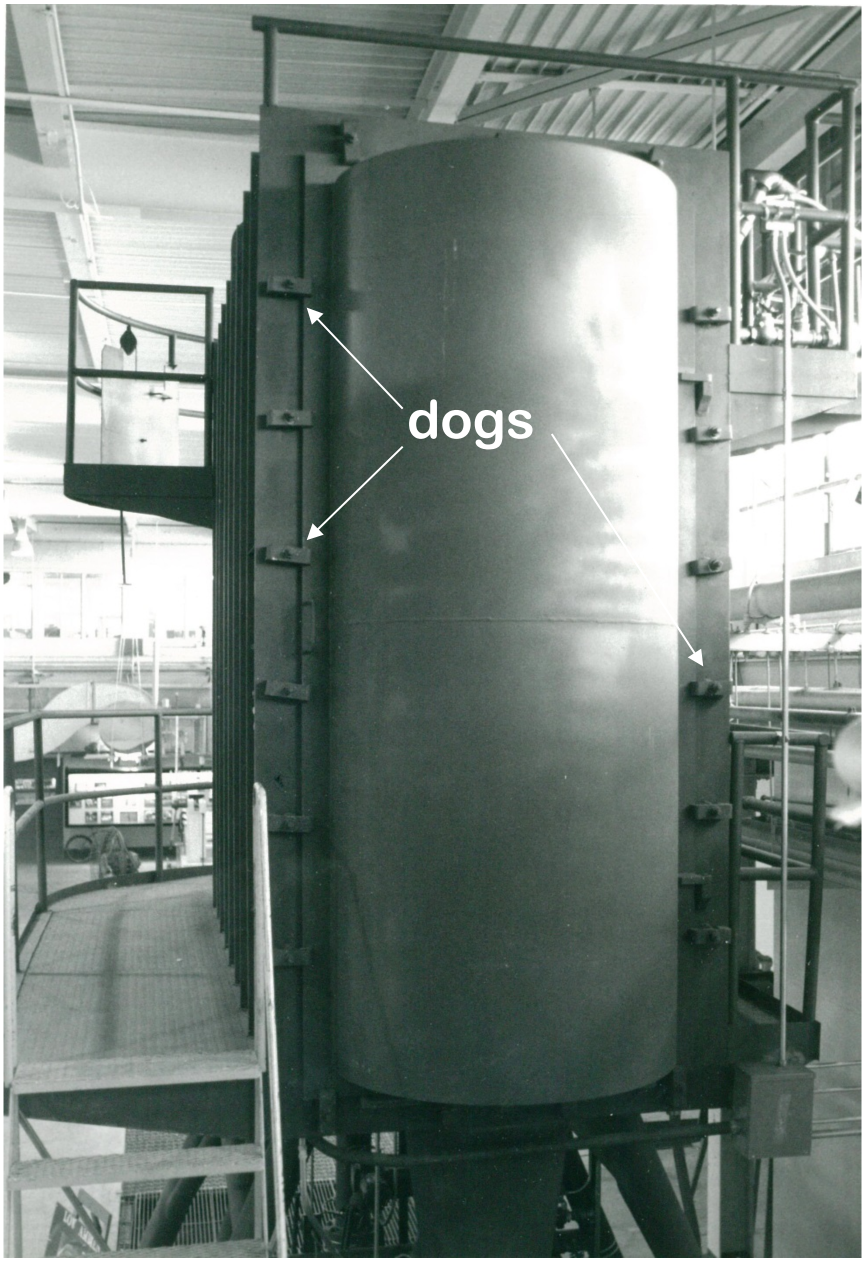

Figure 8: Main door to access interior of chamber. Note clamping dogs, secured with a bolt across the door joint.

Ensure that the emergency shut off switch for the 100 HP Motor is in the ON position. This switch is located on the north wall of the laboratory shops near the spiral staircase (Figure 9).

Figure 9: Remote shutoff for LAPC main motor, located near laboratory shops north door.

Turn on two 480V breakers: one is labeled A on Figure 10, and the other is B on Figure 11. Both boxes are gray and one has a red handle. They are located on the southwest corner of the old air room, to the east and behind the LAPC. Ensure that the breakers in Panel Box LI-8 on the column about 15 ft to the south of the LAPC are set as shown in Figure 12 (1-11 on, 12-14 off, 15-22 on, 23-25 off, 26-28 on, 29 off).

Figure 10: Breakers located directly behind the LAPC.

Figure 11: Breaker and Motor controller.

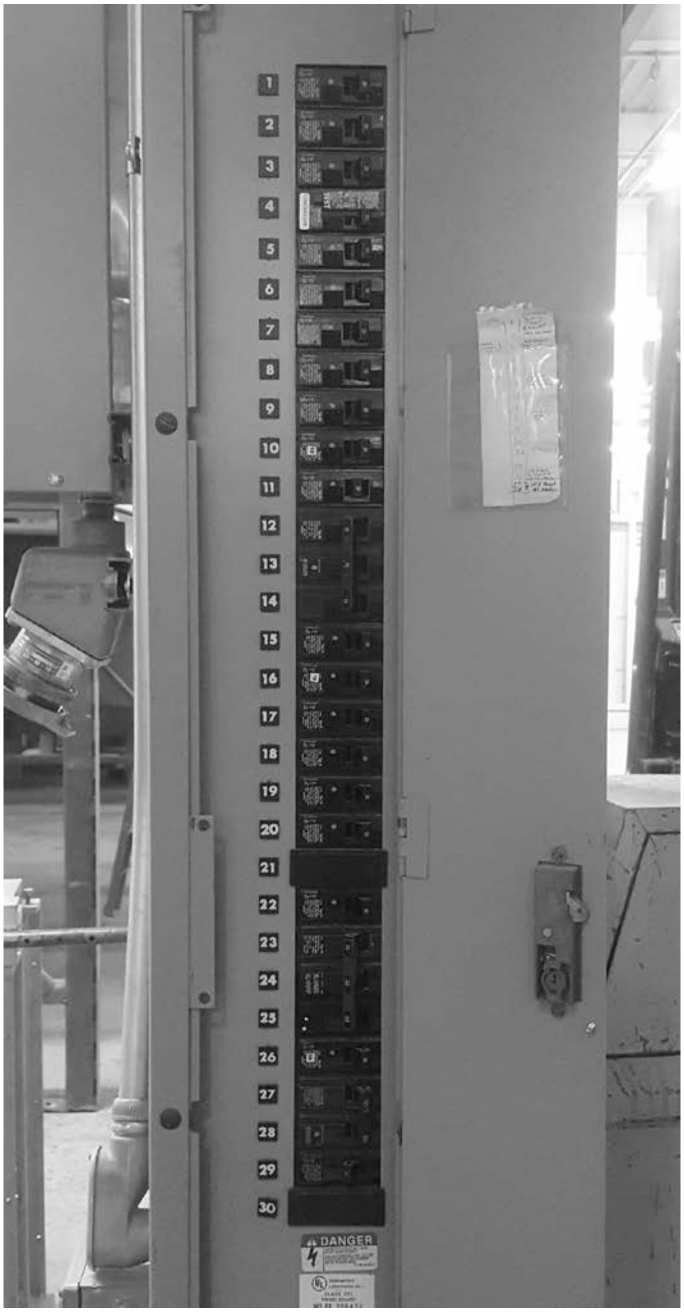

Figure 12: Panel No. LI-8, located to the south of the LAPC on a column about 15 ft away.

On the main level of the chamber is the control panel (Figure 13). Initial settings should be:

- flip switch for panel power ON (lower right corner),
- set main pump switch (a) OFF,
- set vacuum switch (b) OFF,
- throttle valve switch (c) CLOSED,
- speed control switch (d) ZERO,
- selector switch (e) START.

Check that the model is properly installed and that the chamber is clear of personnel.

Figure 13: Main control panel for LAPC at the top of the stairs.

Proceed to the top of the LAPC. Check that the upper chamber access door is closed and sealed with clamped fittings and bolts along the hinge side, fig. 14.

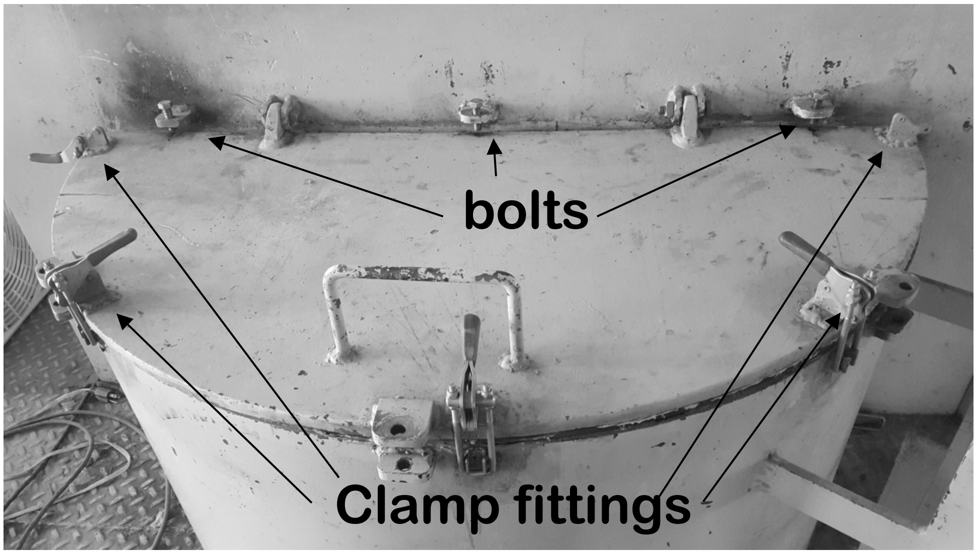

Figure 14: Upper chamber access door.

The seals on the upper chamber access door and the main chamber access door (Figure 6) may need to be adjusted once evacuation of the chamber is initiated by the vacuum pump. These are the two most common locations for leaks. Additionally, the windows can be sources for air leaks.

Open the main vacuum water line valve. It is on the east side, marked A on Figure 15. Open bypass line valve (B), below the electrically controlled valve. The pressure gage (C) should read at least 50 lb/in^2. If it is less, check tank filling line to make sure it is OFF.

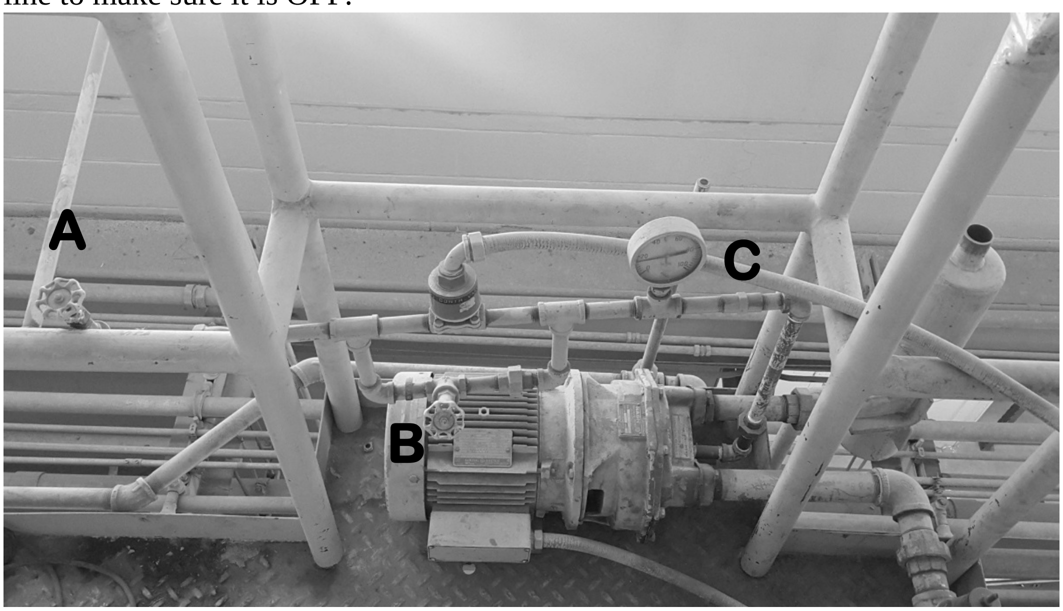

Figure 15: Vacuum pump, on upper level, east side of chamber.

At this point, close the bypass valve (B, Figure 15), and open the two drain valves A & B on the lower right side of the pump (Figure 16), until water is running clear, then close the valves.

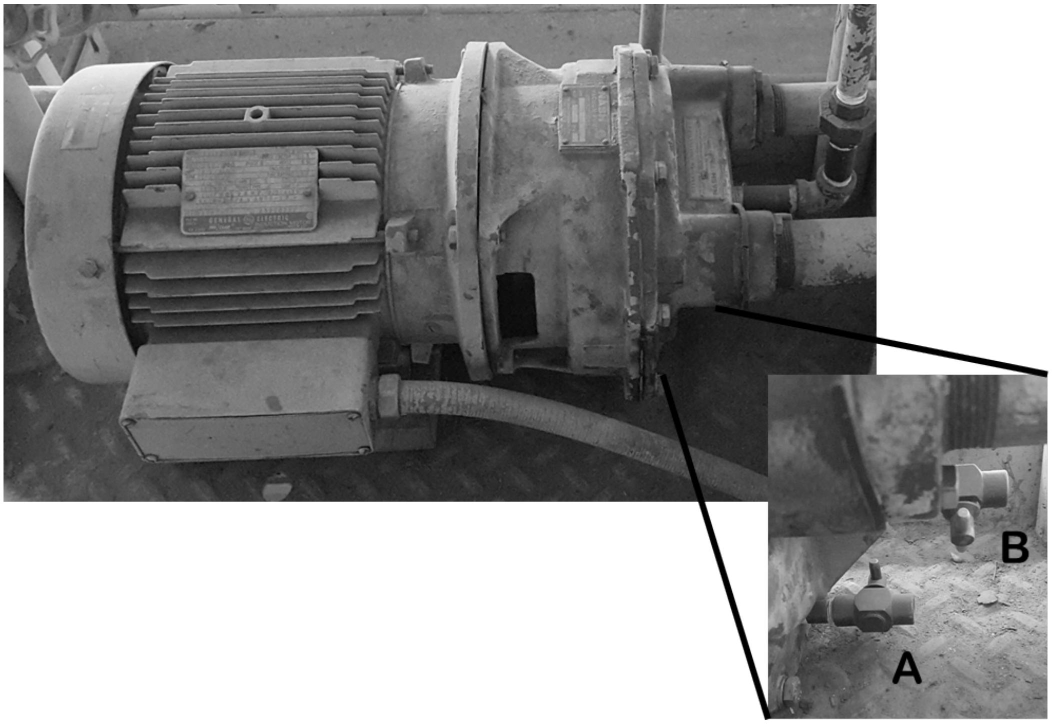

Figure 16: Location of drain valves on vacuum pump.

Open the vacuum relief valve (A) to the chamber (Figure 17). This is a ¼-turn valve just on the chamber side of the walkway across from the vacuum pump. This valve ensures atmospheric pressure within the chamber.

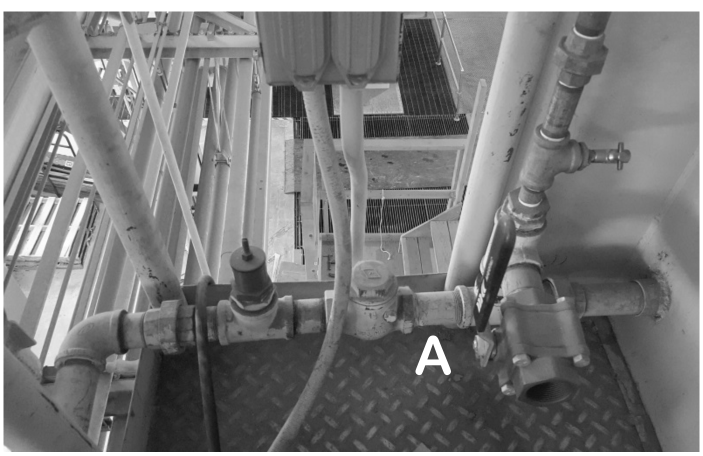

Figure 17: Vacuum relief valve for LAPC, located on the upper level, south east corner.

NOTE: Often, if the chamber has set idle for long periods, the vacuum pump will need to be reworked, i.e. seals replaced, rotating parts unfrozen, etc. See pump manual in maintenance file for LAPC.

Startup

Open fill valve to chamber (A&B Figure 18) and allow water to drain through the main pump drain valve (A Figure 4) until water is clear. Close fill valve and pump drain valves.

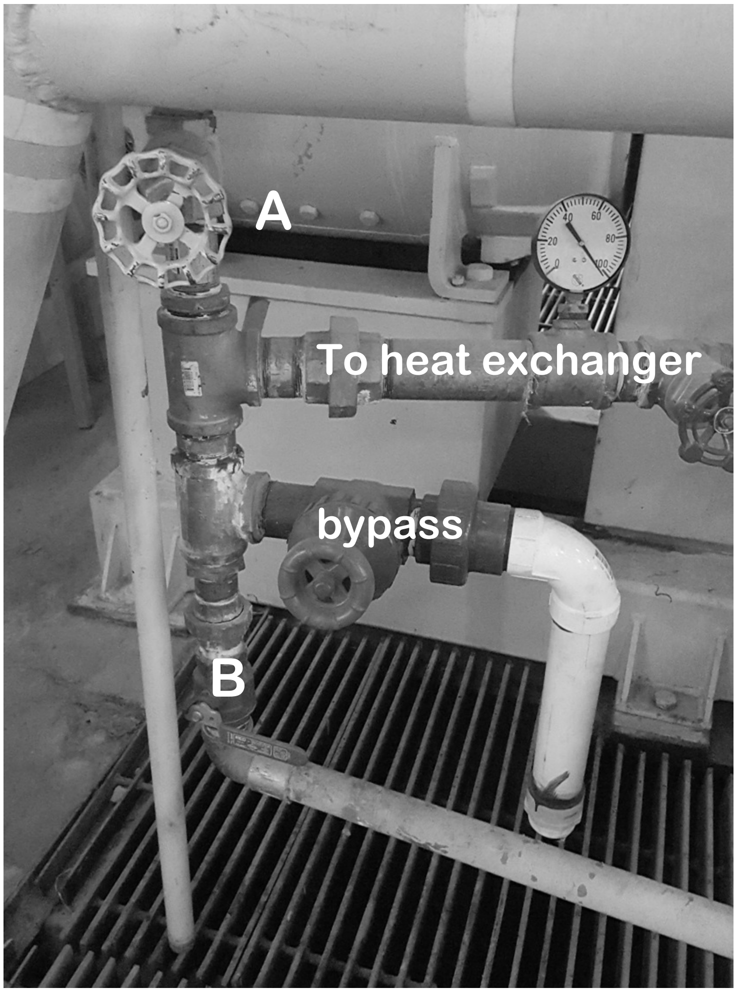

Figure 18: Fill valve A & B on city water line, north end of LAPC.

On the chamber level, make sure control panel is ON and then open the throttle valve ("c" on Figure 13). A light should illuminate for the open position. You can double check by looking at the throttle valve; the stem should be visible above the hand wheel, A on Figure 19.

Open fill valve once again on the lab floor along with the bleed valve on the top of the pump casing (Figure 20). This process will fill the chamber with water. You should carefully monitor the water level once it reaches the chamber so as not to over pressurize a closed conduit arrangement or flood out portions of the model being tested. In addition, monitor the entire chamber for leaks. If leaks occur then stop the filling process and repair before proceeding.

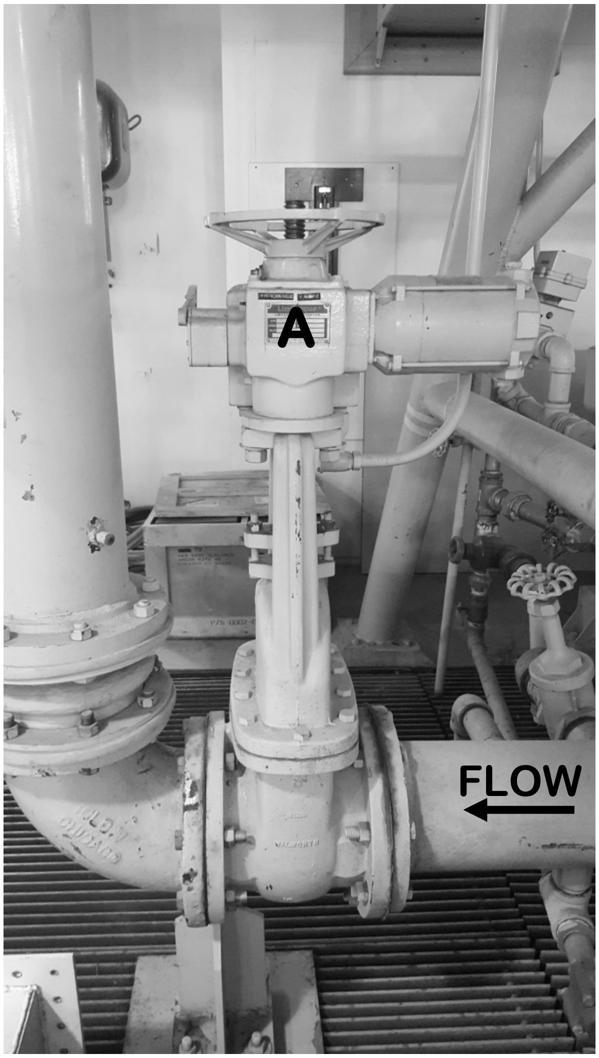

Figure 19: Throttle valve on discharge side of main pump.

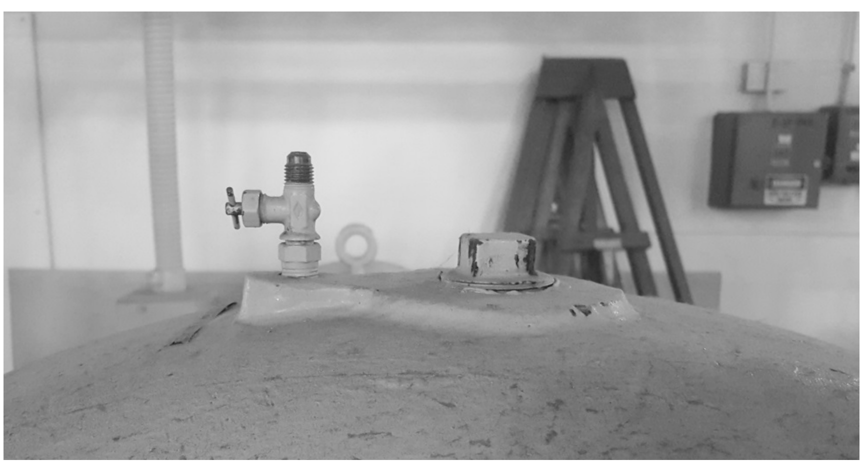

Figure 20: Bleed valve on top of main pump casing. This valve can be closed once the air has been forced out of the pump by the rising water.

If no leaks are noticed and the water has reached the desired level within the chamber, you can close the fill valve and the pump bleed valve. In addition on the chamber level, ensure that the vacuum relief valves are closed (Figure 17A and the valve A near the vacuum gage just above the control panel, Figure 21).

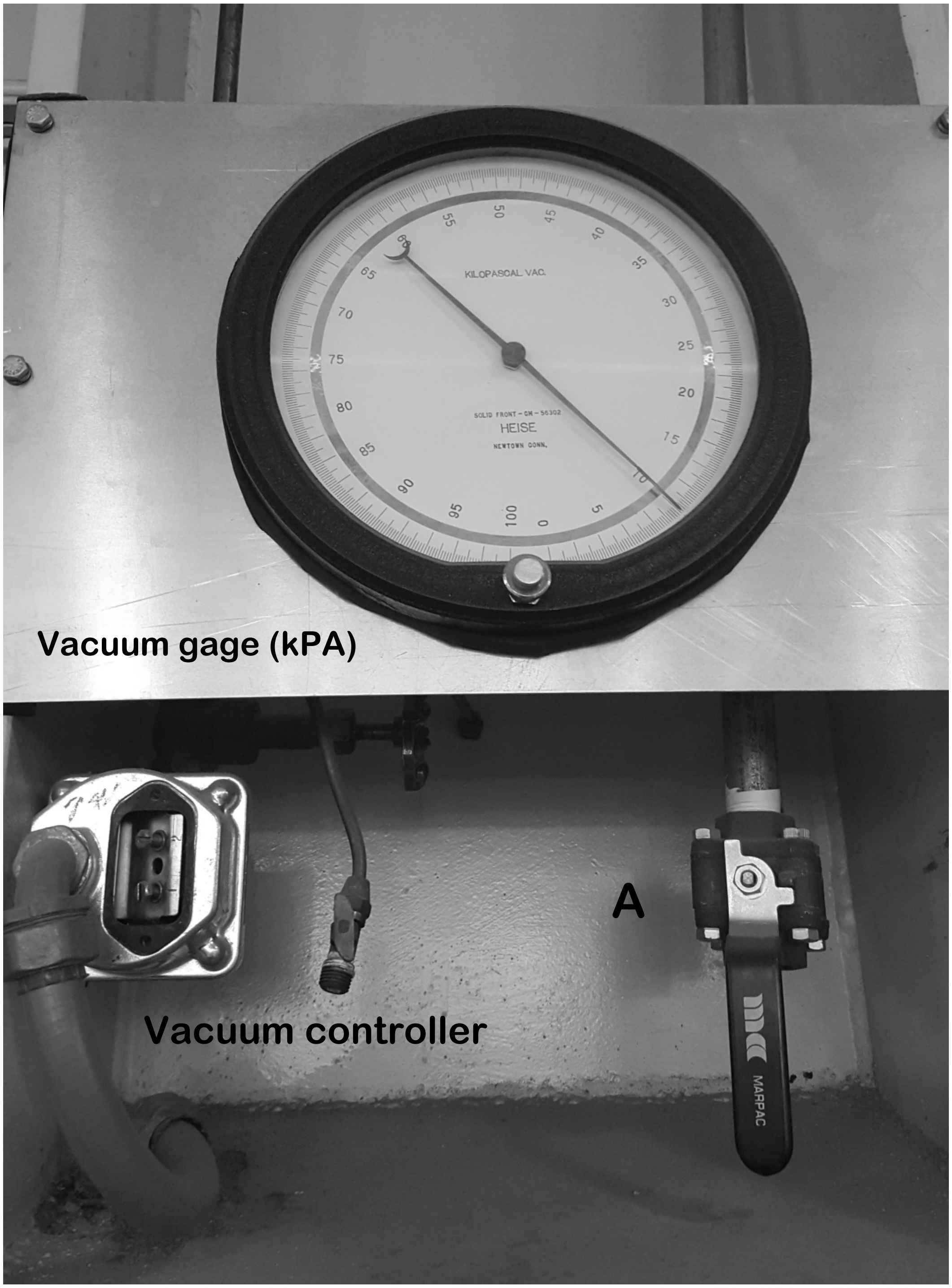

Figure 21: Internal vacuum gage, along with vacuum relief valve and vacuum level controller, located just above control panel.

You can now turn the vacuum pump on. At this point, you also may begin slowly circulating water through the chamber. This process improves the degassing of the tap water that was used to fill the chamber. In order to start the pump, turn the pump control to ON and mode selector to START, then depress the START button. Move the mode selector to manual and then you can adjust the pump speed control to a desired RPM or discharge. This is also the time to adjust the packing box glands on each side of the pump. Figure 22 shows one side of the pump. There should be between 20 to 60 drops/minute dripping from the piping. If necessary, the two bolts on either side of the gland can be adjusted to produce the correct leakage rate from the packing.

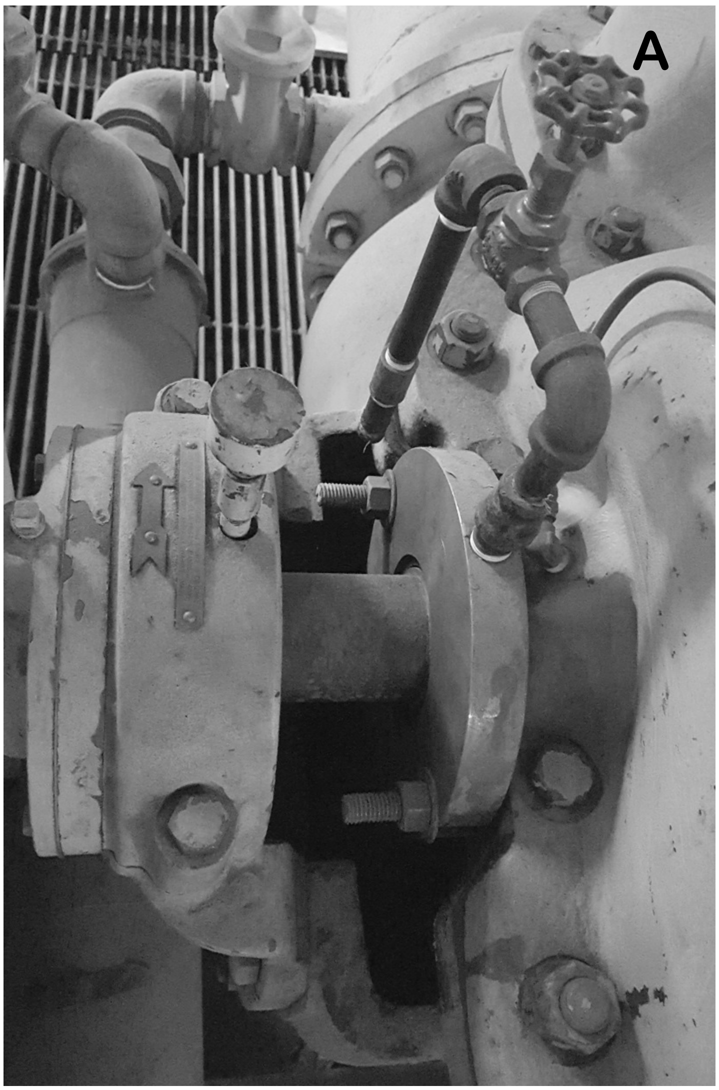

Figure 22: Packing box gland, one on each side of the split case pump.

As the vacuum continues to be applied to the chamber, you may notice air leaks in the chamber. This may be apparent visually if you see air bubbles entering the chamber or possibly you will hear air rushing into the chamber through a small gap. The first course of action is to adjust the clamping dogs on both of the access doors. As the vacuum increases, the clamps may loosen. Continue to adjust these clamps during the evacuation of the chamber. If leaks persist, chances are you will not be able to maintain the level of reduced pressure within the chamber that your test requires. If this is the case (almost always happens!) you will need to shut down and attempt to correct the leaks.

If no leaks occur and you are able to maintain the appropriate level of vacuum, then testing can proceed. Be sure to read and record the atmospheric pressure for the date and time any data are collected. There is a barometer mounted on the wall directly behind the LAPC (Figure 23). The vacuum gage is referenced to atmospheric pressure.

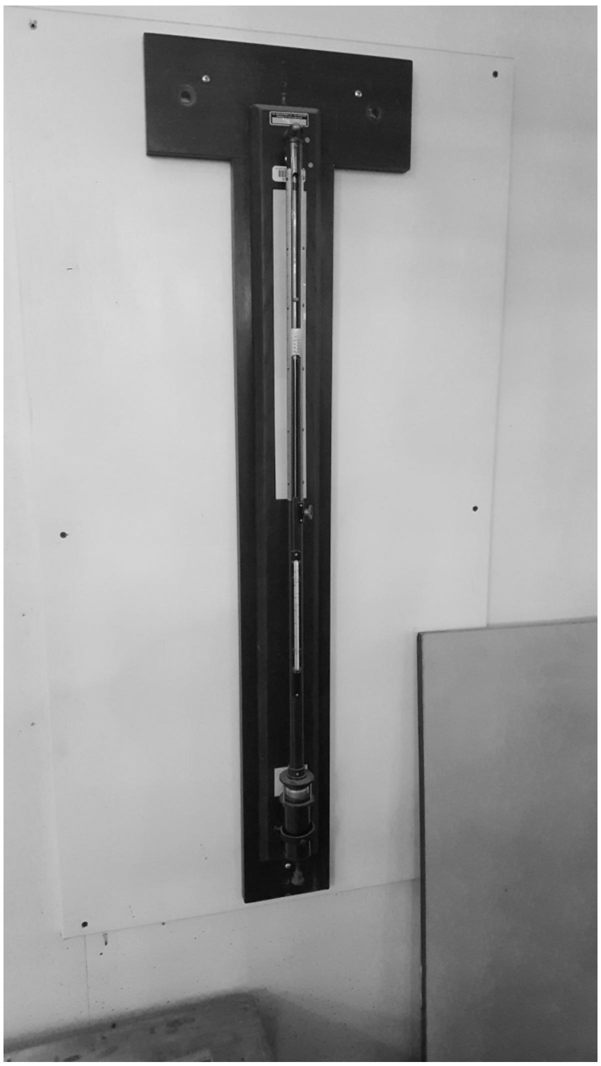

Figure 23: Fortin-type barometer used to measure local atmospheric pressure.

You can increase pump speed to the flow rate needed (up to 10 ft^3/s). Flow is measured using an inline magnetic tube flow meter (Figure 24).

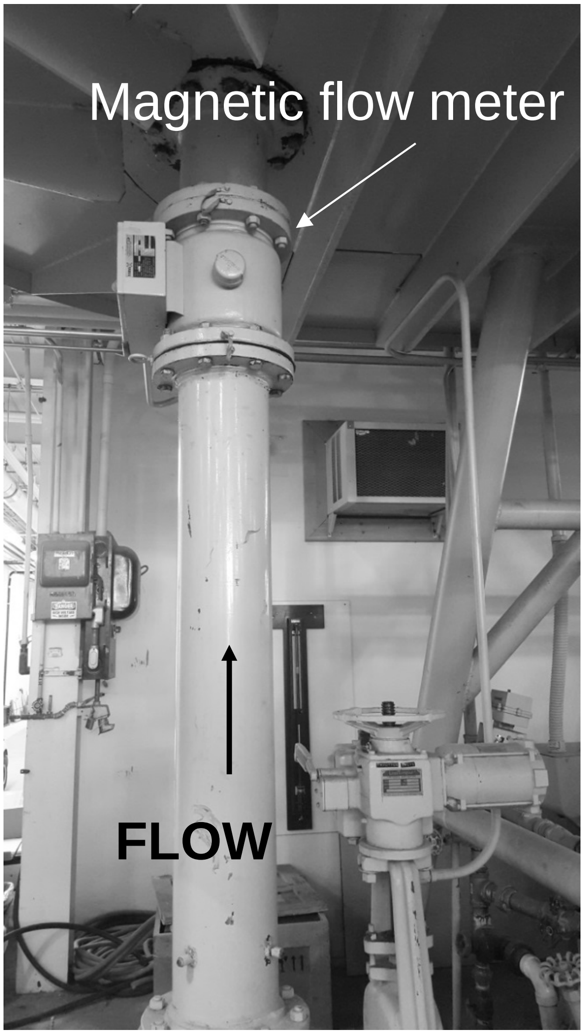

Figure 24: In-line magnetic flow meter.

Shut Down Procedure

At the control panel, turn the pump speed control to ZERO, depress the STOP button. At this point, you may turn off the control panel.

You may open the vacuum relief valve (Figure 21, A) just above the control panel or on the upper level of the chamber (this may be quite noisy). Close the main water supply to the vacuum pump, open the drain valves on the vacuum pump, and drain completely.

If you need to drain the water from the chamber, open both drain valves on either side of the pump (Figure 4, A&B), then open the main chamber drain valve, (Figure 5, A). Turn off all switches and breakers detailed in startup instructions.

Operating Notes

Typically, water tunnels are equipped with some method to control the water temperature, since the temperature tends to increase the longer the closed circuit operates. In addition, many of the more sophisticated tunnels have a means to control the amount of free gas within the flowing stream. As cavitation occurs within the tunnel, free gas bubbles form and will eventually saturate the fluid stream, providing excess nuclei, and making visualization impossible.

The LAPC features a rudimentary heat exchanger (Figure 25). This exchanger provides a cool water jacket around a partial bypass pipe to provide some cooling. The cooling water is city tap water and flows through an outer jacket while an inner pipe bypasses a small fraction of the total flow being pumped through the closed circuit.

The LAPC was not designed with a resorber to remove excess free air from the water stream. The original thought was that most hydraulic equipment or structures that might have cavitation tend to operate with the air content near saturation. Thus there would be a significant number of available nuclei on which cavitation would initially form. With this thought, removing free gas was not a high priority. It is necessary that the tap water be “de-gassed” by circulating water in the chamber while under vacuum. This action will pull enough free gas from the water to reach a condition of just under saturation. The issue still remains that if allowed to operate for extended periods of time, free gas returns to the water stream, especially if a free surface is present, forming lots of bubbles and making visualization nearly impossible.

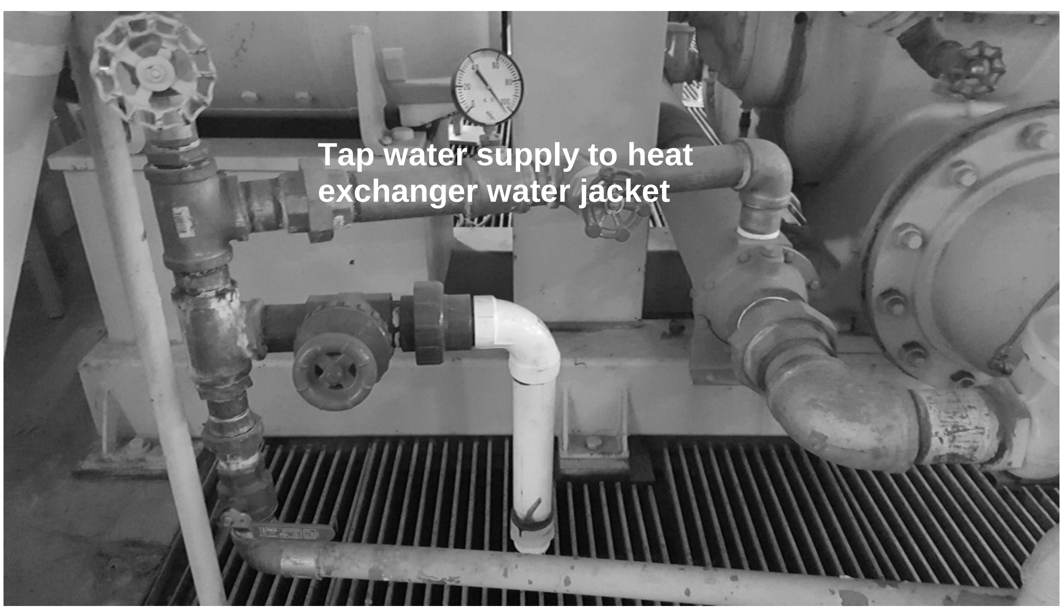

Figure 25: Heat exchanger water jacket.

When operating the LAPC in a water tunnel type configuration, it is necessary to have a free water surface (typically downstream from the test section) in order to expose the water to the reduced pressure. Generally, a downstream bulkhead ike that shown in Figure 26 is constructed to allow a free surface above the suction piping leading to the pump.

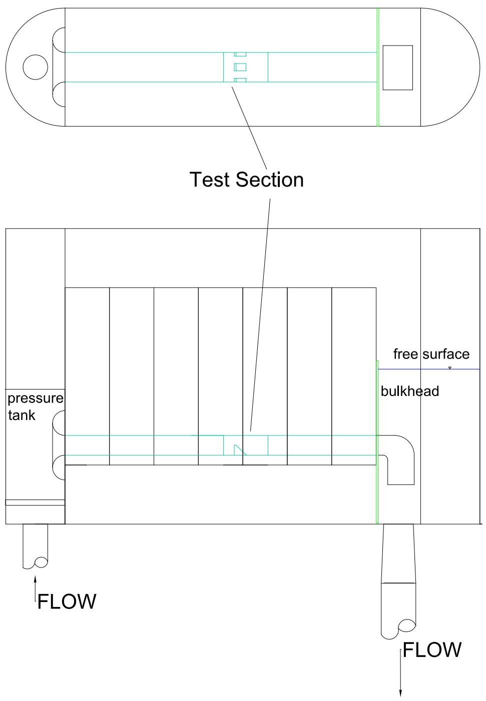

Figure 26: Schematic of LAPC showing tunnel type test section with downstream bulkhead.

Generally, the LAPC sits for long periods between use. Many items should be checked prior to operation.

- Pump and motor; if motor controller is not working properly we have used in-house electronics engineers to help troubleshoot. The pump bearings were replaced in 2012, but may pose problems with excessive leakage, etc.
- Vacuum pump; generally the vacuum pump will need to be disassembled and cleaned and lubricated prior to use. This pump has water flowing to assist in pulling the vacuum and tends to retain at least some water internally that rusts and may cause problems. If the vacuum pump will not maintain a vacuum within the chamber, it can be leakage of the chamber or problems with the seals of the vacuum pump. Documentation and maintenance guides can be found in the permanent data and maintenance files of the hydraulics laboratory.

Conclusions

The Low Ambient Pressure Chamber is a unique facility located in the Bureau of Reclamation's hydraulics laboratory. It may function as a closed circuit water tunnel or allow for open channel flow. It is designed to flow up to 10 ft^3/s and maintain reduced pressures of less than one tenth of an atmosphere. Proper use will allow identification of critical cavitation characteristics for specific flow surfaces including gate slots, specialized surfaces, offsets, singularities, etc.

References

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Data File No. 836, Bureau of Reclamation, Hydraulics Laboratory, located in Denver, CO.