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REPORT OF INVESTIGATION OF THE USE OF COMPRESSED AIR FOR THE QUALITY CONTROL IN POST TENSIONED DUCTS

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Introduction

A number of post-tensioned bridges in Florida have experienced post-tensioning tendon failure due to corrosion induced by grout voids in vulnerable locations. Among these bridges were the Mid-Bay Bridge in the Florida Panhandle and the Niles Channel Bridge in the Florida Keys [1]. In response to difficulties encountered in the field during evaluation of post-tensioning (PT) tendon duct installation, a research project was conducted to simulate field conditions per the Florida Department of Transportation (FDOT) Developmental Specification for Road and Bridge Construction (462-10.9) [2]. Currently, this specification requires that a PT tendon duct be pressurized to 100 psi of air pressure and experience a loss of no more than 10 psi over 5 minutes, to ensure that the duct connections are sufficiently sealed and do not require repair. The Federal Highway Administration (FHWA) Post-Tensioning Tendon Installation and Grouting Manual 4.3.1.4 also recommends the same test be implemented for the pressure check of a PT duct system. [3]. The FHWA document also makes provisions for lower initial pressures when in accordance with manufacturer recommendations for ducts and fittings.

Experience gained during field testing, however, has revealed that the vast majority of PT ducts are unable to maintain the required air pressures as per the FDOT and FHWA documents, and it has been suggested that a 100 psi air pressure is exceedingly high for PT duct testing. There is no cited justification of the initial air pressure of 100 psi in either of the documents and thus there is some ambiguity as to the validity of the pressurized testing of PT duct systems.

It is most likely that the initial pressure of 100 psi was chosen for the PT duct test because the personnel involved in the specification writing were somewhat unclear as to what a reasonable conservative, yet sufficient, initial pressure would be. It is often the case that during the construction of PT bridge structures the PT ducts are located in unconfined space prior to the injection of grout. Many grouting specifications require grout injection pressures as high as 150 psi for construction. Thus, there has been some confusion as to the necessary pressure that should be specified for PT duct leakage testing. Though it is generally accepted that a PT duct system should be able to handle pressures up to 150 psi during the grouting process, implementing such high pressures in the proof testing of the ducts prior to grouting are not necessary in the acceptance of those ducts.

Pressure testing of the PT duct systems themselves was not meant to serve as quality assurance for the pressure carrying capability of the ducts themselves, but as a leakage test for the PT duct system. Engineers tend to error to the side of conservatism regarding quality assurance and quality control of construction practices, which is most likely the reason as to why 100 psi of initial air pressure was chosen for the pressure check of PT systems.

It is generally accepted that the use of 100 psi of air pressure is required to investigate the grouts themselves for bleeding and expansion, but this is not necessarily the case for testing of the PT duct joints on bridges. The purpose of this research was to determine whether it is acceptable to reduce the test air pressure below 100 psi while assigning an acceptable leakage rate at that lower pressure. Although there has been extensive research performed on the grouting processes, grouting techniques, and the grouts used for pressure tendon ducts [4-8], there is currently no published research available which compares air pressure loss with grout mass loss in pressure tendon ducts. Research on joint seepage has been performed. However, such research focused on the PT duct joints and joint preparation [1]. Research correlating air pressure loss to grout seepage loss from PT ducts is currently nonexistent.

Experimental Program

The intent of the experiment was to verify that minimal PT grout seepage will take place in a system that is designed to sustain an air pressure of less than 100 psi. The experiment involved the fabrication of two pressure vessels which served as laboratory representations for PT tendon ducts. Differences in density, viscosity, and surface-tension between gases, fluids and thixotropic materials do not allow for a simple conversion between the two when correlating air pressure to grout seepage loss.

The first pressure vessel used for this experiment was a small scale simulation of a tendon duct which was designed to investigate the viability of simulating grout seepage and air pressure losses from PT ducts in the laboratory. The experiment focused on the comparison of air pressure losses to grout seepage losses in a relatively small pressurized cylinder apparatus as shown in Fig. 1. The size of the pressure vessel was 12” in length with a 3.5” outside diameter. It was fabricated from a clear plexiglass cylinder. The size of this pressure vessel was chosen primarily for convenience and ease of testing, based upon a decision to create a relatively small vessel capable of sustaining 100 psi of air pressure and hold approximately 0.1 ft^3 of grout for initial testing.

The pressure vessel shown in Fig. 1 was fitted with two pressure gages, an air pressure source, and a pressure release valve, which was used to simulate a point of leakage. The valve was calibrated with a protractor in order to allow measurement of the precise area of opening for each test. Prior to testing, the area of the valve opening was determined using various water flow rates at different valve openings, as measured with the protractor. Table 1 contains a data summary for this calibration exercise of valve opening. A sample calculation of the calibration for the valve opening is shown in Appendix A. A best-fit curve of valve opening area as a function of valve opening angle is provided in Appendix B.

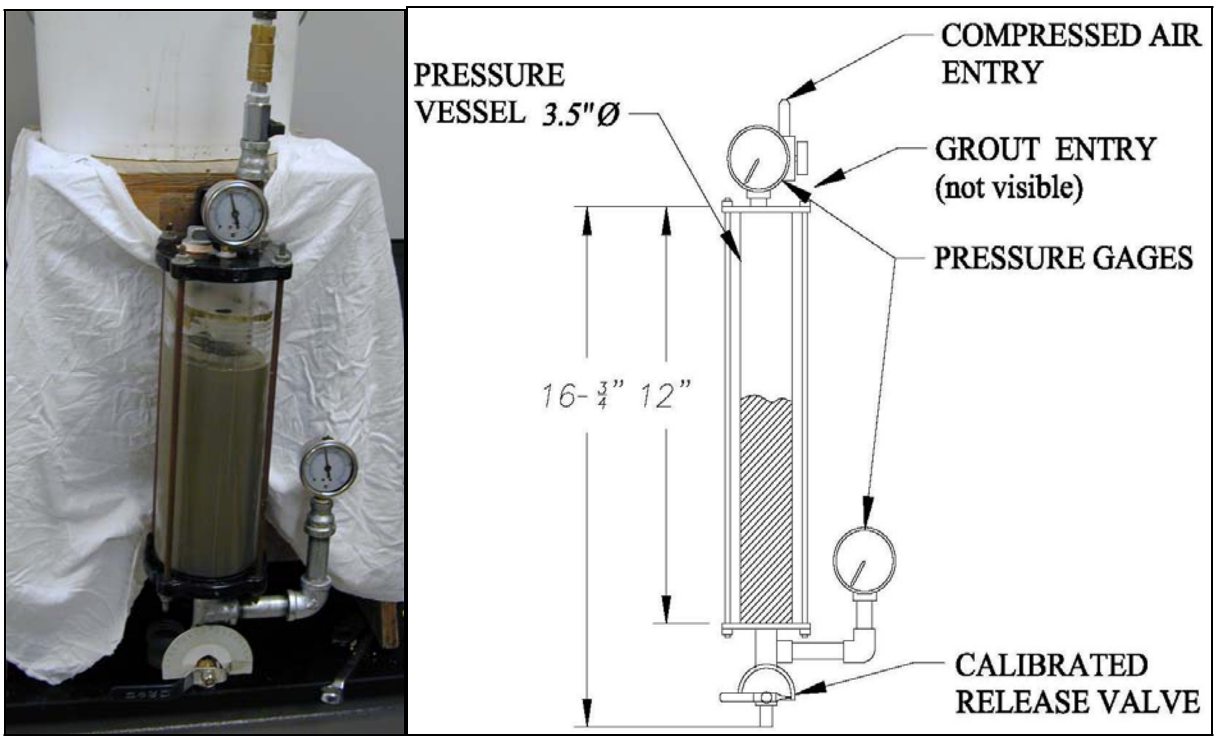

Figure 1 Small Pressure Vessel Testing Apparatus

After the calculation of the area / valve opening angle was completed, the system was pressurized with air to simulate the current method of test required by FDOT specification 462-10.9. Trials were performed using air pressures of 100, 75, and 50 psi. The purpose of this portion of the experiment was to establish any of the valve opening differences in the area required to create pressure losses.

The small pressure vessel was then filled with a laboratory simulated post tensioning tendon duct grout. The grout was composed of Portland cement, water, a water-reducing admixture, and a mix-retarding admixture. The water-reducing admixture was added to produce a grout with relatively high flowability, while the mix-retarding admixture was added to ensure that the grout did not harden inside the pressure vessel prior to the completion of testing. Each of the tests were performed while the grout was still in its plastic state. Subsequent to testing, the grout maintained a fluid state for approximately 30 minutes; therefore it is unlikely that any significant hardening took place while the grout was in the pressure vessel.

Sand was not used in the grout mix design because many non-shrinkage Portland cement based grouts do not contain sand. Since sand particles are larger than cement grains, these larger sand particles within the grout matrix could provide a “plug” for larger holes within the system. Therefore, sand was not used for this study. The water to cement ratio (w/c) used for the grout mixture design was approximately 0.40, which is typically the maximum w/c for PT grouts. The mixture design of the grout was intentionally designed to be flowable to simulate a leakage prone grout used for PT grouting. Trials using the grout were designated as G1, G1, G3, etc. in the data Tables.

After completion of the testing using the small apparatus, it was decided that it would be of interest to create a large apparatus which would represent a full-scale post-tensioning duct. The second pressure vessel used for this experiment was thus designed to simulate a full-scale PT tendon duct. The objective of this portion of the study was to evaluate any potential differences in pressurized air leakage rate and grout seepage rate as a result of the difference in volume between the larger and smaller pressure vessels. The second pressure vessel was fitted with the same air pressure source, release valve and two pressure gages from the first pressure vessel in an effort to ensure consistency within the data. A third pressure gage was also added near the center portion of the apparatus. The experiment focused on the comparison of air pressure losses with grout seepage losses in a relatively large pressurized cylinder apparatus, as shown in Fig. 2. The size of the pressure vessel was 104” long with a 4.0” outside diameter. It was also fabricated from a clear plexiglass cylinder.

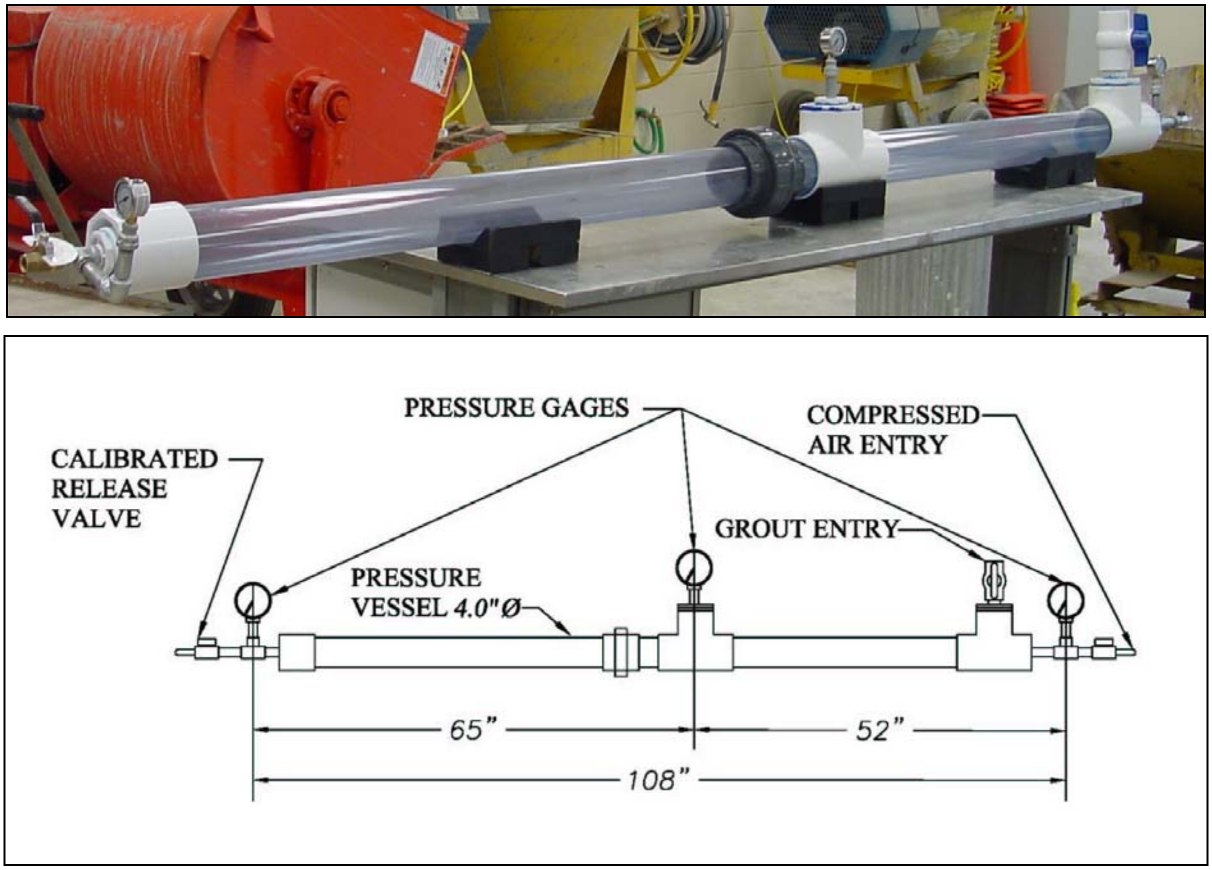

Figure 2 Large Pressure Vessel Testing Apparatus

Research has shown that using approximately 58 psi or water pressure in full-scale PT ducts with epoxied joints can result in failure of the joints themselves [1]. Furthermore, laboratory personnel who experienced the difficulty in pressurizing the small apparatus decided that subjecting the full-scale apparatus to 100 psi of air pressure would be a safety hazard. The objective of utilizing the second, full-scale apparatus was to investigate the differences in grout seepage between a full-scale PT duct and a small-scale PT duct. The use of a larger apparatus was also intended to investigate the occurrence of pressure differentials within a full scale duct in the incidence of grout seepage and pressure loss at one end.

The testing procedure for the full-scale apparatus was the same as that for the small apparatus, with the exception of the use of smaller initial pressures. After the grout was placed in the pressure vessel, several trials of the test were performed using initial air pressures of approximately 50, and 25 psi. The relative loss of grout under pressures (i.e. the mass of grout lost per trial) was recorded.

Results

Small Apparatus

Table 2 contains a summary of the data and test results from the small-scale apparatus. The average pressure denoted in the second and third columns are the average of the two pressure gages on the system. The results indicate that air pressure loss begins when the valve is opened 11 degrees. However, when compared to the data in Table 1, the minimum valve opening required for water leakage was 13 degrees. Therefore, it is possible to experience compressed air loss without experiencing liquid loss. This phenomenon takes place because the density and viscosity of water are several orders of magnitude higher than those of air. Thus, the air is able to move through smaller openings than water.

After the grout was placed in the pressure vessel, several trials were performed using air pressures of 100, 75, and 50 psi. The relative losses of grout under pressure (i.e. the mass of grout lost per trial) was recorded. Table 2 is a summary of the data and test results.

The data in Table 2 shows that the required area needed for the valve opening to generate pressure losses in the small pressure vessel containing grout is significantly larger than the area needed to experience pressure losses with pressurized air alone. This result is consistent with the data in Table 1 that was used to obtain the area of the valve opening. Therefore, the notion that a grout-filled pressurized PT duct requires a larger opening than the same system with pressurized air alone to generate pressure losses was confirmed.

Table 2. Laboratory Test Data (Small Apparatus)

Trial #	Initial Pressure (psi)	Final Pressure (psi)	Pressure difference (psi)	Valve opening Q angle (°)	Time of Apature (sec)	Mass of Grout Seepage(lb)
air 1	100	90	10	11	5	0.000
air 2	75	65	10	11	15	0.000
air 3	50	40	10	12	50	0.000
1	98	80	18	18	15	0.128
2	98	85	13	16	10	0.149
3	75	65	10	17	30	0.193
4	75	65	10	17	35	0.227
5	51	41	10	19	70	0.420
6	49	44	5	17	70	0.166

The purpose of using pressures of 100, 75 and 50psi was to obtain comparative measurements of grout seepage losses between the pressures. The data values in Table 2, "Grout Seepage" reveal an important trend regarding the loss of grout at different pressures. In the trials which utilized a 100 psi initial pressure, the amount of grout seepage is significantly smaller than the grout seepage obtained for smaller pressure losses at lower pressures. Unfortunately, the pressure losses obtained in the trials which used a 100 psi initial pressure were greater than 10 psi. The reason for obtaining such large pressure losses is due to the rate of pressure loss, which was too large to be properly controlled by manual operators in this experiment.

During the time of testing, it was observed that the small pressure apparatus was incapable of achieving a pressurization of 100 psi without extensive application of sealing agents and optimizing the connections of the apparatus itself prior to testing. Laboratory personnel experienced significant difficulty in achieving an airtight seal for the 100 psi trials. Thus, it is feasible to deduce that the installation of a full-scale post tensioning duct required to maintain 100 psi of air pressure would experience even more extensive complications under field conditions.

The rate of pressure loss for the trials with initial pressures of 75 and 50 psi were at a much more manageable rate for this manually controlled experiment and the 10 psi pressure losses were achieved at 75 and 50 psi. However, the data in Table 2 indicates that there is an inversely proportional relationship between initial pressure and mass of grout seepage for this experiment. The mass losses for a 10 psi loss at 75 psi (Trials G3 & G4) and 50 psi (Trial G5) were 0.193, 0.227 lb and 0.420 lb, respectively. The grout seepage for a 5 psi pressure loss at 50 psi (Trial G6) was 0.166 lb, which is similar to the grout seepage observed in the trial with a 100 psi initial pressure. Such data gives validity to the idea that proportionally decreasing the initial pressure and the resultant pressure losses provides similar conditions concerning grout seepage losses.

<u>Large / Full-Scale Apparatus</u>

Table 3 contains a summary of the data and test results from the large-scale apparatus. The average pressure denoted in the second and third columns are the average of the three pressure gages on the system. The experiment revealed no observable pressure gradient along the length of the full scale apparatus before or after seepage loss began.

Table 3. Laboratory Test Data (Large Apparatus)

Trial #	Average initial pressure (psi)	Average final pressure (psi)	Pressure difference (psi)	Aperture opening Θ angle (°)	Time of Aperture Opened (sec)	Mass of Grout Seepage(lb)	Comments
A1	50.7	50.7	0.0	10	300	N/A	Air Test
A2	50.7	50.7	0.0	10	600	N/A	Air Test
A3	50.7	46.3	4.3	12	300	N/A	Air Test
A4	50.7	41.3	9.3	12	600	N/A	Air Test
A5	50.7	40.7	10.0	14	45	N/A	Air Test
A6	26.0	20.7	5.3	12	300	N/A	Air Test
A7	26.0	16.7	9.3	12	600	N/A	Air Test
A8	26.0	16.7	9.3	14	70	N/A	Air Test
G1	50.7	49.7	1.0	12	300	0.0	No Flow/Pressure Loss
G2	50.7	48.7	2.0	12	600	0.0	No Flow/Pressure Loss
G3	48.7	46.5	2.7	14	200	0.0	No Flow/Pressure Loss
G4	48.7	46.0	2.7	16	200	0.0	No Flow/Pressure Loss
G5	46.0	39.0	7.0	18	200	0.459	Pressure Loss/Grout Loss
G6	49.3	19.3	30.0	20	45	3.320	Pressure Loss/Grout Loss
G7	25.3	25.3	0	14	200	0.0	No Flow/Pressure Loss
G8	25.3	25.3	0	16	200	0.0	No Flow/Pressure Loss
G9	25.3	11.3	14.0	18	150	3.180	Pressure Loss/Grout Loss

The data in Table 3 indicates that air pressure losses that take place in relatively the same manner for both the small apparatus and the full-scale apparatus. The major difference in behavior between the two devices was the nature of the loss of pressure over time. As expected, more time was required to achieve the pressure losses due to air and grout seepage using the full-scale apparatus, as compared to the small apparatus. The use of the full-scale apparatus revealed that air pressure losses which take place at a given aperture opening will result in a greater pressure loss in comparison to grout seepage losses under the same conditions. Trials A3 and A4 exhibited higher pressure losses as compared to Trials G1 and G2 (grout seepage) with the same aperture opening incorporating grout seepage as presented in Table 3.

Similar to the phenomenon experienced in the small apparatus, the grout seepage for the large apparatus was approximately equal between trials wherein the initial pressure and pressure loss were reduced by 50% (i.e. trials G6 and G9 experienced approximately the same mass of grout seepage for a 50 psi initial pressure with 30 psi of loss as it did for a 25 psi initial pressure with 14 psi of loss). The data obtained in this experiment exhibits a trend in which the mass of grout seepage stays constant for conditions in which the quotient of the final pressure divided by the initial pressure is near constant, as shown in Equation 1.

$$\frac{P_l}{P_i} \approx M_{seepage} \quad (1)$$

Where: P_l = pressure loss,

P_i = initial pressure and

$M_{seepage}$ = mass of seepage loss

However, further investigation would be required in order to substantiate a clear statistical representation validating Equation 1.

Discussion

The literature review conducted for this experiment revealed that there is very little information available establishing a relationship between grout seepage and air pressure loss in post-tensioning tendon ducts. Currently, the FDOT Developmental Specification for Road and Bridge Construction (462-10.9) is overly conservative regarding the field test for duct pressure, as is the recommendation made in section 4.3.1.4 of the FHWA Post-Tensioning Tendon Installation and Grouting Manual.

While the research did provide some information as to the physical nature of the PT grouting process, and to the required magnitude of applied pressure during testing, it was rather limited in scope. It would be beneficial to conduct more research incorporating actual PT ducts, duct connections and the actual grouting process to obtain the relationship between pressurized gas for use in quality assurance of PT ducts.

Conclusions

The research yielded several conclusions pertaining to the grouting process of pressurized systems.

- Pressurized gases should not be considered to be an exact representation of the physical properties exhibited by pressurized liquids and thixotropic materials for applications involving post-tensioning ducts.
- Compressible gasses can experience pressure losses in systems in which liquids and thixotropic materials do not. A pressurized system containing grout requires a larger area of opening than the same system containing pressurized air alone to generate pressure losses.
- The use of air pressure losses to evaluate the integrity of PT duct systems is overly conservative due to the differences in leakage rates between air and grout.
- The use of 100 psi of air pressure for testing PT ducts is impractical for evaluating the integrity of PT duct systems.
- There appears to be a mathematical relationship between the initial and final air pressure and the mass of grout seepage from pressurized PT tendon ducts.

Recommendations

The FDOT Standard Specification for Road and Bridge Construction should make provisions to adjust the duct field pressure test (462.10.9) as follows:

1. Pressurize the tendon to 50 psi and lock off the outside air source.
2. Record pressure loss for 5 minutes.
3. Determine significance of results. A pressure loss of 10 psi or less is acceptable. If the pressure loss exceeds 10 psi, repair leaking connections using methods approved by the engineer.

Further study is needed to be performed to determine if it is feasible to lower the initial pressure even further for PT duct system for pressure testing.

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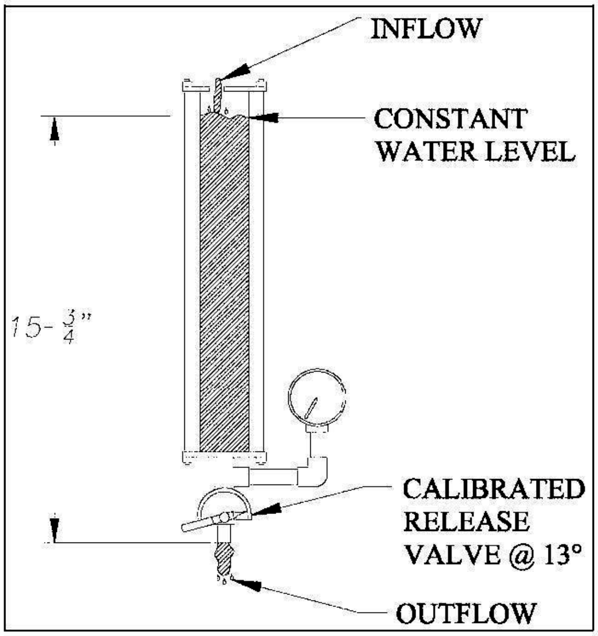
Appendix A
Sample Calculation

Bernoulli equation: $\frac{p_1}{\gamma_w} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma_w} + \frac{V_2^2}{2g} + z_2$

Under Atmospheric presure: $p_1 = p_2 = 0$

Thus, the Bernoulli equation reduces to: $\frac{V_1^2}{2g} + z_1 = \frac{V_2^2}{2g} + z_2$

Set $z_2 = 0$, the Bernoulli equation further reduces to: $V_2 = \sqrt{(2g \cdot z_1)}$



$g = 32.174 \frac{ft}{sec^2}$

$z := 15.75in$

$V_2 := \sqrt{(2g \cdot z)}$

$V_2 = 9.19 \frac{ft}{sec}$

Conservation of Mass Equations:

$Q_1 = Q_2 = \rho_1 A_1 V_1 = \rho_2 A_2 V_2$ With a constant fluid: $\rho_1 = \rho_2$

Thus, the conservation of mass equation reduces to:

$Q_1 = Q_2 = A_1 V_1 = A_2 V_2$

Area calcultaion for a valve opening of 13°

$Q_2 := \frac{1.34}{180} \frac{in^3}{sec}$ -- measured volume over time

$A_2 := \frac{Q_2}{V_2}$

$A_2 = 4.688 \times 10^{-7} ft^2$

Appendix B

Area calculation of valve opening

Trial #	Valve opening angle (°)	Height of Free Water Surface" "Z"(in)	Velocity of water at valve "V_2"(ft/sec)	Time of Test "T" (sec)	Volume of Water "V_1"(ft^3)	Valve opening area "A_2" (ft^2)
1	12	15.75	9.18	xx	0	0
2	13	15.75	9.18	180	$7.56x10^{-4}$	$4.27x10^{-7}$
3	15	15.75	9.18	120	$5.47x10^{-3}$	$4.96x10^{-6}$
4	17	15.75	9.18	135	0.0013	$1.07x10^{-5}$
5	19	15.75	9.18	95	0.0018	$2.02x10^{-5}$

Area calculation of valve opening