This report is dedicated to all little boys who ever have
or who ever will play in the water.
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<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DEDICATION</td>
<td>i</td>
</tr>
<tr>
<td></td>
<td>ACKNOWLEDGEMENTS</td>
<td>ii</td>
</tr>
<tr>
<td></td>
<td>TABLE OF FIGURES</td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>TABLE OF PLATES</td>
<td>vi</td>
</tr>
<tr>
<td></td>
<td>ABSTRACT</td>
<td>vii</td>
</tr>
<tr>
<td>I</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>FORMER WORKS</td>
<td>4</td>
</tr>
<tr>
<td>III</td>
<td>BACKGROUND AND EXPERIMENTATION</td>
<td>9</td>
</tr>
<tr>
<td>IV</td>
<td>MATHEMATICAL ANALYSIS</td>
<td>19</td>
</tr>
<tr>
<td>V</td>
<td>NOZZLE DESIGN</td>
<td>43</td>
</tr>
<tr>
<td>VI</td>
<td>CHRISTENSEN PROJECT: CONSTRUCTION</td>
<td>48</td>
</tr>
<tr>
<td>VII</td>
<td>CHRISTENSEN PROJECT: OPERATIONAL SYSTEMS DESCRIPTION</td>
<td>56</td>
</tr>
<tr>
<td>VIII</td>
<td>A LOOK TO THE FUTURE</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>LITERATURE CITED</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>BIBLIOGRAPHY</td>
<td>93</td>
</tr>
</tbody>
</table>
APPENDIX A  ASSEMBLY DRAWINGS
APPENDIX B  SPECIFICATIONS
APPENDIX C  OWNER'S REPORT
APPENDIX D  PROPERTIES OF INVISCID OSCILLATIONS
APPENDIX E  THE INVISCID SHEAR LAYER
APPENDIX F  INVISCID JETS AND WAKES
APPENDIX G  SOME PROPERTIES OF VISCIOUS OSCILLATIONS
APPENDIX H  FLOWS IN CIRCULAR TUBES
APPENDIX I  HELMHOLTZ INSTABILITY
APPENDIX J  PLATES ILLUSTRATING CONSTRUCTION
<p>| FIGURE 1 | TEST STANDS | 12 |
| FIGURE 2 | DISTURBANCES OF LIQUID JETS | 24 |
| FIGURE 3 | BREAKUP CURVE OF LIQUID JETS | 26 |
| FIGURE 4 | DISTURBANCES OF LIQUID SHEETS | 29 |
| FIGURE 5 | BREAKUP CURVE OF LIQUID SHEETS | 31 |
| FIGURE 6 | LIQUID BEAD FORMATION | 35 |
| FIGURE 7 | CONFIGURATION OF A WATER BELL | 39 |
| FIGURE 8 | NOZZLE ISOMETRIC | 45 |
| FIGURE 9 | PUMP INTAKE FILTERS | 58 |
| FIGURE 10 | MAIN FILTER TANK | 61 |
| FIGURE 11 | MAIN EQUIPMENT COMPARTMENT LAYOUT | 62 |
| FIGURE 12 | ELECTRICAL FILTER ANALOGUE | 63 |
| FIGURE 13 | EXPLODED VIEW OF MANIFOLD ASSEMBLY | 66 |
| FIGURE 14 | PLAN VIEW OF PROJECT | 71 |
| FIGURE 15 | CONTROL PANEL | 72 |
| FIGURE 16 | ELECTRONIC LEVEL SENSOR | 73 |
| FIGURE 17 | ELECTRICAL SCHEMATIC | 74 |</p>
<table>
<thead>
<tr>
<th>Plate</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laboratory Water Bells</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>The Christensen Project</td>
<td>49</td>
</tr>
<tr>
<td>3</td>
<td>Pump Intakes</td>
<td>59</td>
</tr>
<tr>
<td>4</td>
<td>Main Filter Tank</td>
<td>59</td>
</tr>
<tr>
<td>5</td>
<td>Pump and Manifold Assembly</td>
<td>67</td>
</tr>
<tr>
<td>6</td>
<td>Control Panel</td>
<td>67</td>
</tr>
<tr>
<td>7</td>
<td>Main Equipment Compartment</td>
<td>80</td>
</tr>
<tr>
<td>8</td>
<td>Control Panel Artificial Rock Cover</td>
<td>80</td>
</tr>
<tr>
<td>9</td>
<td>Artist's Design Rendering of Conquistador Building Fountain</td>
<td>88</td>
</tr>
</tbody>
</table>
The application of axisymmetric laminar fluid flow to the area of fountain design is studied. The fluid mechanical background of laminar flow is researched, along with the detailed mathematical analysis of the underlying principles. Designs are developed for nozzles capable of generating large scale, free flowing laminar streams. Concurrently, artistic designs for fountains based on laminar flow are pursued, and subsequently a working fountain is built. Finally, consideration is given to imaginative future projects employing what has been discovered and developed during the course of this research.
SECTION I

INTRODUCTION
INTRODUCTION

Man's knowledge of hydraulics and fluid mechanics has always been applied to solve practical problems associated with the transportation of liquids, the storage of liquids, the production of energy, and the control of floods to name just a few. Man has also applied the principles of hydraulics to enhance his world in the form of fountains and pools, but this application has fallen short of its potential. There are many fascinating phenomena of fluids which are understood and used in a practical sense but which have seldom if ever been applied to give variety to fountain design. Fountain design in general is based upon the principal of turbulent flow. That this is true is evident from the fact that most fountains spray jets of water up into the air in various configurations, run water down over rocks or concrete blocks in simulated water falls or shoot water against or drip water on various shapes. The water in these kinds of fountains is controlled to the extent that it comes out where it is supposed to and usually stays within the boundaries of the fountain. However, if more control is designed into the fountain, a variety of visual effects may be achieved instead of just splashing and spraying. One of these possible effects is laminar flow. Laminar streams flow very smoothly, without breaking up into droplets and without splashing or spraying. This phenomenon of laminar flow is due to the fact that the water particles follow parallel paths, whereas water particles in turbulent flow cross paths constantly and a great deal of mixing occurs. Laminar flow may be used in a variety of ways, such as laminar sheets, laminar jets (axisymmetric), and laminar "water bells."
A "water bell" is a bell-shaped laminar sheet of water which is formed when two axi-symmetric laminar jets impinge on each other.

The purpose of this project, at its commencement, was to study the decorative aspects of axi-symmetric laminar flows and "water bells". It was desired to develop some nozzle design criteria to produce laminar flow (axisymmetric), for different fountain applications. However, after a brief period of experimentation, an opportunity arose to actually design and construct such a fountain. Formal experimentation came to an end, but experimentation did continue on a more pragmatic basis as problems arose during the fountain's construction. The construction of a fountain was a valuable experience in that much was learned about the physical limitations of such a system.

Future effort will center on experimentation to establish more fully the effects of the different parameters involved in the design of the nozzles.
SECTION II

FORMER WORKS
FORMER WORKS

For more than a century and throughout many countries, the behavior of axisymmetric liquid jets and axisymmetric liquid sheets, formed by the collision of two liquid jets or one cylindrical jet impinging upon an object, has been studied. This phenomenon was first studied by Savart [1] in the 1830's, who, in his classical memoir, described the appearance and behavior of the liquid sheet produced when a downward vertical jet of water impinged on a small, horizontal circular plate, or a similar coaxial vertical jet projected upwards. The water spreads out horizontally and falls under the effect of gravity. This liquid sheet, under certain conditions, forms approximate hemispherical forms often termed "water bells." Since this time, the dynamical behavior of liquid jets and liquid sheets has been the topic for many investigations.

The first theoretical analysis of jet disintegration was conducted by Rayleigh [2,3,4], who considered capillary force to be of prime importance. Other experimental analysis has been contributed since then by Miesse [5], Haenlein [6], Merrington and Richardson [7], Schweitzer [8], and Tyler [9]. Weber [10] probably developed the most rigorous mathematical analysis of cylindrical jet disintegration in low velocity to date. He extended Rayleigh's work to include the effect of viscosity, with these results agreeing very well with Haenlein's experimental data. Since Weber's analysis, Tomotika [11] has examined the relatively low velocity injection of a liquid jet into another liquid surrounding; the results of which indicate the viscosity ratio of the jet and the sur-
rounding medium to be of prime importance. Gavis and Middleman [12, 13] published several works on the expansion and contraction of capillary jets, finding that the ratio of the final jet diameter to nozzle diameter to be a function of Reynolds and Weber numbers. More recently, the expansion and contraction behavior of laminar liquid jets was reported on by Oliver [14], Chandrasekhar [15] and Alterman [16] investigated the magnetic field effect on the capillary instability of the liquid jet. In addition to the study of instability of liquid jets, areas of investigation included breakup length and velocity distribution of jets.

Here, the relationships between the breakup length of a jet and jet velocity, laminar or turbulent flow, and the physical characteristics of the liquid, were investigated by Smith and Moss [17], Tyler and Richardson [18], Tyler and Waltkin [19], Haenlein, and most recently by Grant and Middleman [20]. The velocity profile of a laminar jet issuing from a tube, and its subsequent profiles downstream have been studied by Rupe [21], who hypothesised that the changing velocity profile might hasten the breakup mechanism. Recently, Brun and Lienhard [22] did a numerical solution of an approximate form of the Navier-Stokes equation describing the velocity distribution in a free jet leaving a Poiseville tube. The impingement angle of two jets issuing from tubes and the length of jets before impingement, both of which change the behavior of the sheet that is formed, were studied by Dombrowski and Hooper [23], and Heidmann and Humphrey [24]. Thus far, this review has dealt entirely with the works on the dynamics of a cylindrical jet. The following will review previous works on liquid sheets formed by the collision of two jets.
As was mentioned earlier, Savart first described the water bell in his memoir. Boussinesq [25, 26] in 1869 and in 1913 applied the differential equation to the form of these liquid sheets and solved it numerically for a few examples. The dimensions of liquid bells for varying flow rates were measured by Buchwald and Konig [27, 28] in 1935 through 1936. During the same time period, Bond [29], in his experiments, measured the dimensions of a horizontal sheet formed by the collision of two vertical jets. From his experiment, he inferred the surface tension value of water. Puis [30] likewise determined the surface tension of mercury by the same procedure. In 1952, Hopwood [31] produced and studied saucer-shaped liquid bells caused by a difference in pressure between the inside and outside of the bell. Lance and Perry [32] continued with Hopwood's work in 1953 and determined equations describing such a bell, and calculated solutions to particular cases by using an extension of Euler's polygon method for the solution of first order differential equations.

To this point in time, investigators failed to find an analytical solution. However, in 1959, G. I. Taylor [33], using Lance and Perry's work as a basis, developed a general water-bell shape equation in dimensionless form, the solution of which was based upon the assumption that gravitational forces and air drag are negligible.

The mechanism of the breakup of thin liquid sheets has still not been explained fully. Two empirical laws for the relationship between the diameters of expanding circular sheets, the pressure of the fluid which produces the jets, and the diameter of the two orifices were
proposed by Savart. Bond derived a formula for maximum radial distance to which a moving sheet will extend, with which Taylor agreed. In 1953, Dombrowski and Fraser conducted a photographic investigation of the disintegration of several liquid sheets. The conclusion of that investigation was that these liquid sheets break up due to the formation of perforations; these perforations expanding due to surface tension. Howarth [34] investigated the boundary layer problem of the motion of the air adjacent to thin liquid sheets moving in still air, whose results were applied by Taylor to the calculation of skin friction. Most recently Huang [35, 36] extended Taylor's equation to include air drag and gravitational effects on the water bell and its breakup mechanism.
SECTION III

BACKGROUND AND EXPERIMENTATION
BACKGROUND AND EXPERIMENTATION

The original idea for this project was conceived in the spring of 1975 during a lecture in a hydraulics class on the possible decorative applications of hydraulic principles. Professor Bard Glenne mentioned a fountain utilizing the principle of axi-symmetric laminar flow which Professor John Roberson of Washington State University had designed for the Spokane World's Fair. A letter was sent to Prof. Roberson inquiring as to any sources of information on the subject which he could recommend. He responded with a sketch of the nozzle which he had used in his fountain and two publications on axisymmetric laminar flow and the formation of water bells.

The summer of 1975 was spent in reading those publications and in constructing two nozzles somewhat similar to those that Prof. Roberson had designed. These nozzles differed somewhat from those of Prof. Roberson in that they were longer, smaller in diameter, and had more screens to act as baffles. They resembled the nozzles finally used in the fountain construction. Some back yard experimentation was undertaken to establish qualitative relationships between some of the parameters involved. Several different sizes and shapes of orifices were tried to see if there was a relationship between orifice shape and size and nozzle diameter. It was found that circular was the best orifice shape because the discontinuous end conditions of the other shapes caused contractions in the sides of the stream which led to its breaking up into turbulent flow. It was also noticed that there was a relationship between the nozzle diameter and the maximum size of stream which that nozzle could support, however
this relationship could not be determined in a back yard. It was observed that there was a limit to the angle of arch which a given stream could support without breaking up into turbulent flow before it hit the ground. As the angle of arch was increased, the vertical velocity of the downward portion of the arch increased faster due to the acceleration of gravity. As the velocity of the stream increased, the area of the stream increased (from continuity, area \times velocity = constant) until it started to pinch off into droplets. This same effect was observed by varying the velocity of the stream at the nozzle instead of the angle of the arch.

Air from the water supply system had a tendency to collect on the screens. A little air would not disrupt the flow too much, but as the air built up, the laminar flow would deteriorate. At this point the only solution to this problem was to drain the nozzles and then refill them very slowly to keep air from being entrapped as they filled. It was possible to create a water bell by directing the laminar stream against smooth concave objects such as spoons, but it proved to be difficult to form a bell using two laminar streams. The difficulty was in holding the nozzles steady enough to maintain equilibrium. The main objective at this time was to reproduce a water bell similar to the ones achieved by Prof. Roberson, so it was decided to build some test stands.

The first test stands, built in the fall of 1975, were the vertical stands shown in Figure 1. It was felt that this system would be easily adjustable and would have enough stability to maintain the equilibrium necessary for a water bell. With these stands, one nozzle was suspended from the top plate about six feet above another nozzle which was supported
Figure 1 Test Stands

NOTE: FASTENER HOLES DRILLED IN TEST STANDS ARE SPACED TO ACCOMMODATE THE LARGE AND SMALL NOZZLES.
by the bottom stand. The nozzles were supplied by a garden hose from the water supply of the Merrill Engineering Building. The water from the nozzles was wasted to a holding tank which was pumped out occasionally. The procedure was to first align the nozzles by turning on the top stream and adjusting the bottom nozzle until the stream from above fell squarely on the orifice below. The bottom nozzle was then turned on and fine alignment was achieved by means of the level adjusting bolts on the bottom stand. It was possible to create a water bell with this set up, and by slowly adjusting the flow to one of the nozzles, the bell would seemingly float up and down, but there were several flaws. One of the major flaws of the supply was its inconstancy. Pressure fluctuations in the system would disrupt the flows even after pressure regulators were added. Water bells were possible only late at night or on Saturdays when the building's water system was not being used. This led to the proposal of using either a pumped system or a constant head tank. There was still the problem of air accumulating on the screens from the system. Large amounts of air would come into the nozzles as air pockets in the system were washed out. This was somewhat alleviated by placing stop-cocks in the nozzles which could be operated by hand to let the air out. The other flaws were in the test stands themselves. Because the nozzles were positioned vertically one above the other, the water from the top nozzle would accelerate as it fell and the water from the bottom nozzle would decelerate as it rose. The water supply to the bottom nozzle had to be increased or else the bottom stream would be drowned out by the top stream. Under these two conditions, the streams met with
such force that only a small water bell was formed and the water droplets sprayed out to wet an area twenty feet in diameter. The stands were also not as sturdy or as easy to adjust as originally hoped. If the two streams got out of alignment just a little, the top frame would begin to rock back and forth and break up any semblance of a water bell or of laminar flow. It was thought that if larger nozzles were built, which could support larger streams, the water would not spray as much because the velocities would be lower. Larger nozzles were built through the sponsorship of Mr. Gordon Christensen. The length and screen-spacing of the original nozzles were retained, but the diameter was increased from six inches to ten inches and interchangeable orifice plates were machined in order to more easily vary the orifice diameter. Air relief valves were also added to these nozzles to replace the hand operated stop-cocks and the screen mesh size was increased from 50 to 20 divisions per inch to allow air to pass through more freely. Increasing the mesh size did not seem to have much effect on the performance of the nozzles. Such a nozzle is shown in Figure 8. Larger nozzles and larger orifices did not alleviate the problem of spraying. The reasoning behind the solution was faulty in this case. The velocity of the water in the top stream did not depend on the diameter of the orifice plate, but on the acceleration due to gravity. It was concluded that spraying could be curtailed only if the vertical separation of the nozzles was reduced to just a few feet, which would reduce the build up of velocity due to gravity. This was impossible with the vertical stands. The vertical method of testing was therefore abandoned and a new set of stands were designed. These were the
cannon type stands shown in Figure 1. They were made of quarter inch plate steel in order to avoid any instability problems. Provisions were included for horizontal and vertical angle adjustment of the nozzles. These stands proved to be a bit unwieldy for initial alignment, but the increased stability was helpful. The alignment procedure for these stands was similar to that for the vertical stands. One nozzle was turned on and the stream adjusted to hit in the orifice of the other nozzle, then the other stream was turned on and fine adjustment made by means of the screws in each stand. It was discovered that a clear piece of plexiglass was very helpful in the fine alignment of the streams. The plexiglass was placed in the stream at the place where the water bell was desired. The ends of each stream could be seen through the plexiglass, facilitating alignment. Generally, the same qualitative results were obtained with the new stands and the larger nozzles, except that it was now possible to create some very nice water bells, as shown in Plate 1. If the streams were very carefully aligned and the arches very closely matched, it was noticed that the water bell would wander back and forth along the arch without any external influence. In order to maintain the water bell in one place, it was necessary to put the arches or streams just slightly out of alignment. This would result in just one position of equilibrium between the two streams instead of many. However, if the streams or arches were too much out of alignment, the water bell would not be stable. It would appear momentarily and then equilibrium would be lost and the streams would splash around for awhile until equilibrium was momentarily relocated. A problem did arise which had not been present with the
Water bell formed using vertical test stands

Water bell formed using cannon type test stands

Plate 1 Laboratory Water Bells
vertical stands. The water coming from the top part of the water bell would fall back on one of the laminar streams, causing it to break up and to break up the water bell in turn. This situation was controlled by adjusting the streams so that the bell formed near one of the nozzles and the water would fall back over the nozzle instead of over the laminar stream. This was not much of a problem with the larger orifice sizes because the falling water didn't have much effect on the larger streams. The larger nozzles could support a laminar stream of up to one inch in diameter, but smaller diameter orifices were used most often because it was impossible to get enough water through a 3/4 inch garden hose, at a reasonable velocity, to supply a one inch stream of water for any distance.

Experimentation for nozzle design pretty well came to an end late in the fall of 1975 because Mr. Gordon Christensen was interested in having a fountain of this type constructed in his recently completed office building. This offer was accepted because it provided an opportunity to study the nozzles more pragmatically as part of a complete system rather than as just one component. The construction of this fountain will be discussed in a later section. Experimentation and discussion did continue, however, in order to solve problems related to the fountain operation. The problem of air accumulation on the screens seemed to be a major obstacle to successful fountain operation. In order to determine the effect of continuous operation on air accumulation, a nozzle was run continuously for a week on a recirculating system. Air did accumulate to a great extent, so it was decided to put the fountain on a timed system which would shut the streams off and drain the nozzles
every night. The air accumulation over an eight hour period was not detrimental and the nightly draining relieved the air which had accumulated during the day. In combination with the air relief valve, this proved to be an effective solution. Another problem which seemed likely to occur was mineral deposition on the screens of the nozzles. However, after a discussion with a professor on the subject, it was decided that the water from the city water supply was not heavily enough mineralized to present a problem. It was also feared that perhaps algae would begin to grow in the nozzles and clog them up. It was soon realized that this was not a problem because the nozzles would be sheltered from the light, the system itself would be somewhat isolated from any external influences, and the system would be replenished often enough from the city water system so that the chlorine residual would kill any algae present.

It is obvious, from the preceding account, that the project followed a different route than originally planned. The experimentation never evolved past the qualitative stage, but this stage was important because most of the problems have now been worked out of the testing system. Future experimentation will center on generating some curves relating the critical orifice diameter with nozzle diameter and the critical vertical angle with stream velocity. Dye tests will also be run in the future to determine the effect of the number and spacing of screens on the flow.
SECTION IV

MATHEMATICAL ANALYSIS
MATHEMATICAL ANALYSIS

It is the intent of this section to present a brief mathematical analysis of the formation and of the breakup regimes of cylindrical liquid jets and thin liquid sheets. The emphasis of our research was not in analyzing this fluid flow phenomenon, but adapting its unique characteristics for use in an architecturally pleasing fountain. The mathematics presented here represented a starting point of this research; for it was felt that a general understanding of the fluid properties involved in this type of flow was needed when attempting to design a successful nozzle.

The theory is complex; so complex, that to totally cover the topic, a book of considerable size would be needed. Therefore, a synopsis of the analysis is presented in the following few pages, with references to several theories involved with the analysis listed in the Appendices.

Cylindrical Liquid Jet

The geometry of cylindrical liquid jets is analogous to the theorems on stability that have been used in Cartesian geometries, such as those proposed by Rayleigh (cf. Appendix D) and the same generalities apply as applied to two-dimensional analysis of axisymmetric flows (cf. Appendix E, F, G).

Batchelor and Gill [37] have made a thorough analysis of the cylindrical jet, which is presented outlined here. The example carries all of the generalities of any axisymmetrical flow of this kind,
subject to inviscid stability considerations.

The mean profile for the axisymmetric jet is given by the stream function:

\[ \psi = \frac{2\nu r \sin \theta}{\text{sech} \theta - \cos \theta} \]

(1)

where \( \tan \theta = e/x \) and the terms defined as follows:

- \( x, y, z \) = cartesian coordinates
- \( \theta \) = density fluctuations; function of \( x, t \)
- \( t \) = time
- \( \nu \) = kinematic viscosity
- \( r \) = radius
- \( \psi \) = stream function

Batchelor and Gill utilize Equation 1, together with the approximation corresponding to far downstream conditions and express the mean flow by:

\[ U = \frac{U_0}{[1 + (r/r_o)^2]} \]

(2)

with \( U \) defined as the mean velocity component. Perturbations are introduced and follow the governing equations A5-1 through A5-4 (cf. Appendix E) when \( \nu = 0 \). Boundary conditions require all perturbations to vanish at infinity. Batchelor and Gill then proceed to show that the other condition of \( p = 0 \) must be such that multiple values of pressure and velocity can be avoided. Thus \( u \) and \( p \) must vanish if \( n = 0 \) and \( v \) and \( w \) must vanish if \( n = 1 \). In the latter case, the combination of \( v + zw \) must be equal to zero at the origin by the flow geometry. The characters \( u, p, v, \) and \( w \) are defined as
complex amplitudes, being functions of $y$ only.

Considering the inviscid set of equations, it is possible to eliminate $u, w, \text{ and } p$ and obtain the Rayleigh equation valid for any $n$, namely

$$
(U - c) \frac{d}{dr} \left[ \frac{r(d/dr)(rU)}{n^2 + k^2 r^2} \right] - (U - c)v - rV \frac{d}{dr} \left( \frac{rU'}{n^2 + k^2 r^2} \right) = 0
$$

(3)

with $c =$ complex phase velocity $= c_r + ic_i$

$k =$ real positive wavenumber.

$n =$ integer

Several general results from an inspection of (3). The generalization of the inflection point theorem, that is, when $n \neq 0$, is expressed by the requirement that

$$
\frac{d}{dr} \left( \frac{rU'}{n^2 + k^2 r^2} \right) = 0
$$

(4)

must occur somewhere. Batchelor and Gill used this result to illustrate that when $n$ is large complete stability occurs, regardless of the jet velocity profile.

Detailed computations were made by Batchelor and Gill for the stability of a jet with a tophat profile. Since it was not studied in our research, it will not be presented. However, a qualitative description of the instability and breakup lengths of liquid jets follows.

At low velocity, any disturbance causes the jet to assume symmetrical or delational oscillations which have a certain wave length $\lambda$. Illustrations of symmetric and antisymmetric disturbances on a jet
are illustrated in Figure 2. If the wavelength \( \lambda \) caused by the initial disturbance is less than a particular value, \( \lambda_c \), the critical wavelength, then the surface tension will tend to damp out the disturbance. If \( \lambda \) is greater than \( \lambda_c \), surface tension will tend to increase the disturbance, which ultimately results in the disintegration of the jet. However, there exists a wavelength \( \lambda_d \), which is most favorable for drop formation and is sometimes called the most dangerous wave length. For inviscid liquids:

\[
\lambda_c = \pi d; \quad \lambda_d = \sqrt{2} \pi d \tag{5,6}
\]

For viscous liquids:

\[
\lambda_c = \pi d; \quad \lambda_d = \sqrt{2} \pi d \left(1 + \sqrt{2} \frac{W_e}{R_c}\right)^{1/2} \tag{7,8}
\]

where the Weber number and Reynolds's number are defined as:

\[
We = \frac{\rho U^2 d}{\sigma} \tag{9}
\]

and

\[
Re = \frac{\rho Ud}{\mu} \tag{10}
\]

respectively, with terms defined as follows:

- \( d \) = diameter of nozzle, orifice, or tube
- \( \mu \) = viscosity of liquid
- \( \sigma \) = surface tension of liquid
- \( \rho \) = density of liquid
- \( U \) = average velocity of the jet

As can be seen, the dangerous wave length is greater for viscous liquids, whereas the critical wave length remains unchanged.
Figure 2: Disturbances of Liquid Jets

(Huang, 1967)
The relative motion between the moving jet and the surrounding gas causes Helmholtz instability (cf. Appendix I). As the jet velocity increases, the effect of Helmholtz instability increases and the disturbances on the jet will change from dilational waves to sinuous disturbance.

The characteristic curve of the breakup length of jets is shown in Figure 3. This plot represents one value of the density ratio between the liquid jet and the surrounding gas, such as a water jet in air. If the density ratio changes, the position of the entire curve will change, but the general shape remains the same. The liquid jet in the linear portion AB of the curve possesses only symmetric disturbances and is influenced only by surface tension and inertia force of the liquid. Therefore, the Weber number is the controlling factor in this range. Weber's prediction for the breakup length of the jet is

$$L_b = \frac{\ln \frac{n_b}{a}}{d} \left( \sqrt{W_e} + 3 \frac{W_e}{R_e} \right)$$

where $n_b$ is the displacement of the jet at the breakup point, and $a$ is the maximum deviation of the jet from the unperturbed position within the validity of the linear theory. The parameter $\ln(n_b/a)$ must be determined experimentally; Weber reported a value of 12. The departure from linearity at point B and the subsequent form of the curve have been ascribed to the influence of Helmholtz instability. At the critical point C, the jet reaches a maximum breakup length. From C to E, the disintegration mechanism of the jet is characterized
Figure 3 Breakup Curve of Liquid Jets
(Huang, 1967)
by antisymmetric disturbances. The Weber number is still the major variable determining the breakup length, but the Reynolds number has a minor effect.

The dotted line D to F designates the breakup length for turbulent jets. One can deduce that turbulence seems to stabilize the jet.

In the above discussion of instability and breakup length, it is assumed that the velocity distribution is uniform throughout the jet, which is correct for the streams obtained when issuing from a sharp-edged orifice. However, when a laminar jet leaves a tube, a parabolic velocity profile is obtained; and this profile gradually flattens out further downstream. This changing velocity profile, it has been hypothesised, might hasten the breakup mechanism. It is thought that the decay of the laminar parabolic velocity profile to a flat profile results in the creation of a radial pressure gradient, which produces a radial velocity component. Once these radial velocities overcome the inertia and surface tension forces, the jet disintegrates.

So far, the analysis has dealt with the analysis of the cylindrical jet. This section will now focus its attention to the analysis of the liquid sheets, and then conclude by briefly reviewing the dynamical analysis of the total system of jets and bells.

Axisymmetric Liquid Sheets

For laminar liquid sheets, a nearly flat sheet is obtained at a low pressure head and a wavy sheet is obtained at a high pressure head. For a low velocity regime, the diameter of the circular sheet
is proportional to the square of the diameter of the two orifices of the nozzles. The formula for this is derived by equating the outward momentum of the moving sheet of the inward force of surface tension and is given by

\[ 2(2\pi R_0) = Q\rho U \]

or

\[ R = \frac{Q\rho U}{4\pi \sigma} \]  

with

- \( Q \) = flow rate
- \( U \) = velocity of sheet
- \( \rho \) = density of the fluid
- \( R \) = radius
- \( \sigma \) = surface tension

which is true under the condition that no other forces are applied at the surface or edge of the liquid sheet.

When sheet velocity is high, Helmholtz instability will cause waves on the sheet. It has been found that, as is the case, for cylindrical jets, liquid sheets have two types of oscillations, antisymmetrical and symmetrical. In the asymmetric wave the displacements of opposite surfaces of the sheets are in phase; in the symmetric wave, the displacements of opposite surfaces of the sheet are in opposite phase (cf. Figure 4).

The wave amplitude \( \eta \) is assumed to be of the form:

\[ \eta = ae^{i(kx - wt)} \]  

(12)
Figure 4 Disturbances of Liquid Sheets
(Huang, 1967)
with $a$ = maximum deviation from the unperturbed interface

$k$ = wave number

$w$ = angular frequency

If $w$ is real, then the sheet will remain stable, but if $w$ also possesses an imaginary value, then the disturbance will grow. Using Squire's work as an illustration for antisymmetric waves on a two-dimensional sheet of constant thickness $h$, applying the theory of Helmholtz instability, the derivations for $w_i$ and $w_r$ - the real and imaginary components respectively - is as follows:

$$w_r = kU/\left[1 + \rho_r \coth(kh/2)\right]$$

(13)

$$w_i = w_r \left[\rho_r \coth(kh/2)(1 - \sigma k^2/\rho_a U w_r)\right]^{1/2}$$

(14)

where $\rho_r$ = density ratio of the surrounding gas $\rho_a$ and the liquid $\rho$ and the other factor being defined as before. With $kh < 2$, coth $(kh/2) \approx 2/kh$, and neglecting the smaller order terms, the most dangerous wave length, $\lambda_d$, is

$$\lambda_d = \frac{4\pi \sigma}{\rho_a U^2}$$

(15)

and the corresponding maximum growth rate is

$$w_{c_{\text{max}}} = \frac{\rho_a U^2}{\sqrt{2\sigma \rho h}}$$

(16)

A characteristic breakup curve, much like that for the cylindrical jets, exists for the sheets. Again, this characteristic curve could represent any liquid in a gas medium, but in this discussion, the system is water in air. For other fluids, the curve would be similar but shifted. The curve (cf. Figure 5) consists of three distinct regimes.
Figure 5 Breakup Curve of Liquid Sheets
(Huang, 1967)
The first portion from A to B (linear in log-log scale) represents a stable liquid sheet regime. The sheet develops a near perfect circular edge in this regime. The curved portion from B to C to D is termed the transition regime. From B to C, the liquid sheet forms a cusp-shaped edge. In the critical zone C, the sheet obtains a maximum breakup radius. Within the region from C to D, the cusps on the edge of the water bell diminish in size and the edge remains fairly circular; with large-amplitude, antisymmetric waves forming. The second linear portion, from D to E, represents an unstable regime for the liquid sheet. The large-amplitude, antisymmetric waves become more pronounced and the liquid sheet flaps in a wave-like motion.

These three regions are designated breakup regime I, the transition regime, and breakup regime II, respectively. A more detailed analysis for each section is presented for a water-in-air system.

Breakup Regime I

In the first breakup regime, the inertia force exerted radially outward on the edge of the circular sheet is balanced by the inward radial and circumferential surface forces. The force balance on the edge of the liquid sheet is then

\[
\begin{bmatrix}
\text{Inertia force which acts radially outward}
\end{bmatrix} = \begin{bmatrix}
\text{Surface tension force which acts radially inward}
\end{bmatrix} + \begin{bmatrix}
\text{Surface tension force which acts circumferentially inward}
\end{bmatrix}
\]

(17a)
or

\[ Q_pU = 2(2\pi R_o) + \frac{\sigma}{R} (2\pi R h_b) \]  

(17b)

where \( R = \) maximum radial distance to which the liquid sheet can extend

\( h_b = \) thickness of the sheet at the edge

The flow rate \( Q \) is equal to

\[ Q = 2\left(C_c \frac{\pi d^2}{4}\right) U = 2\pi R h_b U \]  

(18)

or

\[ h_b = \frac{Q}{2\pi RU} = \frac{C_c d^2}{4R} \]  

(19)

After substituting equation (19) into (17b), \( R \) is obtained as

\[ \frac{R}{d/2} = \frac{C_c}{8} \text{We} + \frac{1}{2} \left[ \frac{C_c}{4} \text{We}^2 - 2C_c \right]^{1/2} \]  

(20)

The negative component of the bracket termed is dropped for it is physically impossible. The last term may be neglected for most cases (unless the Weber number is less than 10). Equation (20) then is

\[ \frac{R}{d/2} = \frac{C_c}{4} \text{We} \]  

(21)

If the average value of \( C_c = 0.67 \) obtained by Hsich under low pressure head is used, Equation (21) becomes

\[ \frac{R}{d/2} = 0.167 \text{We} \]  

(22)

which agrees well with experimental data of Huang.
The physical model for the formation of liquid beads along the periphery of the liquid sheet is assumed as shown in Figure 6. When the liquid arrives at the edge, the surface-tension force balances the inertia force. Small disturbances in the radial direction will roughen the smooth cylindrical edge. The forces across the interface along the perturbed semicylindrical edge can be expressed as

\[
\begin{align*}
\text{Fluctuation pressure between liquid and gas interface} & = \text{Pressure difference across the interface caused by surface tension on the curve in the } \varepsilon \text{-direction} + \text{Pressure difference across the interface caused by surface tension on the curve in the } r \text{-direction} \\
\end{align*}
\]

Since \( R >> \frac{h_b}{2} \), \( \varepsilon \) can be assumed as a straight line in comparison with the curvature \( \frac{h_b}{2} \). Then the first and second terms on the right-hand side of the equation represent the axial, \( \varepsilon \), direction and transverse, \( r \), direction surface tensions. Lienhard and Wong applied Rayleigh-Taylor's linear instability theory and obtained the equations for critical and most dangerous wave lengths.

\[
\lambda_c = \frac{2\pi}{\sqrt{\frac{g(\rho-\rho_a)}{\sigma/2/h_b^2}}} 
\]

\[
\lambda_d = \frac{2/3\pi}{\sqrt{\frac{g(\rho-\rho_a)}{\sigma/2/h_b^2}}} 
\]

where \( g \) = gravitational acceleration

\( h_b \) = thickness of liquid sheet at edge
Figure 6 Liquid Bead Formation
(Huang, 1967)
However, the predicted $\lambda_d$ is somewhat smaller than its real-life counterpart because beads of water are several times larger than $\lambda_d$.

Transition Regime

When the Weber number of the liquid sheets goes slightly beyond regime I ($> 500$), small disturbances originate at the colliding point of the two jets. These disturbances originating at the center of the sheet propagate throughout the sheet to the edge. The cusp-shaped edge is the result of these disturbances and follows a fairly regular pattern. This disturbance at the center forms two cardoidal wave lines, represented in polar coordinates $(r, \theta)$ as

$$\frac{2r}{R} = 1 - \cos (\theta - \theta_0)$$

(26)

where $R =$ maximum possible radius

$\theta_0 =$ constant representing the angular position measured from an arbitrary zero.

When the characteristic breakup curve reaches its critical zone $C$, liquid sheets generally are stable but are sensitive to any perturbation. No distinct cardoid wave edge is formed. The sheet reaches its maximum radius with an almost perfect circular periphery. When the sheet is perturbed by an external source, three different kinds of disturbances are known to exist.

1) U-shaped breakup

2) Portion of edge rolls up
3) Portion of edge rolls down
When the Weber number exceeds that of the critical zone (> 1000), the liquid sheet becomes slightly unstable. Antisymmetric waves propagate radially with growing amplitude.

Breakup Regime II
Increasing the Weber further (> 2000), the sheets become unstable. Little is known of this regime as compared to the other two. Characteristics of this regime include the formation of antisymmetric waves and the subsequent build-up and collapse of these at the edge and the many noticeable holes in the sheet due to an increase in sensitivity of the flow to outside disturbances.

The mathematical analysis has now generally covered the cylindrical jets and liquids sheets independently. This paper will now turn its attention to these two topics as a system and briefly present a mathematical background for such.

Dynamical Analysis of the System
When two jets impinge upon each other axially, the thin axisymmetric liquid sheet that is formed reveals certain unexpected behavior, namely the formation of water bells. The dynamical analysis of this phenomenon follows.

Let x and y be the axial and radial coordinates respectively. Two jets under the same heat with different diameters \( d_1 \) and \( d_2 \),
impinge from opposite directions along the x axis. They then spread out at an initial angle $\phi_0$ with respect to the x axis. The resulting thin liquid sheet moves in still air along a meridian curve, s, and forms a bell shape as shown in Figure 7.

Conservation of momentum of the incoming jets and the outgoing sheet requires that

$$\rho A_2 u_0^2 - \rho A_1 u_0^2 = \left[\rho (A_1 + A_2) u_0\right] u_0 \cos \phi_0$$

or

$$\phi_0 = \cos^{-1} \frac{A_2 - A_1}{A_2 + A_1}$$

(27)

where $\rho = \text{liquid density}$

$A_1$ and $A_2 = \text{cross sectional areas of jets 1 and 2, respectively.}$

$u_0 = \text{initial velocity at point of impingement.}$

The contraction coefficients of the jets are $C_{c1}$ and $C_{c2}$, respectively.

Therefore, Equation (27) can be written as

$$\phi_0 = \cos^{-1} \frac{C_{c2} d_2^2 - C_{c1} d_1^2}{C_{c2} d_2^2 + C_{c1} d_1^2}$$

(28)

A reference axis, z, will be established perpendicular to the surface as shown in Figure 6. The angle $\theta$ is the variable slope of the surface with respect to the vertical x axis, t is the thickness of the sheet of any point, $p$ is the pressure difference between the inside and outside of the bell, $a$ is the surface tension of the fluid, $u$ is the velocity of the moving sheet, and $r_c$ is the radius of curvature of a meridian section. The force-balance equation along the reference axis z is
Figure 7 Configuration of a Water Bell
(Huang, 1965)
\[
\frac{2\sigma}{r_c} + \frac{2\sigma \cos \phi}{y} - p + \rho g t \sin \phi - \frac{u^2 \rho t}{r_c} = 0
\] (29)

where the gravitational acceleration \( g \) carries a negative sign when the bell is concave upward.

The equation for the velocity \( u \) of the moving sheet, neglecting air friction, is

\[
\mathbf{u} = \mathbf{u}_0 + 2gx
\] (30)

In accordance with the continuity equation, the flow rate \( Q \) is

\[
Q = 2\pi y u t
\] (31)

and the following dimensionless group

\[
X = \frac{x}{R}; \quad Y = \frac{y}{R}; \quad R_c = \frac{r_c}{R}; \quad S = \frac{S}{R}
\] (33)

\[
U = \frac{u}{u_0}
\] (34)

\[
\alpha = \frac{\rho u_0 Q}{\pi \sigma^2} \rho
\] (35)

\[
\beta = \frac{\rho u_0 Q}{4\pi u_0 \sigma}
\] (36)

The terms \( \alpha \) and \( \beta \) represent the pressure difference and gravitational acceleration in dimensionless form respectively.

Using the geometrical relation

\[
r_c = -\frac{ds}{d\phi}
\] (37)
and substituting Equations (31) through (37) into (30), the non-dimensional equations

\[ -\frac{ds}{d\phi} \left(1 - \frac{U}{y}\right) + \cos \frac{\phi}{y} - \alpha + \beta \frac{\sin \phi}{Uy} = 0 \]  \hspace{1cm} (38)

and

\[ U^2 = 1 + 2\beta x \]  \hspace{1cm} (39)

are obtained. With these two equations and another geometrical relation

\[ \sin \phi = \frac{dY}{ds}, \]  \hspace{1cm} (40)

the shape of the water bell can be determined.

Neglecting the pressure difference and gravity acceleration, and settling \( U = 1 \), Equation (38) becomes

\[ \left(1 - \frac{1}{Y}\right) \sin \phi \frac{d\phi}{dY} = \frac{\cos \phi}{dY} \]  \hspace{1cm} (41)

Integrating and substituting in the boundary conditions

\[ \phi = \phi_o \ @ \ Y = 0 \]

yields

\[ (1 - Y) \cos \phi = \cos \phi_o \]  \hspace{1cm} (42)

Integration of the geometrical relation

\[ \tan \phi = \frac{dY}{dx} \]  \hspace{1cm} (43)

and substituting into Equation (42) gives

\[ X = \cos \phi_o \left[ \cosh^{-1}(\sec \phi_o) - \cosh^{-1}\left((1 - Y) \sec \phi_o\right) \right] \]  \hspace{1cm} (44)
or

\[ Y = 1 - \cos \phi_0 \left( \cosh \left[ \cosh^{-1} \sec \phi_0 - X \sec \phi_0 \right] \right) \]  

(45)

This final dimensionless solution is a simple relation between \( X \) and \( Y \), being symmetrical in \( X \) with respect to the maximum value of \( Y \).
SECTION V

NOZZLE DESIGN
NOZZLE DESIGN

An axi-symmetric laminar flow nozzle must be designed so that the paths of the water particles leaving the nozzle orifice are as parallel as possible. The problem is to straighten out the constantly crossing flow paths in ordinary turbulent flow. Laminar flow occurs at Reynold's numbers lower than 2000. The Reynold's number is a dimensionless parameter which is equal to velocity multiplied by diameter and divided by kinematic viscosity. Kinematic viscosity for water at constant temperature is constant, so the Reynold's number, in this situation, is controlled by the velocity of the flow and the diameter of the vessel through which it is traveling. It is desirable therefore to have as small a diameter and as low a velocity as possible. Since flow is constant, that is velocity multiplied by area is a constant, the body of the nozzle must be large enough to sufficiently reduce the velocity of the incoming water. However, increasing the area of the nozzle increases the diameter of the nozzle which would tend to negate the effect of reducing the velocity. This problem is solved by inserting a short section of soda straws, as shown in Figure 8, in the first part of the nozzle which provides a lot of small diameter pipes for the water to travel through. Laminar flow is created at this point. The screens on either side of the nozzle are simply to hold the straws in place. The section of straws is short to reduce the head loss due to friction from the sides of the straws, and to prevent the flow from developing a turbulent boundary layer caused by shear stress on the sides of the straws. The two other screens act as baffles to maintain the laminar flow set.
Figure 8 Nozzle Isometric

MATERIALS LIST
ITEM DESCRIPTION
1 STREET VALVE
2 BASE PLATE - SEE SHEET NO. 5
3 20 MESH SCREEN
4 20 MESH SCREEN
5 20 MESH SCREEN
6 20 MESH SCREEN
7 COLLAR - SEE SHEET NO. 5
8 RUBBER GASKET
9 \( \frac{1}{2} \) IN HEX HEAD BOLT WITH WASHERS AND NUT (10 REG'D)
10 SPACER - SEE SHEET NO. 4
11 ORIFICE PLATE - SEE SHEET NO. 5
12 FACE PLATE - SEE SHEET NO. 5
13 \( \frac{1}{4} \) IN HEX HEAD BOLT AND WASHER (6 REG'D)
14 AIR RELIEF VALVE
15 ACRYLIC TUBING - SEE SHEET NO. 4
16 PLASTIC SODA STRAWS
up in the soda straws. The orifice is machined to as sharp an edge as possible, as shown in the Figure 8, in order to preclude any turbulence which might be set up as the water flows through the orifice. If the orifice were just a hole drilled through the material, large shear stresses would develop as the water passed through it. These shear stresses would cause the boundary layer to become unstable and introduce turbulence into the stream. The most efficient number and spacing of screens in the nozzle is uncertain at this time. A test was conducted on one of the nozzles with the end screen removed. Under this condition, the nozzle would not sustain laminar flow as well as with the two screens in place. Therefore, it could be concluded that, for the set of parameters present in this nozzle, two screens are more effective. There are so many parameters involved which must be determined empirically, i.e. the length of the nozzle, the number of screens, the position of the screens, the length of the soda straws, the number of sections of soda straws (perhaps more than one would be helpful), the position of the soda straws, etc., that it would require a huge amount of experimentation, varying one parameter at a time, to find the most efficient system. It is felt that there is definite relationship between the maximum orifice size and the diameter of the nozzle. For a given number and spacing of straws and screens, this relationship could be determined by using a suitable measure, such as length of laminar flow at a given vertical angle and velocity, and interchanging orifice plates to vary the orifice size. As mentioned earlier, experience indicates that 20-mesh screen works well because that size allows air to pass more freely through the nozzle.
An air relief valve is required on each nozzle to bleed off any air which might pass through the nozzle. The nozzle was fabricated with removable face plates and removable spacers and screens so that it could be dismantled if it ever became clogged or needed cleaning.
SECTION VI

Christensen Project: Construction
Plate 2 The Christensen Project
CHRISTENSEN PROJECT: CONSTRUCTION

During the experimentation process in the laboratory, an opportunity arose to construct a working fountain in an office building. Although it was not expected that actual construction would be pursued so soon in the investigation, the offer was too good to refuse for two reasons:

1. It supplied the needed capital to continue research, and
2. It allowed the actual construction of a fountain where the many facets and complexities of installing and maintaining a working, decorative fountain could be explored.

Therefore, the offer of Mr. Gordon Christensen, owner of the Conquistador Building, was accepted and the design process initiated.

The location of the proposed site was 1354 East 3300 South, Salt Lake City, Utah, in the Conquistador Building. The design was to be incorporated within an existing planter in a center indoor atrium of the building. A rock waterfall and some large plants had already been installed (whose presence later proved to be very impeding as the construction process proceeded). The original design entailed two nozzles, to be located opposite each other length-wise in the fiberglass collection pond (cf. Figure 14). The materials necessary for two ten-inch diameter plexiglass nozzles were purchased, and the machine work commenced.

At this point in time, Ron Crosby, the set designer for Pioneer Memorial Theatre, was asked to aid as a design consultant. Upon his suggestion, a new and more elaborate design was conceived which would enhance the already existing landscape and visually uplift the garden area into the three-floor air space above the planter. All parties
involved agreed, and this design was pursued.

The design called for three nozzles to be placed behind the rock waterfall to create a fan-shaped effect as the three laminar streams shot out over the rocks, and for one nozzle to be placed in the fiberglass pool where its laminar stream would impinge upon the center stream of the other three nozzles, creating the water bell. Four nozzles were thus needed; two would have to be machined and the other two would be the smaller nozzles used in previous experimentation.

Although the construction of this laminar fountain involved many months of work, and many painstaking hours to solve numerous problems that were encountered, only the major points of the installation process will be mentioned.

About the first of November, 1975, the first shovelful of dirt was removed. Little was it known that it would be five months before the finishing touches would be added to complete what was thought to be a simple installation. Besides the system for supporting the laminar flow nozzles—which included a considerable amount of plumbing, as well as a pump, vibration dampeners, and much more—several other systems were added, some for the benefit and convenience of the owner, and others to safeguard the operation of the fountain. These are indicated in the following list and will be discussed subsequently:

1.) fountain system
2.) drain system
3.) watering system
4.) electronic control system
5.) lighting system

In addition, this section will briefly discuss the painting and final appearance preparation of the fountain.
The piping for the fountain was sized so that the flow conducted through it would be laminar, that calculation being based on expected volumes of the cylindrical streams (8 and 10 gallons per minute for the small and large nozzles respectively). Intakes were positioned in the collection pond (cf. Figure 9) and the necessary piping laid. Great care was taken when installing the intakes to prevent future leakage. A double-gasket pipe nut in combination with a plastic gel were used. The intake lines were laid on a 2% grade sloping from the intakes up to the pumps to allow the escape of air as the pool fills. An automatic air-bleeder was positioned on the top of the pump impeller housing to bleed off this air. A distribution manifold, fabricated and galvanized earlier, was positioned in the main equipment compartment (cf. Figure). To prevent clogging of the nozzles, a filter tank was located inline between the pump and manifold. It was designed so that ordinary furnace filters could be used and changed easily (cf. Figure 10). The nozzle stands were anchored to the concrete wall with lead plugs and bolts. To be able to fit the nozzles behind the waterfall, much rock was broken away to provide the needed area.

An unexpected problem surfaced when the fountain was turned on for the first time. The 3500 rpm of the centrifugal pump was transmitted throughout the system, causing the breakup of the cylindrical streams prematurely. Since this had not occurred in laboratory testing, the differences in the two systems were systematically reviewed to determine the reason for this happening. It soon became evident that the garden hose used in the laboratory acted as an absorptive element, thereby
dampening out the small vibrations. To carry this analysis further, an electronic analogy was made by comparing the system to a low-pass R-C (resistance, capacitance) filter network. For each nozzle, a 50-foot length of garden hose with an air surge tank located at mid-length acted as the R-C filter. The hose dampened out the small 3500 rpm noise; the surge tanks dampened out the larger oscillations of the system. Unlike a previous system by Dr. John Roberson of Washington State University, which used a constant head tank (the optimum solution), this system worked on a closed network recirculation system—the first of its kind for this purpose. The remainder of the work was everyday plumbing, as was the work for installing the drain and garden watering systems.

The drain system and garden watering system were added to the planter area. Since these systems were not originally present, it was felt that they would be beneficial and that the added convenience would create an additional incentive for the owner to maintain the proper fountain conditions. Quick-connects were provided as easy hook-ups to these systems.

As elaborate as the fountain itself, the electronic monitor and control system (cf. Figure 17) was designed to monitor all crucial aspects of the fountain and to allow the owner complete control (both through automatic and manual override options) of the operation of the fountain. The parts of this system are listed below:

1.) control panel
2.) water level monitor
3.) timer
4.) electrically operated diaphragm valve

The control panel (cf. Figure ) was installed to allow the operator finger-tip control of all fountain activities, as well as to provide
a visual readout of operational status. The water level monitoring device installed in the collection pond maintains a constant level of water and safeguards against a pump burn-out with a low-level-lockout feature. It was designed to maintain a constant head by triggering the diaphragm valve and allowing water from the city supply to enter the pool. Finally, a commercial timing device was installed to automatically turn on and off the fountain. A manual override of the timer was provided in the controls. A more detailed description of these elements is contained elsewhere in this report.

For an understanding of these systems and of the general layout, reference is made to the drawings and specifications of Appendices A and B.

In addition to the engineering aspects of the fountain, aesthetic constraints were imposed on all elements of the system. As the setting was very natural, all exposed elements—nozzles, control panel cover, and access lid of the main equipment compartment—were disguised under artificial rocks, modeled after the natural lava rock used in the rock waterfall. For this aspect of the design, theatrical scenic techniques were extensively utilized. Materials used to achieve the appearance of natural rock were fiberglass, wire, plaster, cork and epoxy paints. The wire was molded around the element to be covered, over which fiberglass cloth and plastic resin were spread to give strength and a unifying quality. On top of this, plaster and cork were added to give the desired rough texture. This product was then painted with epoxy paints to blend with the surroundings and to waterproof the plaster. In addition to
these artificial rocks, the existing waterfall was painted to cover all mortar joints and to add visual highlights to the drabness of the existing brown rock. Since the amount of water cascading down the rock prevented natural moss growth, paint was used to give the appearance of moss. The collection pond--originally a bright turquoise--was also painted to blend with the surroundings and to add an element of visual depth.

Although many hours of work, thought and worry were expended on the construction of this fountain, only a brief overview and a few highlights have been presented here.

In summary, the education received from this actual construction has proved invaluable. The large jump from laboratory experimentation to real-world application has been made. Although this step was not an easy one by any definition, it has answered numerous questions as to the future possibilities of working with laminar flow fountains.
SECTION VII

CHRISTENSEN PROJECT: OPERATIONAL SYSTEMS DESCRIPTION
FLUID SYSTEMS

The water-handling components of the fountain comprise three basic subsystems. One supplies the nozzles during normal fountain operation, one maintains a sufficient quantity of water in the fountain during normal operation, and the third is an independent drain system.

The design criteria for the recirculating nozzle supply consist of continuously recirculating the water through the system, and in so doing maintaining the pre-selected pressures and flow rates to each individual nozzle and to the waterfall. Additionally, the water must be filtered to remove dirt and debris. The water must also be supplied to the nozzles free of any vibrations or pressure surges from the pump or other system components. Each element in the system must be capable of purging itself of any air build-ups, and the filter units must be able to be simply cleaned.

The elements of the recirculating subsystem consist of filters, water lines, and a pump-distribution system. The filters are of two types; one is for debris and particulate matter removal, and the other is for vibration and surge removal. There are four debris removal filters. The first two (Plate 3 and Figure 9) are inside the pool at the intake. One is a coarse screened cage designed to stop leaves and objects such as paper towels which may be thrown into the pool. The second filter, located inside this cage, is a 50-mesh cylindrical intake. As the finest screen in the nozzles is 20-mesh, nothing which passes
ure 9 Pump Intake Filters
Plate 3 Pump Intakes

Plate 4 Main Filter Tank
the intake filters can be large enough to cause nozzle clogging.

The next filter is located on the outflow side of the pump, and is for maintaining the visual clarity of the water. This unit (Plate 4 and Figure 10) is a canister containing fiberglass material of the "furnace filter" type. The top of the canister is removable for cleaning. This filter is capable of removing material down into the micron range. The fourth and final filter is located following this one, and is a 50-mesh, two-inch diameter Y-strainer. It cannot be opened, but is cleaned by flushing through the use of a blow-out valve (Figure 11). As the three preceding filters can be readily opened or removed for cleaning, it is possible, and even probable, that dirt, stones, or other material may be inadvertently knocked into them by cleaning personnel. This final filter is for removing such material.

The requirement of supplying the nozzles with vibration, or "noise" free water is met by a combination of mechanical connections and a specially designed noise filter. The mechanical part consists of isolating the pump with flexible hose connections, and bolting it to a concrete foundation which is not in direct contact the the concrete wall to which the nozzles are anchored. The noise filter functions in a manner similar to a low-pass R-C filter in an electrical network. A sketch of the water noise filter, and its electrical analog, is shown in Figure 12. The action of this filter is as follows: The first hose coil offers a resistance to the water flow ($R_f$). The surge tank is partially pressurized due to the additional resistance from the second hose coil ($R_h$) and the nozzle ($R_n$). As a positive pressure surge enters
Figure 10 Main Filter Tank
Figure 11 Main Equipment Compartment Layout
Figure 12 Electrical Filter Analogue
the system, a significant portion of it is absorbed by further compression of the air in the tank. The tank then slowly bleeds off this additional pressure into the nozzle. If a negative pressure surge enters, the pressure in the tank forces water out of the tank to compensate for the sudden pressure loss. The nozzles themselves offer little flow resistance (they are equivalent to low impedance loads) and thus the second hose coil ($R_h$) must be added to prevent loading down the filter network. Additionally, the hose is flexible and is capable of absorbing some pressure vibration through mechanical absorption. The hose effectively absorbs the higher frequency vibrations, and the surge tank the lower frequencies. The 3500 rpm pump is the principal noise source in the system, 3500 rpm being equivalent to 60 Hertz. This noise is effectively removed by this filter network.

The elevation of these tanks is such that the three which feed the rear nozzles will completely drain when the system is shut off. This insures a replenishment of the air supply in the tanks (which otherwise tends to dissolve into the water under operating pressure). The hydraulic grade line is such that the tank which feeds the lower pool nozzle will not self-drain, and so the following modification is made. A small hose leads from one-third of the way up the side of the tank to the waterfall. This allows air to enter this tank when the system is off, and drains this tank. During operation, this line simply sends water over the waterfall.

All interconnecting waterlines are sized so that flow velocities
are three to four feet per second. Inside diameters of the piping range from 1\(\frac{1}{4}\) to 2 inches.

The pump supplying the nozzles is a 3500 rpm, closed impeller centrifugal pump. It maintains approximately 40 psig into the distribution manifold (Plate 5 and Figure 13). This manifold feeds five teflon-lined brass ball valves. One of the one-inch valves feeds another smaller distributor network connecting to seven small vinyl lines which send the water to various locations on the waterfall. The other two one-inch valves feed the two side nozzles behind the waterfall. The two 1\(\frac{1}{2}\) inch valves feed the central nozzles, one in the pool and one behind the waterfall. Located on the top of the manifold is an automatic air-bleeder to remove air from the system when it is powered up. A similar bleeder is located on the top of the pump volute.

In overall operation, then, a complete water cycle is traced as follows: From the pool the water is drawn through the two intake filters, and into the pump. It then is sent through the main filter tank, and then to the distribution manifold. It leaves through one of five valves. One feeds the waterfall through seven smaller lines. The other four each feed into separate 25 foot lengths of 3/4 inch flexible hose, into surge tanks, through additional 25 foot hose coils, and then to their respective nozzles. Water reaches the nozzles at approximately 4 psig. The pump, manifold, and noise filters are pictured in Figures through
Figure 13 Exploded View of Manifold Assembly
Plate 5  Pump and Manifold Assembly

Plate 6  Control Panel
The second fluid subsystem is responsible for maintaining a sufficient water level in the pool--making up for any losses due to evaporation, splashing, or leakage. A city-pressure water line enters the garden area and is divided at a tee, one leg of which feeds an electrically operated solenoid valve. When this valve is energized, city water is fed to the waterfall, and the pool fills. Control of this valve is described in the Electronic Systems section. The other leg of the tee feeds a quick-connect which is used to water the garden plants. Flow to this quick-connect is restricted by a pre-set stop and waste valve to a level appropriate for garden watering.

The third fluid subsystem drains the pool. Through a separate, 50-mesh screened intake, located near the main intake in the pool bottom (Figure 9), water is drawn by a drain pump and fed to a drain quick-connect. From this a hose can be attached to waste the water to a nearby sewer connection.

Electrical Systems

Operating, monitoring, and control of the entire fountain complex are accomplished by a sophisticated electronic and electro-mechanical network. Following are the design criteria selected for this system:

--The entire fountain complex has to completely shut down in the event of water leakage into the main equipment compartment.

--Any power carrying elements in contact with the pool water (such as
level sensing probes) must be low voltage, and have built-in current limiting to the micro-ampere range.

--The entire fountain must be operated by a timer, with no manual attention required.

--The timer must be able to be overridden with one switch, for off-hour operation.

--All pertinent operational data must be read out by indicator lamps.

--The control panel must be small and compact, with miniature switching elements, and only low voltages present.

--Two separate, dimmable, presettable lighting circuits must be supplied for decorative lighting control.

--All circuitry must be solid state for long life. Indicator lamps must be light emitting diodes (LED's) for the same reason.

--Mechanical relays must all be snap-in, socket mounted for easy replacement.

--The main pump circuitry must not be capable of operation when the water level in the pool is too low for safe pump operation.

--The pool water level must be automatically maintained to make up for losses.

--The pool circuitry should not be capable of overfilling through inadvertent switching, even though a manual override to automatic pool filling is provided.

--Power consumption of every element in the system should be minimal.

--All electrical and switching equipment, including the control panel itself, must be protected, and must be buried or thoroughly camouflaged
into the garden setting.

The visible electrical hardware is most easily classified by loca-
tion (Figure 14), whereas a circuit by circuit description most
conveniently describes the actual operation. The bulk of the switching
equipment is located in the main equipment compartment, together with
the timer, pumps, and dimmers, and the mechanical switching relays.
Located inside the pool itself is a solid state control unit which
controls the pool water level, and insures that a minimum level has
been reached before enabling the main pump to be switched on. The
third principal block of electronics is the control panel, located
remotely from the main equipment compartment. Both of these last two
are entirely low voltage systems, with all 110V power confined to the
underground main equipment compartment.

Several different power supplies are found throughout the system,
including:

- 110VAC (1)
- 24VAC (1)
- 12VAC (1)
- 24VAC pulsating (1)
- 12VDC (2)
- 3.5VAC (8)
- 5.1VDC (2)

Plate 6 and Figure 15 show the control panel. Figure 16 pictures the
electronic level sensor unit in the pool, and the principal electrical
components in the main equipment compartment. Figure 17 is the integra-
ted electrical schematic of the entire system. In the ensuing
Figure 14 Plan View of Project
CONTROLS
(PANEL FRONT)

TERMINAL CONNECTIONS
(PANEL REAR)

SEE SHEET NO. 14 FOR
ELECTRICAL SCHEMATIC

Figure 15 Control Panel
Figure 16  Electronic Level Sensor
The following abbreviations are used:

- **ALC** -- automatic level control
- **ELS** -- electronic level sensor
- **MEC** -- main equipment compartment
- **CP** -- control panel

The main electrical components are next described.

**Control Panel**

The control panel is supplied both with a continual and a timed source of 24VAC. The individual functions of the panel are listed below:

--- For lighting control there are two independent lighting circuits, which both run to each of the five flood-light housings. The two lights focused on the waterfall are wired into circuit number one, and the three lights focused on the foliage are wired into circuit number two. The levels of these lights are controlled by two solid state, phase control dimmers located in the MEC. These are commercial 600W dimmers, modified to operate from 30KΩ potentiometers, which are located on the CP. These potentiometers can be preset to desired lighting levels, and then the lighting circuits activated by the two lighting switches on the CP. These switches activate two 24VAC-coil relays in the MEC which switch 110VAC to the dimmer units. The 24VAC supplied to these switches on the CP is either constant, timed, or absent, depending on the position of the "Main" switch on the panel.

--- The drain pump is activated by a relay through a CP switch. This
relay energizes a standard electrical outlet, into which the 110VAC drain pump is plugged.

--The main pump is activated by a heavy duty relay which energizes an outlet into which the pump is plugged. The pump is a 3/4 horsepower, 3500 rpm, Bell and Gosset closed impeller centrifugal pump. This pump relay is energized by a switch on the CP, which receives its power from the "Main" CP switch. The ground circuit for this relay is only completed by activation of the low-level-lockout circuitry in the ELS unit in the pool; hence, the pump will not operate without sufficient water in the pool. Additionally, the ALC must be active for the pump to operate, as is described below.

--The automatic level control circuitry energizes the entire ELS unit, either in the constant or the timed mode. When activated by the proper water level, the ELS then completes ground for the solenoid fill valve (to which 24VAC power is always supplied, regardless of any switching). As this switch provides all power to the ELS unit, the low-level-lockout portion of the ELS will not allow the pump to operate without the ALC being switched on. This insures automatic pool refilling whenever the pump is on. Whenever the "Main" switch is set to the "On" position (effectively a manual override of the timer), the ALC is automatically switched to the constant mode, regardless of its switch position. The manual fill button provides a direct ground path for the fill solenoid, bypassing the ELS entirely.

--The "Main" switch controls power to both lighting circuits, and to
the main pump circuit. It provides a master control for off, timed, or constant operation of these functions. It provides a one-switch, manual turn on of the entire fountain complex when the timer itself is in the off state.

--The indicator lamps on the CP are all LED's. They are color coded so that green indicates normal, timed operation; yellow indicates manual override; and red (especially flashing red) indicates an extraordinary condition. With the exception of the two flashing LED's, all lamps are powered by 3.5VAC which is supplied through individual voltage divider networks, located behind the CP. Power for the two flashing LED's is supplied from an independent power supply. A 12VAC transformer, located in the MEC, sends power to the CP, where it is converted to 12VDC by a Zener diode regulated power supply. This drives a flashing circuit built from a 555 integrated circuit timer, which in turn powers the two LED's. These two lamps indicate operation of the drain pump and indicate that the low-level-lockout in the ELS has switched off the main pump relay. Power to the flasher is supplied only when it is needed, due to the following circuitry: When the drain switch is on, the drain pump relay also energizes the 12VAC transformer. This transformer is also energized through a separate relay when the "Main" CP switch is set to constant power, or when it is set to timed power and the timer is in the on state. Flashing power is reduced from 12VDC to 5.1VDC for the LED's by one of two voltage dividers. When the drain switch is on, this power is sent to the drain indicator lamp. Whenever the pump switch is on, and power is supplied to it
through the "Main" switch, flashing power is also sent to the low-level indicator lamp. However, whenever the pool water level is high enough for the ELS to complete the ground for the main pump relay, ground is also completed for a separate relay, which when activated, shorts out the power to the low-level LED, and completes ground for the green pump indicator lamp. When the water level is too low, this relay is open, the flashing LED is on, and the green one is off. All CP components and circuitry are located on a stand-off mounted perfboard beneath the CP itself. The control panel is mounted inside an artificial rock, with a hinged access cover, and is camouflaged from view (Plate 8).

Main Equipment Compartment

The MEC contains the above mentioned six relays, the two transformers, the two pumps, the two dimmers, the solenoid fill valve, the timer, and all of the interfacing terminals between this equipment, the ELS, and the CP.

--The timer is motor driven by 110VAC. It switches 24VAC. It has a day-skipper with which any day or days can be left completely off. Timer on and off positions can be set to within 15 minutes.

--A power switch is located in the MEC which shuts off all power to the entire complex immediately inside the container.

--A probe pair directly preceding this switch is located near the compartment bottom. If water should somehow enter the MEC and flood it more than two inches, these probes which dead short the entire circuit
supplying the fountain complex, and blow the appropriate building
circuit breaker. This is to minimize the potential of water damage to
the electrical equipment by providing emergency shutdown.

--The 24VAC and 12VAC power transformers are isolated, and thus these
systems are each electrically floating.

--Work light in the MEC is supplied by a lamp which is switched on
whenever the lid is raised.

--Access to the MEC is provided by raising a hinged, artificial rock
which camouflages into the garden setting (Plate 7).

Electronic Level Sensor

The ELS unit, located in the pool, is interfaced with the MEC
equipment via a four-conductor waterproof cable which runs inside the
pool drain-line from the pool to the MEC.

--The ELS is supplied with pulsating 24VDC power when the ALC switch on
the CP is on. This is converted to 12VDC by a Zener diode regulated
power supply in the ELS. Figure 17 includes the schematic of the
complete ELS.

--The principal components are the four probes, the CMOS (complementary
metal oxide semiconductor) logic unit, the power switching components,
the self-contained 12VDC power rectifier, the four-wire cable extending
from the unit, and the plastic body itself. The entire unit measures
only 3½ by 2 by 1½ inches. All internal components are mounted on a
Plate 7 Main Equipment Compartment

Plate 8 Control Panel Artificial Rock Cover
printed circuit board, which is encapsulated in the body compound, thereby insuring a rugged, watertight package. The case material itself has a very high wetting angle, thus minimizing surface effects between the probes.

--The probes are made of quarter-inch diameter stainless steel 316 rod. Due to the material properties of the stainless steel, and the minute amounts of current flowing through them (less than one microampere), the probe life is estimated to be in excess of 300 years—even in saline or chlorinated waters.

--The bottom of the four probes establishes a common ground potential with the water. The second probe up is the low-level-lockout probe; it does not allow the main pump to be switched on if the pool water is below the probe level. If, during operation, the water level falls below this point, the main pump is automatically shut off by this device. The third probe is the low-level fill indicator. Whenever the pool water falls below this point, the fill system valve is activated, and the pool water is replenished. The fill valve remains on until the water rises high enough to contact the fourth and topmost probe, then it is shut off. Thus, the height differential between the top two probes provides a drawdown of \( \frac{1}{2} \) inch, which prevents continual on-off activation of the fill system by minute water level fluctuations. Each of the probes is connected through a five second time delay, which prevents false triggering by waves splashing against or away from the probes.
The cable from the ELS has four color-coded conductors: red, black, white, and green. The black is the supply line for the device. The white is ground, and is connected to the other side of the 24VAC transformer. The green wire is connected to the ground side of the main pump relay. The red wire is connected to the ground side of the fill solenoid. When the fill logic switches to the on state, it internally connects the red and white leads together, completing a ground path for the solenoid. When the low-level-lockout logic is satisfied, the green and white wires are internally connected, providing a ground path for the pump relay.
SECTION VIII

A LOOK TO THE FUTURE
A LOOK TO THE FUTURE

Future considerations for laminar flow fountains fall into one of three categories: modifications of existing equipment; applications of new technologies; and entirely new aesthetic designs and overall fountain layouts.

Hardware Modifications

With the experience gained at the Conquistador Building fountain, several hardware improvements have become obviously desirable. Much better fluid control could be maintained if the system were run from a constant-head tank, rather than from closed system-direct recirculation. This would eliminate the need for the noise filters required at the Conquistador fountain, and also make possible the achievement of complete independence among the nozzles; i.e., adjusting the flow into one would not affect the pressures of the others.

A second, and somewhat minor, change would involve the sizing of the suction line into the pump. In the Conquistador installation, the line was made large to eliminate any head loss due to pipe friction. However, better operation could be achieved with a smaller line which would cause higher velocities, and more efficient purging of air pockets trapped in this suction line.

Whether a constant head tank, or closed-system recirculation is used, the pump should be physically isolated by as great a distance as possible from the nozzles. This will eliminate the transmission of mechanical vibrations more efficiently than is done at the Conquistador
Building. Consideration should also be given to two further aspects of pump installation. An automatic priming system would assist in purging the air from the pump during start-ups from a dry fountain. Also, a straight entrance line; i.e., no elbows, for a great distance preceding the pump entrance would further reduce vibrations.

New Technologies

Some alterations and additions to the hardware would be of sufficient magnitude that they would be more appropriately classified as the applications of new technologies. These would all be concerned with adding dynamic elements to the fountain designs, and thus enabling "water show" types of installations.

One of these would involve the use of a switching system to automatically turn different nozzles on and off according to a planned sequence. In addition to simply switching nozzles on and off, a system for gradually varying the flow to each of the nozzles would greatly expand the repertoire of fountain operations. The other elements which could then be altered would be the nozzle orifice diameters, changing the stream diameters during operation. In a water bell configuration, this would also change the direction of curvature of the bells, as the bells always curve toward the smaller of two impinging streams. And finally, entire fountain systems could be put under the control of programmable microprocessors (microcomputers). This would allow complete water shows to be developed, and even "orchestrated" to follow a musical
accompaniment. All of the above mentioned dynamic changes could be controlled by the microprocessor, as well as the more routine operating functions, such as timing and filling, which are accomplished through hardwired logic in the Conquistador Building fountain.

Design Concepts

There are virtually limitless possibilities for fountain designs using laminar flow, and incorporating the above mentioned techniques. Certainly, far more possibilities exist than have ever been explored in all extant fountains using turbulent flow. One reason for this is simply that much more precise control of the water can be obtained under laminar flow conditions.

Several very exciting concepts for designs are presently being explored in conjunction with designer Ron Crosby. Although it is difficult to imagine the visual impact of these designs without seeing the actual renderings (which, at this writing, are in preparation), brief descriptions of several ideas are presented here.

--A striking entrance-way to a mall or airport concourse could be achieved using nothing more than a series of laminar stream arches of sufficient height, say fifteen feet, for people to walk freely underneath them. A set-up of this nature has been made in the laboratory, and the effect is that of walking beneath glass rod archways--but combined with the realization that tremendous volumes of water are flowing overhead, the feeling is truly uncanny.
--A modification of this archway concept involves using a greater number of streams in a toroid, or doughnut shaped, configuration—perhaps with the entire unit in slow rotation.

--An interactive conglomerate of streams of different sizes and at different angles would give the appearance of a huge glass sculpture. Yet, unlike conventional sculptures, by switching on and off different streams, the entire sculpture could be made to change with time.

--By impinging streams vertically, water bells could be formed which rest in the center of vertical water rods. The bells would always curve toward the smaller diameter stream, and thus by altering the relative diameters, the bells could be made to butterfly up and down. Additionally, by altering the relative pressures for two impinging streams, the bell could be made to glide up and down over the entire length of the water column.

A few glimpses into the myriad possibilities of design concepts employing laminar flow have been presented. It is felt that the utilization of these concepts can lead to the creation of some of the more astonishing water fountains in existence.
Plate 9  Artist's Design Rendering of Conquistador Building Fountain (Ron Crosby, 1975)
LITERATURE CITED

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2. Ray, J.

14. Oliver, R. 1978, The Flex
LITERATURE CITED


BIBLIOGRAPHY


APPENDIX A

ASSEMBLY DRAWINGS
A DECORATIVE FOUNTAIN
UTILIZING
AXI-SYMMETRIC LAMINAR FLOW

DRAWING INDEX

<table>
<thead>
<tr>
<th>SHEET</th>
<th>TITLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TITLE SHEET &amp; DRAWING INDEX</td>
</tr>
<tr>
<td>2</td>
<td>GENERAL PLAN</td>
</tr>
<tr>
<td>3</td>
<td>ISOMETRIC VIEW OF NOZZLE</td>
</tr>
<tr>
<td>4</td>
<td>LARGE NOZZLE</td>
</tr>
<tr>
<td>5</td>
<td>LARGE NOZZLE DETAILS</td>
</tr>
<tr>
<td>6</td>
<td>SMALL NOZZLE</td>
</tr>
<tr>
<td>7</td>
<td>SMALL NOZZLE DETAILS</td>
</tr>
<tr>
<td>8</td>
<td>MAIN EQUIPMENT COMPARTMENT</td>
</tr>
<tr>
<td>9</td>
<td>PUMP &amp; MANIFOLD BOX</td>
</tr>
<tr>
<td>10</td>
<td>MANIFOLD ASSEMBLY</td>
</tr>
<tr>
<td>11</td>
<td>MANIFOLD</td>
</tr>
<tr>
<td>12</td>
<td>MAIN EQUIPMENT COMPARTMENT - ELECTRICAL &amp; LIQUID LEVEL CONTROL UNIT</td>
</tr>
<tr>
<td>13</td>
<td>CONTROL PANEL</td>
</tr>
<tr>
<td>14</td>
<td>ELECTRICAL SCHEMATIC</td>
</tr>
<tr>
<td>15</td>
<td>ELECTRICAL COMPONENTS</td>
</tr>
<tr>
<td>16</td>
<td>INLINE FILTER &amp; SURGE TANK DETAILS</td>
</tr>
<tr>
<td>17</td>
<td>POOL CONNECTION DETAILS</td>
</tr>
<tr>
<td>18</td>
<td>WALL NOZZLE SUPPORT</td>
</tr>
<tr>
<td>19</td>
<td>NOZZLE STAND IN POOL</td>
</tr>
<tr>
<td>20</td>
<td>TEST STANDS</td>
</tr>
</tbody>
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SENIOR DESIGN PROJECT
LAMINAR JET FOUNTAIN

TITLE SHEET & DRAWING INDEX
FEBRUARY 1970

DESIGNED BY
DAVE AYER, MARK FULLER, LEE SM...
MATERIALS LIST

ITEM DESCRIPTION
1 STREEY VALVE
2 BASE PLATE - SEE SHEET NO. 3
3 20 MESH SCREEN
4 20 MESH SCREEN
5 20 MESH SCREEN
6 20 MESH SCREEN
7 COLLAR - SEE SHEET NO. 5
8 RUBBER GASKET
9 1/4 IN. HEX HEAD BOLT WITH WASHERS AND NUT (10 REQ'D)
10 SPACER - SEE SHEET NO. 4
11 ORIFICE PLATE - SEE SHEET NO. 5
12 FACE PLATE - SEE SHEET NO. 5
13 1/4 IN. HEX HEAD BOLT AND WASHER (6 REQ'D)
14 AIR RELIEF VALVE
15 ACRYLIC TUBING - SEE SHEET NO. 4
16 PLASTIC SODA STRAWS

SENIOR DESIGN PROJECT
LAMINAR JET FOUNTAIN
ISOMETRIC VIEW OF NOZZLE
FEBRUARY 1976
DESIGNED BY
DAN AYER, MART FOLMER, LEE SIM
SHEET 3 OF 20
NOTE: THE ACRYLIC SPACERS ARE MADE FROM 1/8" IN SECTIONS OF 1/4 IN. O.D. ACRYLIC TUBING BY REMOVING A 3/4 IN SECTION FROM THE CIRCUMFERENCE. THE SPACERS ARE NOT LAMINATED TO THE OUTSIDE TUBING.
NOTE: THE FACE PLATE AND COLLAR ARE MACHINED FROM 1/8 IN. ACRYLIC SHEET STOCK. THE BASE PLATE IS MADE OF TWO PIECES MACHINED FROM SIMILAR STOCK AND LAMINATED TOGETHER.
AIR RELIEF VALVE, PLACE AS CLOSE TO UPPER SIDE OF NOZZLE AS POSSIBLE

LAMINATED

1/8" IN X 3/4" O.D. ACRYLIC TUBING (1/8" WALL THICKNESS)

ACRYLIC SPACER

LAMINATED

80 MESH SCREEN

PLASTIC DRINKING STRAINS (CUT TO LENGTH)

1/4 IN BOLT WITH WASHERS AND NUT (6 REQ'D)

BASE PLATE

SEE SHEET NO. 7

ORIFICE PLATE

SEE SHEET NO. 7

1/4 IN BOLT WITH WASHERS AND NUT (6 REQ'D)

1/8 IN RUBBER GASKET 8 IN O.D. X 4 3/4 IN. I.D.

WITH BOLT HOLES TO MATCH COLLAR

COLLAR

SEE SHEET NO. 7

NOTE 8 THE ACRYLIC SPACERS ARE MADE FROM 1/8" IN SECTIONS
OF 3 IN O.D. ACRYLIC TUBING BY REMOVING A 3/4 IN SECTION
FROM THE CIRCUMFERENCE. THE SPACERS ARE NOT LAMINATED
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SENIOR DESIGN PROJECT
LAMINAR JET FOUNTAIN
MANIFOLD ASSEMBLY

SCALE 14" = 1" FEBRUARY 1976
DESIGNED BY
DAVE AYER - MARK FULLER - J.L. S.M.
SHEET 10 OF 20
CONTROLS
(PANEL FRONT)

TERMINAL CONNECTIONS
(PANEL REAR)

SEE SHEET NO. 14 FOR ELECTRICAL SCHEMATIC
## ELECTRICAL COMPONENT LIST

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<td>Q2</td>
<td>2N3904, NPN</td>
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<td>T1</td>
<td>H1235, TRIAC</td>
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<tr>
<td>T2</td>
<td>2N2222, 6 AMP TRIAC</td>
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</tr>
<tr>
<td>T3</td>
<td>572, DIAC</td>
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<tr>
<td>D1</td>
<td>12 V, 1 WAT, ZENER</td>
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<tr>
<td>D2</td>
<td>50 PIV, 1 AMP</td>
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<td>D3</td>
<td>12 V, 5 WAT, ZENER</td>
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<td>S1</td>
<td>N.O., MOM. PUSH BUTTON</td>
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<tr>
<td>S2</td>
<td>DPDT, CENTER OFF</td>
<td>2</td>
</tr>
<tr>
<td>S3</td>
<td>DPDT, CENTER ON</td>
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<tr>
<td>S4</td>
<td>SPST, 2 AMP</td>
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<td>S5</td>
<td>SPST, 15 AMP</td>
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<tr>
<td>FLOOD LIGHT</td>
<td>150 WATT, OUTDOOR</td>
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<tr>
<th>ITEM</th>
<th>DESCRIPTION</th>
<th>AB. REGD.</th>
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<tbody>
<tr>
<td>P1</td>
<td>30 K, LINEAR TAPER</td>
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<tr>
<td>RL1</td>
<td>DAYTON 24 VAC COIL, 1 HP SPST-NO-ON RELAY (GRANGER NO. 51609)</td>
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<td>RL2</td>
<td>DAYTON 24 VAC COIL, 110 V DPDT RELAY (GRANGER NO. 51637)</td>
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<td>TR1</td>
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<td>TR2</td>
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<td>I1</td>
<td>100 μH, 6 AMP</td>
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<tr>
<td>PROBE</td>
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<tr>
<td>R1</td>
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<td>R2</td>
<td>620 kΩ, 2 WATT</td>
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<td>R4</td>
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<td>R5</td>
<td>150 Ω, 1 WATT</td>
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<td>R6</td>
<td>75 Ω, 5 WATT</td>
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<td>R7</td>
<td>10 MEG, 1/2 WATT</td>
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<td>R8</td>
<td>22 MEG, 1/2 WATT</td>
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<td>R9</td>
<td>20 kΩ, 1/2 WATT</td>
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<td>R10</td>
<td>62 kΩ, 1/2 WATT</td>
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<td>R11</td>
<td>1/2 kΩ, 1 WATT</td>
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<td>IC1</td>
<td>NE 555 V</td>
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<tr>
<td>IC2</td>
<td>5513, 400 Ω</td>
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<tr>
<td>TIMER</td>
<td>DAYTON INDOOR 24 HR TIMER WITH DAY SKIPPER (125 V) (GRANGER NO. 20024)</td>
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---

**ELECTRICAL COMPONENTS**

**SENIOR DESIGN PROJECT**

**LAMINAR WAT VET FOUNTAIN**

**DEIGNED BY:** DAVID EYER, MARK FISHER, LEE SIM

**FEBRUARY 1976**

**SHEET 15 OF 20**
# MATERIAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>ITEM</th>
<th>SPECIFICATION</th>
</tr>
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<tbody>
<tr>
<td>2. Drain Pump</td>
<td>Submersible or open air service pump, nylon pumping head and impellor. Little Giant no. 2E-38M (Granger no. 1P372) or approved equal.</td>
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<tr>
<td>3. Manifold</td>
<td>Fabricate from 8 in. I.D. x 18 in. steel pipe as shown on sheet 11 of the drawings. Galvanize inside and outside after fabrication.</td>
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<tr>
<td>4. Large nozzles</td>
<td>Fabricate as shown on sheets 4 and 5 of the drawings using cast acrylic plastic and 20 mesh stainless steel screen.</td>
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<tr>
<td>5. Small nozzles</td>
<td>Fabricate as shown on sheets 5 and 6 of the drawings using cast acrylic plastic and 20 mesh stainless steel screen.</td>
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<tr>
<td>6. Wall nozzle supports</td>
<td>Fabricate as shown on sheet 18 of the drawings. Galvanize after fabrication.</td>
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<tr>
<td>7. Nozzle stand in pool</td>
<td>Fabricate as shown on sheet 19 of the drawings.</td>
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<tr>
<td>ITEM</td>
<td>SPECIFICATION</td>
</tr>
<tr>
<td>------</td>
<td>---------------</td>
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<tr>
<td>7. continued</td>
<td>Galvanize after fabrication.</td>
</tr>
<tr>
<td>8. Surge tanks</td>
<td>Fabricate as shown on sheet 16 of the drawings using extruded acrylic plastic and 20 mesh stainless steel screen.</td>
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<tr>
<td>10. Air relief valves</td>
<td>Bell and Gossett no. 7 automatic air vents or approved equal.</td>
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<tr>
<td>11. Pipe, fittings, and couplings</td>
<td>Polyvinyl Chloride (PVC) - schedule 40 Galvanized iron</td>
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<tr>
<td>12. 2 in. hose</td>
<td>Steel-reinforced, neoprene, marine exhaust hose.</td>
</tr>
<tr>
<td>13. 1 1/2 and 1 in. hose</td>
<td>USBM</td>
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<tr>
<td>15. Ball valves</td>
<td>Teflon seated, brass. No. 1101-T or approved equal.</td>
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<tr>
<td>16. Inline filter</td>
<td>Fabricate as shown on 16 of the drawings, epoxy paint inside. Spun fiberglass furnace filter.</td>
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<tr>
<td>ITEM</td>
<td>SPECIFICATION</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------------------------------------------------------------------------------</td>
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<tr>
<td>17. Manifold supports</td>
<td>Cut from 2 x 6 wood stock.</td>
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<tr>
<td>18. Electrical</td>
<td>All electrical components and work shall conform to NEMA and NEC specifications.</td>
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<tr>
<td>19. Flood lights</td>
<td>100 watt, indoor-outdoor. Position and color as shown on sheet 2 of the drawings.</td>
</tr>
<tr>
<td>20. Pressure regulator</td>
<td>3/4 in., supply pressure 125 psi, standard reduced pressure 10-35 psi. Wilkins no. 600 LPV or approved equal.</td>
</tr>
<tr>
<td>21. Solenoid valve</td>
<td>1 in., PVC, normally closed, 24 VAC coil.</td>
</tr>
<tr>
<td>22. Plumbing</td>
<td>All plumbing components and work shall conform to the Utah State Plumbing Code.</td>
</tr>
</tbody>
</table>
APPENDIX C

Owner's Report
OWNER'S REPORT--
AXISYMMETRIC LAMINAR FLOW FOUNTAIN

prepared by
Dave Ayer, Mark Fuller, Lee Sim

February, 1976

for
Gordon Christensen
Conquistador Building
The information in this manual has been reviewed and is believed to be entirely reliable. However, no responsibility is assumed for inaccuracies. The material in this manual is for informational purposes only, and is subject to change without notice.
# TABLE OF CONTENTS

ABSTRACT ........................................................................... C-iv
INTRODUCTION ........................................................................ C-1
TECHNICAL SYSTEM DESCRIPTION ............................................. C-2
OPERATING INSTRUCTIONS ..................................................... C-6
ROUTINE MAINTENANCE AND SERVICE REQUIREMENTS .......... C-8
TROUBLESHOOTING ............................................................ C-11
LIMITED WARRANTY ............................................................... C-12
CONCLUSION .......................................................................... C-13
ABSTRACT

OWNER'S REPORT--AXISYMMETRIC LAMINAR FLOW FOUNTAIN

An architectural water display fountain based on laminar flow has been built at the Conquistador Building in Salt Lake City. Fountain operation is fully automated, with some manual override functions available. Maintenance is simple, and is confined to a few regularly scheduled operations. The fountain is covered by a limited, thirty day warranty.
INTRODUCTION

The idea of building a water fountain display was first conceived in May of 1975 in a hydraulics class during a discussion of the unusual properties of ordinary liquid under laminar flow conditions. Mark Fuller, David Ayer, and Lee Sim felt that the many striking effects often seen by students in laboratory demonstrations could attractively be displayed in a large scale public water fountain. Both the principles of laminar flow and of hydraulic jumps were considered, but laminar flow was selected as offering the greatest variety of display possibilities.

The goal, then, became to display the desired laminar fluid streams in an attractive format—one that would stand on its own aesthetically. As much as possible, a "science fair" type of display was to be avoided. To this end, Ron Crosby, a well known theatre set designer, was engaged to work on the overall design layouts.

The only previous substantial work in the area of impinging laminar streams had been done by Dr. John A. Roberson, at Washington State University. His work culminated in a display built at the Spokane World's Fair. Dr. Roberson's work was used as a starting point. After several months of study, laboratory prototypes were built to provide the desired effects, and were successfully tested. Both arches composed of laminar streams, and water bells formed by the impinging of two laminar streams could be produced and controlled.
At this point in time, an opportunity arose to install a small version of a fountain in the new Conquistador Building in Salt Lake City which was just nearing completion. The opportunity to build a public display was highly tempting, and it was felt that another opportunity might not arise for a year or more. However, the fact remained that none of the prototypes had yet been tested for long-term reliability, and that the back-up equipment needed to continuously recirculate the water under the exacting conditions required, was liable to be both ponderous and expensive. (This last presumption later turned out to be prophetic.) But the decision was made to go ahead, and it was hoped that solutions could be found for the anticipated problems while the initial equipment was being fabricated and installed.

The completed fountain now consists of four laminar streams--two of which impinge to form a water bell which showers over the fifth element of the design, a lava rock waterfall.

TECHNICAL SYSTEM DESCRIPTION

An overall equipment description is best given by tracing the flow path of the water for one complete cycle through the fountain. The pool at the base of the waterfall serves as the collection reservoir. From the bottom of the pool, the water is drawn through a screened intake and piped underneath the garden area into the main equipment compartment, where it enters the pump, is pressurized to approximately forty pounds per square inch, and then is piped out under the garden to the primary filter tank. From the filter the water is returned to
the equipment compartment, is passed through a secondary Y-strainer filter, and is piped into the distribution manifold.

There are five outlets from the manifold, and each is controlled by a ball valve. The end valve feeds the lava waterfall through a series of seven small hoses which distribute the water over the rocks. The four remaining valves are paired, a large and a small, on each side of the manifold. The larger two valves feed the water bell streams, and the smaller ones the laminar arches. The water lines from each valve exit the equipment compartment and travel to a large underground box. Here each is connected to a twenty-five foot coil of hose. The lines then leave this box and are connected to plexiglass surge tanks. From these tanks the lines return to the hose box and connect to additional twenty-five foot hose coils. The hose-tank-hose configurations serve as "noise" filters to eliminate pump-produced vibrations from the water streams--an important requisite for laminar flow. From the final coils, each stream is piped directly to its respective laminar jet nozzle in the fountain.

In addition to the main system, three independent auxiliary water systems exist. One is the drain system. Water is drawn from the lowest point in the pool through a screened intake (adjacent to the primary intake) and piped into the equipment bay. Here the drain pump is located, which expels the water back out underneath the garden area to a quick connect valve fitting. A hose may be attached to this quick-connect, and the water drained into a nearby sink or toilet.

A second auxiliary is the fill-system, designed to automatically monitor and maintain the correct water level in the pool. A city
pressure water line enters the equipment compartment, connects to a pressure regulator, and then to an electrically operated solenoid valve. When this valve is actuated, the fill water is piped over the waterfall and then cascades into the pool.

The third water system consists of another quick-connect located in the garden area. This is directly fed by a city-pressure line, and is used to water the plants in the garden area. A valve is located beneath this quick-connect, and is preset to limit the amount of water through this line to a flow suitable for garden watering.

The entire fountain system is completely controlled by a fully automated electronic and electro-mechanical monitoring system. For purposes of description, this system is broken down into three principal elements. The first is the electronic level sensor. This unit is about the size of a package of cigarettes, and is mounted inside the top rim of the pool. From it extend four stainless steel probes, which reach into the pool. The bottom probe establishes a common ground potential with the water. The second probe up is the "low-level lockout" probe; it does not allow the main pump to be switched on if the pool water is below the probe level. If, during operation, the water level falls below this point, the main pump is automatically shut off by this device. The third probe is the "low level fill indicator." Whenever the pool water falls below this point, the fill system valve is activated, and the pool water is replenished. The fill valve remains off until the water rises high enough to contact the fourth and topmost probe, then it is shut off. Thus the height differential between the
top two probes provides a drawdown range of 0.50 inches, which prevents continual on-off activation of the fill system by minute water level fluctuations. Each of the probes is connected through a five second time delay, which prevents false triggering by waves splashing against or away from the probes.

The second element in the electrical system is the control panel. Located under a hinged, artificial rock lid in the garden area, this panel permits simple, but disguised access to the control functions. The individual functions controlled by the panel switches are described in the OPERATING INSTRUCTIONS section. All power and signals flowing into the panel are twenty-four volts or less, for reasons of safety. This panel interfaces with the equipment compartment mechanisms through a twelve foot, eighteen conductor underground cable. There is an array of electronic components mounted directly behind the panel. These components are primarily concerned with supplying the correct voltages to the indicator lamps, and to flashing the appropriate lamps.

The third block of electrical equipment consists of the considerable number of electro-mechanical devices located inside the underground equipment compartment. Primary among these are the main pump, the drain pump, and the timer. The timer can be set for a daily on and off setting, and any day or days of the week can be set to remain off entirely. Located directly below the timer is an electrical switch box, containing a switch and two electrical outlets. The switch controls the main 110VAC line entering the equipment compartment, and can cut off all power, including that to the timer drive motor. Into the top outlet is plugged
the main pump. This outlet is energized by the switch panel and the automatic control system. The bottom outlet is similarly controlled, and the drain pump is plugged into it.

The other active devices in the compartment include the six electrical relays mounted on the east wall. Facing the wall, and numbering from right to left, they serve the following purposes:

1. Activates the lighting circuit "Lights 1," which powers the waterfall.
2. Activates the lighting circuit "Lights 2," which powers the foliage lights.
3. Activates the drain pump.
4. Activates the "On," or the "Low Level" indicator lights on the "Main Pump" section of the control panel.
5. Activates the flashing circuitry on the control panel.
6. Activates the "Main Pump."

These relays are all twenty-four volt, ac coil relays. The two dimmer units for the lights are also located in the equipment compartment, as well as the numerous electrical cross-connections and terminal strips necessary to interface the equipment.

OPERATING INSTRUCTIONS

With the exception of the timer (on which settings must be directly made in the equipment compartment), the entire fountain can be monitored and controlled by the control panel. For each panel item, a detailed description follows.
1. **Lights 1:** This switches two spotlights, which are focused directly on the waterfall. The knob directly below the switch controls the light level. The green indicator lamp is on when the lights are on, regardless of the light level. This circuit is master controlled by the "Main" switch, as described below.

2. **Lights 2:** This switch, knob, and indicator function similarly to "Lights 1." They operate three floodlights which are focused on the foliage in the garden area. This circuit is also master controlled.

3. **Main Pump:** This switches on the pump which controls the waterfall and the laminar streams together. When the pump is on, the green indicator lamp will be lit. When the pump is switched on, but the water level is below the lock out point, the green lamp will not be lit but the red "Low Level" indicator will flash brightly. When the water level is again high enough, the red flasher will extinguish, the green lamp light up, and the pump automatically turn on. This circuit is also master controlled. Additionally, the "Low Level" indicator will flash if an attempt is made to operate the main pump when the "Automatic Level Control" switch (described below) is off.

4. **Automatic Level Control (ALC):** This switch has three positions: "Constant," "Timed," and "Off." It energizes the electronic level sensor (ELS) unit in the pool. In the "Timed" position, the ELS will be active only when the timer is on. In the "Constant" position, the ELS will monitor and replenish the water in the pool twenty-four hours of every day, regardless of the timer. A green light indicates timed operation, and a yellow light indicates constant operation. The "Timed" position is considered the normal operating mode. Operation of this circuit is sometimes interdependent with the "Main" switch, as described below.

5. **Manual Fill:** When pushed, this switch adds water to the pool regardless of the ALC system. It provides the only way for the owner to override the ELS monitor and add water above the preset maximum pool level. The button is active only while held in, however, which assures that inadvertent overfilling will not occur.

6. **Filling Light:** This lamp glows red whenever water is being added to the pool, either through the "Manual Fill" or by the ALC system. It should be remembered that when the ALC is switched on, water will be added (and this light lit) only if water is needed, and then only after the appropriate system logic decisions have been made—-which in many cases involves a several second time delay.
8. Main Switch: This switch master controls the two lighting circuits and the "Main Pump" circuit. When this switch is off (center position), these three subcircuits will be off, regardless of their individual switch positions. Their indicator lamps will also be off. When the "Main" switch is set to "Timed" operation (green light), the three subcircuits will be turned on and off appropriately by the timer—provided their individual switches are "On." When the "Main" switch is set to "On," any of the three subcircuits which are individually set to "On" will be activated, regardless of the timer. Thus in normal operation, "Lights 1," "Lights 2," and "Main Pump" would be switched "On," and the "Automatic Level Control" and "Main" switches would both be set to "Timed." The entire fountain would then be switched on and off by the timer. To turn the entire fountain on when the timer would normally have it off, the "Main" switch would simply be turned to "On." In the "On" position, the "Main" switch has one additional function. It places the ALC circuitry in the "Constant" mode, regardless of the position of the "Automatic Level Control" switch. This is to prevent manual operation of the main pump when the ALC circuitry is switched off.

Note: By color, the panel should have only green lights normally lit. Yellow indicates that some type of manual override is being made. Glowing red indicates water is entering the pool, and should not be on for long. Flashing red indicates an abnormal condition (either the drain is on or the pool level is too low).

ROUTINE MAINTENANCE AND SERVICE REQUIREMENTS

The following items require regular owner maintenance attention:

1.) The main filter tank: The need for a filter change is indicated by cloudy water in the pool, or by any pressure loss through the system, which will manifest itself by a change in position or misalignment of the laminar streams. In no case should the period between filter changes exceed two months. The filter material consists of three rolled fiberglass furnace filters, held in position by a wire cage. Clogging of the system by the filter material will occur if the cage is not repositioned correctly in the tank. It is recommended that the fiberglass material
be replaced when changed, but in the interests of economy, the owner may elect to thoroughly wash the filters every other change, replacing them only on alternate changes.

2.) After the main filter has been changed and the pump restarted, the Y-strainer in the equipment compartment should be flushed. This is accomplished by opening the blue-handled blow-out valve in the equipment compartment. It should not be left open, but should be fully opened, then closed immediately. This will result in a substantial water discharge around the rear base of the waterfall, but this is normal for this procedure. The purpose of the Y-strainer is to capture any debris in its 50-mesh screen that may have passed through the earlier filter, including any soil that may have been knocked into the filter tank during filter changing.

3.) The screened intake for the main pump in the pool must be kept free from any clogging debris, including relatively fine particulate or humus matter from the garden. The screened intake unit unscrews from the pool bottom by hand and should be washed thoroughly in a sink. It is made of 20-mesh screen, and will pass anything smaller without difficulty. This screened intake is surrounded by a larger mesh cage with half-inch openings, whose primary purpose is to protect the system from paper towels which may be thrown into the pool, and which would otherwise collapse the screened intake and damage the pump. It is, however, the responsibility of the owner to see that no such foreign objects enter the pool, or that they are removed immediately, before damage occurs. The period between cleaning these screens will be determined by visual
inspection, but can obviously be greatly prolonged if, when watering
the garden area, care is exercised to see that no soil is washed into
the pool. The intake screens should be cleaned at least as often as
the main filter tank is changed.

4.) The pool should be drained and refilled at least once per
month. Chlorine may be added if algae growths appear; however, dosage
should be sparing to avoid damage to the surrounding plants by the
splashing or leakage of chlorinated pool water.

5.) When dirt or film has accumulated in the pool, it should be
sponged clean when drained. Care must be exercised not to damage the
pool paint. It is also extremely important that the laminar jet nozzle
and its surrounding artificial rock housing which are located in the
pool not be jarred or moved at all. Nozzle realignment may be accom­
plished by slightly shifting the nozzle inside its rock housing, using
something similar to a broom handle to reach through the exit hole in
the rock. Care must be taken not to damage either the nozzle or the
rock.

6.) The diaphragm in the electric solenoid fill valve must be
replaced every two years. It is recommended that this be done through
the equipment compartment access lid. However, removal of the entire
equipment compartment top may facilitate the operation. The six inches
of soil must first be removed from the compartment top, which is then
secured by screws on six inch centers around its perimeter. The micro­
switch which activates the equipment compartment work light must be
disconnected from the top before the top removal. Power to the entire
compartment should be shut off before this switch is removed, and should remain off until it is reconnected, to prevent electrical shock. This will necessitate resetting the timer. To change the valve diaphragm, the valve cover plate (secured by eight screws) must be removed. The diaphragm and spring assembly may then be lifted out and replaced. Failure to properly maintain this valve may result in an eventual diaphragm or spring failure. Such failure would cause unrestricted flow from the city-pressure water line into the pool, and could only be shut off by a water-main valve in the building. As there is no drain in or near the fountain area, severe flooding damage could result from such a failure occurring when the building was unoccupied. This entire maintenance operation must be performed only after city water to the fountain area has been cut off. Before reactivation of the electrical system, water pressure must be restored, or the fill valve will be damaged by dry operation.

7.) When the fill valve diaphragm is replaced, the inline filter screen in the pressure regulator should be cleaned. Located in the bottom of the regulator, the screen should be removed, washed, and replaced.

TROUBLESHOOTING

In the event of failure of any part of the fountain system, the following items can easily be checked:

1.) Is the main circuit breaker to the area on?
2.) Is the main equipment compartment switch on?

3.) Are the filters (screen intakes, filter tank, and Y-strainer) clean?

4.) Is the water level in the pool sufficiently high?

5.) Are all of the relays in the equipment compartment pressed firmly into their sockets? (Five of the relays are socket mounted, and must be tightly pressed in.)

6.) Are the two pumps plugged into the correct electrical outlets in the equipment compartment? (Main pump into top outlet, drain pump into the bottom outlet.)

7.) If none of the above remedy the failure situation, power should be cut off to the fountain area by the blue-marked building circuit breaker in the janitor closet, and professional assistance sought.

LIMITED WARRANTY

Neither the University of Utah, nor any University of Utah personnel, offer any warranty whatsoever on this fountain.

David Ayer, Mark Fuller, And Lee Sim (hereinafter referred to as the designers) offer a thirty day limited warranty on labor costs for repair of this fountain. During the thirty day period, beginning at the date signed below, The designers will replace or repair any malfunctioning element of the fountain of which they are made aware during said thirty day period. Repairs will be made for the retail list cost of parts and materials, to be paid for by the owner, Gordon Christensen. After the expiration of this period, no other warranty is expressed or implied, and except for such repairs or replacement, this fountain is without other warranty or liability. Specifically, the designers assume no liability for any damage done to or by the fountain, or any element thereof,
to the fountain, to the garden area, to the whole or any part of the Conquistador Building, or to any person or persons owning, operating, repairing, or viewing said fountain. This includes damage by overfilling, flooding, leakage, foundation damage, or electrical damage.

In the event of system or component failure, the designers may, at their discretion, elect to enact repairs or to lend repair assistance. Fair market labor charges will be assessed against the owner for any such work or assistance.

_____________________  _______________________
Owner                      Date

_____________________
Designers

CONCLUSION

The laminar flow water fountain installed in the Conquistador Building stands unique among architectural water display fountains of the world. Together with its sophisticated monitoring and control systems, it comprises a highly technologically and visually exciting creation.
APPENDIX D

SOME PROPERTIES OF INVISCID OSCILLATIONS

(Betchov and Criminale, 1967)
Appendix D
Some Properties of Inviscid Oscillations

Significance of an Inflection Point

In the following discussion it is concerned with two-dimensional oscillations, but the Squire theorem could be applied to extend the conclusions to three-dimensional oscillation.

For neutral oscillations, both $\alpha$, the wave number and $c$, wave velocity, are purely real. Moreover, instability occurs if the imaginary part of $c$ is positive and vice versa. Neglecting the viscous stresses, the Orr-Sommerfield equation reduces to the Rayleigh equation

$$(U - c) (v'' - \alpha^2 v) - U'' v = 0 \quad (A4-1)$$

By multiplying this equation by $V^*$, the complex conjugate of $V$, dividing by the factor $(U - c)$, and integrating the result between some limits $y_1$ and $y_2$, the equation becomes

$$\int_{y_1}^{y_2} \left[ (v'v^*)' - v'v^* - \alpha^2 vv^* \right] dy - \int_{y_1}^{y_2} \frac{U''v v^*}{(U - c)} dy = 0 \quad (A4-2)$$

The first term can be integrated exactly

$$\int_{y_1}^{y_2} (v'v^*)' dy = (v'v^*)_{y_1}^{y_2} \quad (A4-3)$$

A decision must now be made as to whether the limits $y_1$ and $y_2$ are located at walls or at $\pm \infty$, so that either $v$ or $v'$ will vanish.
From the positive nature of the two following terms, it follows that

\[ \int_{y_1}^{y_2} \frac{U'' v v^*}{(U-c)} \, dy = -k^2 \]  

(A4-4)

where \( k \) is a real number and \( \alpha \) is assumed real.

In this equality, all terms are real except \( c = c_r + ic_i \).

Considering only the imaginary part of (A4-4),

\[ c_i \int_{y_1}^{y_2} \frac{U'' v v^*}{(U-c_r)^2 + c_i^2} \, dy = 0 \]  

(A4-5)

it is inferred that either \( c_i \) is zero or the integral must vanish. When \( c_i \) is not zero, (A4-5) cannot be satisfied unless \( U'' \) has at least one zero.

Now considering the case of \( c \) purely real and \( \alpha \) complex, the imaginary part of equation (A4-2) reduces to

\[ 2\alpha_r \alpha_i \int_{y_1}^{y_2} vv^* \, dy = 0 \]  

(A4-6)

From this, one can conclude that the problem of an inviscid flow has no solutions unless its velocity profile has at least one inflection point. This refers to oscillation with a real \( \alpha \). Oscillations with a purely real \( c \) and a complex \( \alpha \) are excluded.

Many experimental conditions occur with a real frequency \( \omega = \alpha \omega \) and a complex \( \alpha \). Thus both \( \alpha \) and \( c \) are complex. With the proviso that \( \omega \) is purely real, which implies that the oscillation is periodic with time, in imaginary part of (A4-2), leads to the relation

\[ \int_{y_1}^{y_2} \frac{U'' v v^*}{(U-c_r)^2 + c_i^2} \, dy = \frac{2\alpha_r^2}{c_r^2} \int_{y_1}^{y_2} vv^* \, dy \]  

(A4-7)
Hence, for real $\alpha$, an inflection point is necessary for instability of an inviscid flow and the collection of available facts even suggests that an inflection is sufficient.
APPENDIX E

THE INVISCID SHEAR LAYER

(Betchov and Criminale, 1967)
Appendix E

"The Inviscid Shear Layer"

This section will present the theory for the stability of a shear layer between two parallel streams. For this purpose, it is convenient to specify a particular mean velocity profile

\[ U = U_0 \tan h \frac{y}{H} \]  

(A5-1)

The free-stream velocities are \( \pm U_0 \) and \( H \) is a measure of the thickness of the layer. A unit of time, therefore, is \( H/U_0 \). For simplicity, viscous shear effects are neglected, and with \( U = 0 \), the basic equations reduce to the following

\[ v' = ia \]  
\[ p' = ia(U - c)v \]  
\[ ia(U - c)u + U'v + iap = 0 \]  

(A5-2)  
(A5-3)  
(A5-4)

H should be noted that the inviscid assumption also disregards any concern of the mean flow not being parallel, that \( U \) is taken as a function of \( y \) only.

The pressure can be eliminated by differentiating (A1-4) and substituting into A5-3). The result is

\[ v' = iau \]  
\[ u' = \frac{i}{a} \left( \frac{U''}{U-c} + a^2 \right)v \]  

(A5-5)  
(A5-6)

By differentiating (A2-5) and eliminating \( u \), a more compact equation is obtained

\[ v'' = \left( \frac{U''}{U-c} + a^2 \right)v \]  

(A5-7)

This equation governs the stability of parallel inviscid flows and was obtained first by Rayleigh in 1880.
APPENDIX F

INVISCID JETS AND WAKES

(Betchov and Criminale, 1967)
Appendix F

Inviscid Jets and Wakes

Symmetric Jet: As a simple example of a symmetric jet, consider

\[ U = \text{sech}^2 y = \frac{1}{\cosh^2 y} \]  \hspace{1cm} (A6-1)

where maximum velocity is unity and \( U \) is almost zero if \( |y| > 3 \). The equation governing the oscillations is, when considering the inviscid problem

\[ v'' = \frac{U''}{U - C} + \alpha^2 v \]  \hspace{1cm} (A6-2)

This profile has the advantage that three particular solutions of (A6-2) are known. Examining the possibility of a solution in the form of

\[ v = (\cosh \beta y)^m, \ m \geq 0 \]  \hspace{1cm} (A6-3)

Some calculations lead to the equation

\[ m^2 \beta^2 - m(M+1)\beta^2 (\cosh \beta y)^{-2} = -6 \cosh^{-2} y \left( \frac{1-2}{3} \cosh^2 y \right) + \alpha^2 \]  \hspace{1cm} (A6-4)

This leads to a solution with

\[ c = 2/3 \]
\[ \beta = 1 \]
\[ m = \alpha = 2 \]

which is compatible with boundary conditions.

A second choice could be made by writing

\[ v = \frac{\sinh \beta y}{(\cosh \beta y)^2} \]  \hspace{1cm} (A6-5)
Substitution and further calculations lead to

$$\beta^2 - 6\beta^2 \cosh^2 \beta y = -6 \cosh^{-2} y \left[ \frac{1 - \frac{2}{3} \cosh^2 y}{1 - c \cosh^2 y} \right] + \alpha^2 \quad (A6-6)$$

A solution exists if

$$c = 2/3$$

$$\beta = \alpha = 1$$

Asymmetric Jet: The solution of an asymmetric jet is similar to the symmetric jet with different parameters, and is therefore not presented in this section.
APPENDIX G

Some Properties of Viscous Oscillation

(Betchov and Criminale, 1967)
Appendix G

Some Properties of Viscous Oscillation

$R_c$, the critical Reynold's number, marks only the beginning of a regime in which certain disturbances are amplified while being washed downstream. These disturbances are amplified while being washed downstream. These disturbances are amenable either to mathematical analysis or to numerical computations. When these become sufficiently large, certain nonlinear effects suddenly open the door to random fluctuations and the flow becomes turbulent. The Reynold's number characteristic for the location of this turbulent transition is known as the transitional Reynold's number. This section deals with certain inequalities contributed by Synge concerning $R_c$.

Considering a two-dimensional flow, with real $\alpha$ and complex $c$, the boundary conditions $v = v' = 0$ are applied at $y_1$ and $y_2$ so that the results are applicable to boundary layers, shear flows, jets, and wakes.

The Orr-Smithfield equation

$$(\mathbf{U} - c) \left( v'' - \alpha^2 v \right) - \mathbf{U}'' v = -\frac{i\nu}{\alpha} \left( v''' - 2\alpha^2 v'' + \alpha^4 v \right)$$  \hspace{1cm} (A7-1)$$

is multiplied by $v^\ast$ and integrated, yielding the following in condensed notation:

$$I_0^2 = \int_{y_1}^{y_2} v v^\ast dy$$  \hspace{1cm} (A7-2)$$

$$I_1^2 = \int_{y_1}^{y_2} v' v'^\ast dy$$  \hspace{1cm} (A7-3)$$

$$I_2^2 = \int_{y_1}^{y_2} v'' v''^\ast dy$$  \hspace{1cm} (A7-4)$$
\[ Q = \int_{y_1}^{y_2} [(U_{a}^2 + U'')v'v'\ast + Uv'v'\ast] dy + \int_{y_1}^{y_2} Uv'v'\ast dy \quad (A7-5) \]

which leads to the following integral

\[ I_2^2 + 2a^2 I_0^2 + \alpha^4 I_0^2 = \frac{i\alpha}{\nu} \left[ -Q + c(I_1^2 + \alpha I_0^2) \right] \quad (A7-6) \]

The real part of this relation is

\[ \frac{I_2^2}{2} + 2a^2 I_1^2 + \alpha^4 I_0^2 = -\alpha \left[ \frac{Q^* - Q}{2c} + c_1 (I_1^2 + \alpha I_0^2) \right] \quad (A7=7) \]

It follows that

\[ |Q - Q^*| \leq 2 \int_{y_1}^{y_2} \left| \int_0^y (v^*v' - vv') dy \right| dy \quad (A7-8) \]

Taking the absolute value, the following inequality is obtained

\[ |Q - Q^*| \leq 2 \int_{y_1}^{y_2} |U'|/\nu//v'/ dy \quad (A7-9) \]

With \( U_{\text{max}}' \) for the maximum value of \( |U'| \) and an application of the Schwarz inequality, (A7-9) becomes

\[ |Q - Q^*| \leq 2 U_{\text{max}}' I_0 I_1 \quad (A7-10) \]

It now follows from (A4-7) that

\[ \frac{\alpha c_1}{\nu} (I_1^2 + \alpha^2 I_0^2) \leq \frac{\alpha}{\nu} U_{\text{max}}' I_0 I_1 - (I_2^2 + 2a^2 I_1^2 + \alpha^4 I_0^2) \quad (A7-11) \]

A rough estimate for the critical Reynolds number was developed by Lin. The analysis will not be presented. Assuming \( \alpha = 1 \), the minimum Reynolds number is approximately

\[ \frac{U_0 L}{U} = (3.5)^3 \frac{U_0}{hU'(h)} \left( \frac{L}{h} \right)^2 \quad (A7-12) \]
APPENDIX H

Flows in Circular Tubes

(Betchov and Criminale, 1967)
Appendix H

Flows in Circular Tubes

In this section, a class of parallel flow which as a simple geometry in cylindrical-polar coordinates is considered. The flow is incompressible, viscous, and three-dimensional without body forces. The mean flow proceeds along the x-axis and \( U \) is a function of the radius \( \rho \) only. The fluctuations are functions of \( x, \rho, \phi, \) and \( t \).

Because the fluctuations must be periodic in \( \phi \), one can consider one Fourier component at a time and take every fluctuation as complex and proportional to \( \exp(ia(x-ct) + in\phi) \) in which \( n \) is an integer.

Thus for \( n = 0 \), rotationally symmetric flow is obtained; for \( n = 1 \), the perturbations are constant along a simple helix; for \( n = 2 \), the properties are constant along two intertwined helices, and so forth.

With \( u(\rho) \) for the complex amplitude of the fluctuation parallel to the x-axis, \( v(\rho) \) for the radial velocity, and \( w(\rho) \) for the azimuthal velocity, the linearized equations of Havier and Stokes are

\[
\begin{align*}
\alpha u + \frac{1}{\rho} v' + \frac{in}{\rho} w &= 0 \quad (A8-1) \\
\alpha(U-c)u + U'v + i\alpha^2 - v\left[ u'' + \frac{1}{\rho} u' - \left( \alpha^2 + \frac{n^2}{\rho^2} \right) u \right] &= 0 \quad (A8-2) \\
\alpha(U-c)v + p' &= \nu \left[ v'' + \frac{1}{\rho} v' - \left( \alpha^2 + \frac{n^2+1}{\rho} \right) v - \frac{2n}{\rho^2} w \right] \quad (A8-3) \\
\alpha(U-c)w + \frac{in}{\rho} p &= \nu \left[ w'' + \frac{1}{\rho} w' - \left( \alpha^2 + \frac{n^2+1}{\rho^2} \right) w + \frac{2n}{\rho} v \right] \quad (A8-4)
\end{align*}
\]

If \( n = 0 \), the function \( w \) is completely independent of the others.

Within the content of the stability theory, there is no production of \( w \), and it is assumed to vanish under the effects of friction.
Going further for the case \( n=0 \), it becomes possible to use a stream function so defined that

\[
u = \frac{1}{p} \psi, \quad v = \frac{i\alpha}{p} \psi
\]  

(A8-5)

Then, in terms of \( v \), the vorticity equation reads

\[
i\alpha(U-c)(v'' + \frac{1}{p}v' - \frac{1}{2}v^2 - \alpha^2 v) + i\alpha_p(U'/p)'v = \\
\nu(v'' + \frac{2}{p}v'' - \frac{3}{p^2}v'' - \frac{3}{p^3}v' - 2\alpha v'' - 2\alpha^2 v' + \frac{\alpha}{p} v + \frac{\alpha}{p} v')
\]

(A8-6)

The production of vorticity fluctuations therefore must be proportional to \( (d/d\rho)(U'/\rho) \) in place of the usual term \( U'' \), as found in two-dimensional flows in Cartesian coordinates.
APPENDIX I

HELMHOLTZ INSTABILITY

(Betchov and Criminale, 1967)
Appendix I

Helmholtz Instability

This section will briefly review an instability problem that has come to be known as Helmholtz instability since its first description by Helmholtz in 1868. The review will treat the case of two parallel flows, separated by an intermediate layer of fluid; friction forces will be neglected.

Because the displacements of the boundaries of the intermediate region can cause difficulties, the consequences of the following pair of assumptions will be examined:

a) the pressures are matched through the intermediate layer, and
b) the displacements are also matched.

From equation

\[ h' + U h_x = \tilde{\nu} \]  \hspace{1cm} (A9-1)

where

- \( h' \) = fluctuation in the cartesian component of the magnetic field
- \( \tilde{\nu} \) = fluctuation in the viscosity

one develops the following:

\[ h_{1t} + U_1 h_{1x} = \tilde{\nu}_1 \quad @ \quad y = H \]  \hspace{1cm} (A9-2)

\[ h_{2t} + U_2 h_{2x} = \tilde{\nu}_2 \quad @ \quad y = -H \]  \hspace{1cm} (A9-3)

After some manipulations the second condition leads to

\[ \frac{h_1}{h_2} = -\left(\frac{U_2 + c}{U_1 - c}\right)^2 = 1 \]  \hspace{1cm} (A9-4)
This means that \( c \) is no longer arbitrary and the above relation yields
\[
c = \frac{U_1 - U_2}{2} + i \frac{U_1 + U_2}{2}
\]  
(A9-5)

Thus there are two solutions, one exponentially growing with \( t \) (time) and the other decaying. A discussion of initial conditions reveals that, except for extraordinary cases, the growing solution becomes dominant and the flow is unstable. The values of \( \tilde{v}(H) \) can also be determined, finding,
\[
\frac{v_1(H)}{v_2(H)} = \pm i.
\]  
(A9-6)

There is, therefore, a phase difference of \( \pi/2 \) between the \( \tilde{v} \) fluctuations across the intermediate layer, but is perfectly acceptable. The flow is shown in the following sketch, with \( U_1 = U_2 \).

Figure A9-1: The Helmholtz Instability.  
(Betchov and Criminale, 1967)
APPENDIX J

Plates Illustrating Construction
Christensen Project
Laminar Flow
An application of axisymmetrical laminar flow to fountain design.