PAP-758

DENVER WATER

TREATED WATER STORAGE RESERVOIR

HYDRAULIC MODEL MIXING STUDY

November, 1996

Prepared by

Bates Engineering, Inc.
7333 W. Jefferson Avenue, Suite 155
Lakewood, Colorado 80235-2017
(303) 980-1212 Fax (303) 980-6300

ACKNOWLEDGMENTS

The hydraulic model was conceived, designed and plumbed by Bob Bates of Bates Engineering. The model itself was fabricated by AIA Plastics of Denver. The model stand, supply tank, temperature monitoring equipment and air supply system were set up at the Bureau of Reclamation Hydraulic Laboratory with the help of Jerry Fitzwater, Don Clem and Lee Elgin under the oversight of Phil Burgi, Laboratory Manager. The temperature monitoring equipment was designed and calibrated by Warren Frizell. Dr. Hank Falvey, retired from the Bureau of Reclamation, provided technical assistance pertaining to flow equations, stratification and the air bubbler mixing system.

Lee Cesario, the project manager for Denver Water, provided technical assistance, system flow and temperature data as well as independent observations of the model. The tests were performed by Dave Woodward of Bates Engineering and Jim Light and Steve Lavato of Denver Water. This report was prepared by Dave Woodward and reviewed by Bob Bates, Lee Cesario and Jim Light.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report discusses the results of a hydraulic model study examining mixing in treated water storage reservoirs. The study was performed by Bates Engineering in cooperation with Denver Water and the U.S. Bureau of Reclamation using a 1:22.75 scale model of a 3 MG reservoir. During six tests, the effect of four variables affecting mixing were evaluated: outlet configuration, water temperature, flow rates and the use of an air bubbler mixing system.

The report concludes that the most important influences on reservoir mixing, and hence water quality, are: inlet/outlet geometry, flow rate and water temperature. An air bubbler mixing system effectively promotes mixing but requires further evaluation.

General reservoir and system design criteria are presented. Specific design recommendations are made for the Chatfield and Colorow Reservoirs. Operators are encouraged to fluctuate reservoirs on a fill/draw cycle and regularly turn the water over. Potential areas for future research are also outlined.

I. PURPOSE

Three reservoirs within the Denver Water system were in view for this study: Hogback, Chatfield and Colorow. The Hogback Reservoir is existing while the other two are still proposed. The need for specific design and operation recommendations for these reservoirs was the driving force behind the study.

Economics is an important concern for the design of the Chatfield and Colorow Reservoirs. The additional piping to add a separate outlet 90 or 180 degrees from the inlet could amount to several tens of thousands of dollars. Could adequate mixing be assured if a single inlet/outlet was provided for the reservoir? In terms of operation of the reservoirs, what would be the effects of low wintertime flow rates and potential temperature differentials between the reservoir and the inflowing water? If there was a problem, would an air bubbler mixing system significantly improve mixing?

The purpose of this study was to use a physical model to examine reservoir mixing in terms of three parameters: outlet configuration, water temperature, and flow rate. In addition an air bubbler mixing system was evaluated for its ability to promote reservoir mixing. The study was to result in specific recommendations for the design of the Chatfield and Colorow Reservoirs.

II. WATER QUALITY IN STORAGE RESERVOIRS

Until recently not much attention has been paid to issues of water quality in treated water storage reservoirs. With increasing legislation on water quality more municipalities and water districts are looking into their treated water storage facilities. An issue of particular concern is detention time in the reservoirs. Too little time may not permit sufficient chlorine contact, while too long a period may result in inadequate chlorine residuals leaving the reservoir. A strong chlorine dosage can be unpleasant while a weak dosage can mean that the water has lost its disinfection. In addition, chlorine by-products such as trihhalomethane can actually pose health risks[1,2].

This detention time issue is further complicated by the fact that water may not pass through the reservoirs in a uniform way. The last water in is not necessarily the last water out, so different zones or strata within the reservoir can have water of different ages and thus chlorine residuals. For these reasons the study of mixing in reservoirs has been brought increasingly into focus.

Mixing in reservoirs can be broken into three components: inlet dispersion, horizontal mixing and vertical mixing. Inlet dispersion is a localized phenomenon affecting only the zone within a few pipe diameters of the inlet. Horizontal and vertical mixing, however, affect overall mixing in reservoirs. Lack of horizontal mixing means stagnation in particular zones of a reservoir. Lack of vertical mixing results in warmer water rising to the surface resulting in temperature stratification.

It is apparent that the location of the reservoir inlet and outlet will have some effect on the horizontal mixing within the tank. Could "short circuiting" of the reservoir take place if the inlet and outlet were relatively close to each other or even combined in the same piping? In addition one would surmise that the rate of inflow and outflow affects both horizontal and vertical mixing. Does halving the flow rate, for example, double the retention time in a reservoir? It is also clear that temperature differences between the inflowing water and the reservoir could result in temperature stratification. For example, cold water released from a treatment plant (say 40° F) entering a reservoir where the water temperature is near that of the surrounding soil (say 55° F) might tend to push the old water upward. Does this water ever exit the reservoir, or is it forever trapped at the surface?

In some cases physical limitations of existing reservoir systems or operational constraints may result in poor reservoir mixing. For example, in above-ground tanks, atmospheric temperature changes may swing reservoir water temperatures dramatically. Extremely cold reservoir inflows or oversized reservoirs are other examples of limitations. What can be done in these cases? Is it there an effective means of "turning over" water in the reservoir. Would an air bubbler mixing system serve this purpose?

---

[1] Bates, Robert T., *Zone 10E Reservoir Site Evaluation and Capacity Study*, prepared for the Southgate Water District, August 1995, page 11.

[2] Pizzi, Nick, "Optimizing Distribution System Operations", published in *Opflow* of the American Water Works Association, Vol. 22, No. 11 (Nov. 1996), p. 3.

III. RESERVOIR MODELING

Two valuable means of investigating reservoir mixing are computer models and physical (scale) models. Computer models are useful because the inputs can be readily changed to simulate various reservoir geometries and water temperatures. However, the results may be somewhat unrefined due to cell size limitations, imperfect boundary conditions and simplified flow theory models[3]. Physical models provide a tangible "feel" for mixing in reservoirs, but are locked into a specific geometry and are subject to scaling factors, especially with smaller models. Both types of models are best used when they can be cross-calibrated with each other and also if they are calibrated with prototype (full-scale) data.

Walter Grayman and others have compared computer and physical models of the 4 MG (million gallon) Ed Heck Reservoir in Azusa, California.[4] Their physical model was 1:42 scale with a 3-foot, 8-inch diameter. They looked at mixing with different outlet locations and shapes as well as the use of flow-directing baffles. Mixing was evaluated qualitatively by means of a tracer dye injected at the inlet. While the study was useful in terms of examining mixing in this particular reservoir, the model was of relatively small scale, the flows were of short duration and the results were primarily qualitative. Horizontal mixing and not vertical mixing was addressed. Temperature variations in the model were not directly addressed in the report.

Lewis Rossman at the U.S. Environmental Protection Agency National Risk Management Research Laboratory in Cincinnati, is in the process of performing mixing tests using a 4-foot-diameter model.[5] Conductivity measurements are being used in addition to a tracer dye to quantitatively verify mixing. Mr. Rossman is investigating the effects of flow rate, reservoir diameter and water level as well as temperature differentials on reservoir mixing. In the future, he would like to vary the inlet location and configuration to determine their effects on mixing.

Bates Engineering in conjunction with Burns and McDonnell and the U. S. Bureau of Reclamation investigated the effects of inlet piping configuration on reservoir mixing for a 3 MG reservoir under design for the City of Aurora, Colorado. A clear acrylic, 8-foot-diameter, 1:22.75 scale hydraulic model was constructed of the proposed reservoir. Various inlet geometries were studied to determine the effect of mixing by varying the number, size and location of inlets as well as various piping arrangements using bends, varied heights, angles with respect to the walls, and manifolds. Tracer dye was used to observe the initial effects of mixing and to locate stagnant or "dead" zones. The broad conclusion drawn from these qualitative tests is that the influence of inlet configuration is minimal in the overall picture of reservoir mixing. It remains a relatively localized phenomenon due to the relatively large size of reservoirs with respect to their inlet piping.

One unexpected phenomenon which was observed during the inlet configuration testing proved to be more interesting: the effect of thermal stratification in the model. Even with very small differences in the inflow and model temperatures, stratification was clearly observed in the model. Was cold water entering the reservoir, creeping along the floor and disappearing out the outlet without ever mixing vertically? Denver Water observed the City of Aurora tests and became interested in the potential of this

---

[3] Grayman, Walter M., et. al., "Water quality and mixing models for tanks and reservoirs," *Journal of the American Water Works Association,* Vol. 88, No. 7 (July 1996), p. 61.

[4] ibid, pp. 70ff.

[5] Telephone conversation with Lewis Rossman, U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, October 22, 1996.

phenomenon in their reservoirs. They asked Bates Engineering to conduct another series of tests using the same model focusing on horizontal and vertical mixing.

As part of the study, Bates Engineering asked Dr. Hank Falvey, formerly of the Bureau of Reclamation, to provide a computer model of mixing in a large, shallow reservoir. The potential flow solution (flow net) is based on Navier-Stokes equations and determines the flow patterns and velocities in a reservoir.[6] The variables for the model are: the diameter of the reservoir, the water depth, the angle between the inlet and outlet, the distance of the inlet and outlet from the outside wall, and the flow rate. Each of these variables can be adjusted to determine the streamlines and velocities for a given reservoir. In this manner some optimization of reservoir geometry can be made prior to physical model studies. A copy of Dr. Falvey's report is included in Appendix A.

---

[6] Falvey, Henry T., "Potential Flow Solution Flow in a Water Supply Tank," Report prepared for Bates Engineering, August 19, 1996, p. 1.

IV. MODEL DIMENSIONS

As mentioned above, the model is an eight-foot-diameter, 12-inch-high clear acrylic model with 16 column pads and columns (see Figure 1). The model is based on the City of Aurora 3 MG Reservoir with an 182-foot diameter and 20 feet high walls. The model was set up at the Bureau of Reclamation Hydraulic Laboratory in Lakewood, Colorado (see Appendix E for photographs).

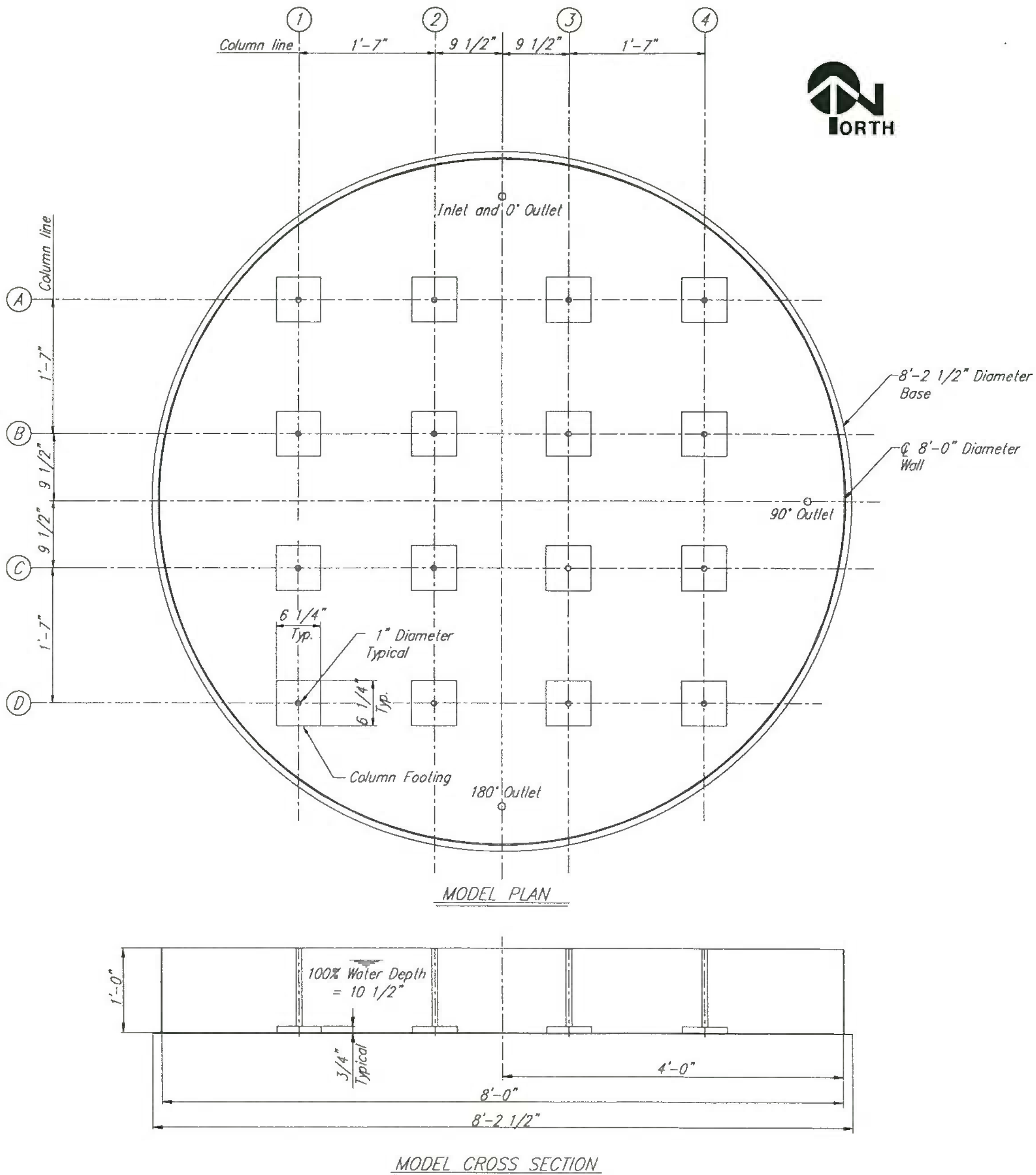


Figure 1. Model Dimensions

V. MODEL SIMILITUDE

In order to derive quantitative data from a physical model, relationships between the prototype and model parameters such as length, flow and time must be established. These relationships are expressed in terms of similitude. For flowing water the choice of an appropriate similitude relationship is based on the forces which dominate the flow, whether inertia, friction, gravity, compressibility, surface tension or pressure.[7] For flow under atmospheric pressures characterized by turbulence, the Froude similitude relationship is the appropriate choice. However, the Froude number does not directly account for the effects of viscosity related factors such as temperature. The Reynolds number includes viscosity term, but the Froude and Reynolds similitude factors cannot readily be tested together.[8]

The length scale factor for the model, L_R, is 8:182 or 1:22.75. For Froude similitude, model lengths are scaled directly by the scale factor so that, for example, the one-inch diameter model inlet and outlet pipes correspond to roughly to 24-inch prototype pipes.

For Froude similitude, flow rates for the model were scaled by the five-halves power so that 8 MGD corresponds to a model flow rate of

$$Q_M = Q_P/L_R^{5/2} = 8 \times 10^6 /22.75^{5/2}/(24*60) = 2.25 \text{ gpm.}$$

For Froude similitude, time is scaled by a factor of the one-half power. One minute in model time thus corresponds to

$$T_P = T_M*L_R^{1/2} = (1)(22.75)^{1/2} = 4.77 \text{ minutes}$$

in prototype time. A 24-hour cycle in the prototype corresponds to 302 minutes in model time. Each test thus took approximately five hours to complete.

---

[7] Daugherty, Robert L. and Joseph B. Franzini. *Fluid Mechanics with Engineering Applications*, 7th ed., McGraw Hill, 1977, pp. 174-181.

[8] Hydraulic Laboratory Techniques, U.S. Bureau of Reclamation, Denver, 1980, p. 47.

VI. MODEL FLOWS

The inlet and outlet pipes were plumbed flush with the floor of the model so that the water entered and exited the model at a 90° angle. Water was provided to the inlet using a 250-gallon plastic supply tank in conjunction with a small centrifugal pump and flexible plastic piping. The location of the outlet was adjusted by plugging all the one-inch floor taps except the one at the desired location (see Figure 1). Water was drawn through the outlet by means of a second small pump and was discharged to the below-grade channel network in the Bureau of Reclamation lab. Inflow and outflow rates were measured using valved, acrylic, panel-mount, water rotameters appropriate for the flow range.

Since water demands tend to be lower in the wintertime, and it was believed that periods of low demand coincide with water quality problems, a "typical" wintertime demand hydrograph was sought for the model. It was desired to simulate a full 24-hour cycle in the life of the proposed Chatfield Reservoir to examine longer term effects of mixing. To produce the outflow hydrograph, January 1996 system-wide demand data was selected because January traditionally has the lowest average temperature and because the data was current. Upon observing the data, it was clear the demands in any one day varied enough that it was felt that data from at least a ten-day period should be averaged. Eleven days (the 16th through the 26th) worth of hourly system-wide water demands were provided by Denver Water. The dates were started on the 16th because the 15th was a holiday so the demands were not at all typical for the month. The data was entered into a spreadsheet (see Appendix B). The average daily system-wide demand for this period turned out to be 114.79 MGD (million gallons per day).

The system-wide demand curve was then scaled for to achieve an assumed average daily demand of 8 MGD for the proposed Chatfield Reservoir. The demand curve was approximated by a step function in order to simplify operation of the model. The demand was set at 6 MGD for first six hours of the day, 9 MGD from 6:00 a.m. to 6:00 p.m. and back to 8 MGD from 6:00 p.m. to midnight. These flows were then scaled by similitude to achieve the outflow hydrograph found in Appendix B.

The inflow hydrograph assumed a constant pumping rate. The inflows were held constant at a prototype flow rate of 8 MGD so that the reservoir level at the beginning and end of the 24-hour-day test would be the same.

The tests were begun with calm water in the model. It was decided to begin and end the tests with a 75% full reservoir (7 7/8 inches water depth) since this was felt to be the most likely average wintertime reservoir level. Although it might be assumed that fuller reservoirs would tend to have greater stratification problems, the Aurora tests showed that this is not always the case.

The inflow and outflow rotameters were simultaneously started at time t = 0 minutes. The inflow rotameter was set for the entire test time period and the outflow rotameter was adjusted twice during the experiment to match the outflow hydrograph. The low initial outflow resulted in the reservoir raising to about 87% of the reservoir height by about 6:00 a.m. prototype time and falling back to the 75% level by 6:00 p.m.

VII. DATA COLLECTION

Stagnation and temperature stratification are not independent of each other, but they can be measured separately. Both stagnation and temperature stratification can be visually observed using a tracer dye. Dye was introduced into the model by adding yellow liquid dye to the supply tank. The initial horizontal and vertical mixing could be observed and photographed with this method. However, after 15 to 45 minutes, all the water in the model was sufficiently dyed to prohibit further observation of mixing patterns. Even when dye was injected with a hypodermic needle directly into the inflow piping, only a few seconds of dispersion could be observed. Quantitative means were thus needed to verify mixing.

Stagnation can also be measured in terms of temperature because areas of low water turnover in the model would tend to increase in temperature towards room temperature since the supply tank and model water were always colder. Temperature could thus be used to measure the absolute effects of temperature stratification. However, there is no means of directly correlating the temperature differential in the model with prototype temperatures.

Conductivity can also be used to measure both horizontal and vertical mixing. If tap water is introduced into a model full of de-ionized water, areas of low ion concentrations in the model indicate a lower turnover rate than areas of high concentrations. Stagnant zones could thus be located to evaluate horizontal mixing, while the differences between the conductivity between the top and bottom of the model would indicate lack of vertical mixing or stratification.

For the Aurora tests, only dye was used. For the Denver Water tests, all three means of determining the extent of stagnation and temperature stratification were used. The dye was a qualitative method whereas, the temperature and conductivity were quantitative.

For temperature monitoring in the model, the Bureau of Reclamation was asked to provide thermistors at five levels corresponding to 0%, 25%, 50%, 62.5% and 75% reservoir height at four column locations (A2, B4, C1, D3, see Figure 1). The thermistor lead wires were enclosed in 1/2-inch PVC pipes mounted to the columns. The twenty column thermistors, as well as one each from the inlet (supply tank) and outlet (at model outlet), recorded voltages into a laptop computer using Labtech® Software. The thermistors were then individually calibrated to convert voltages into temperatures (for data see Appendix D). For the first two tests, the probes were not in place so hand held alcohol thermometers were used to make temperature measurements.

After the first two tests, conductivity measurements were added to provide further understanding of quantitative behavior. The model was filled with de-ionized (distilled) water (with zero conductivity) and the supply tank was filled with tap water (conductivity about 100 μS/cm). For Test 3, the de-ionized water was produced through a de-ionizer provided by Denver Water. Due to slow model filling rates, however, this was abandoned in favor of having the Bureau of Reclamation Chemistry Lab provide the de-ionized water for the last three tests. An Orion Model 160 conductivity meter provided by Denver Water was used to record conductivity (and verify temperature) at the surface and floor at the same four columns where temperature was monitored.

VIII. SUMMARY OF TESTS PERFORMED

The variables for each of the six tests run is summarized in the table below:

Table 1. Summary of Tests Performed

Test No.	Outlet Config.	Flows (MGD)	Temp Diff.	Bubbler	Data Taken
1	0°	8	No	No	Hand Temperature
2	90°	8	No	No	Hand Temperature
3	180°	8	Yes	No	Conductivity/Probe Temperature
4	180°	8	No	No	Conductivity/Probe Temperature
5	180°	2	Yes	No	Conductivity/Probe Temperature
6	180°	2	Yes	Yes	Conductivity/Probe Temperature

Outlet configuration refers to the angle between inlet and outlet measured by an angle whose vertex is at the center of the model (see Figure 1). Zero degrees means that the inlet and outlet used the same piping.

Flows indicates the average prototype inflow and outflow rate over the 24-hour prototype time period. The 2 MGD flows were produced by using 25% of the hydrograph in Appendix B.

Temperature difference means that a temperature differential was purposely induced between the model and inflowing water. This was accomplished by filling the model the night before the test and using colder tap water in the morning to fill the supply tank. Because the laboratory was not climate controlled and the outside air temperature varied dramatically, because the tap water temperature also varied, and because the differing aspect ratios between the supply tank and the model allowed the model to reflect laboratory air temperatures more readily, it was not possible to begin the experiment with a constant temperature difference. At the start of the tests, the model water temperature ranged from 0.6°C to 2.2°C warmer than the inflowing water when no temperature difference was induced. When a temperature difference was induced, the model was 2.2°C to 3.3°C warmer than the inflow.

The fifth column indicates if the air bubbler mixing system was used or not.

Data collection is as described above.

IX. EFFECT OF OUTFLOW LOCATION

The effect of outflow on horizontal mixing was examined by comparing temperature data from Tests 1, 2 and 4. All three tests used the same flow rate (8 MGD) and no planned temperature differential between the inflow and model. Because the 90° outlet was located toward the east of the model, it was decided to look at temperature data from column C1 since it was furthest from this outlet (see Figure 1).

In order to evaluate stagnation or "dead" zones, an indicator called "relative stagnation" was created. Relative stagnation is defined as the ratio of the difference between the average model temperature at Column C1 and the inflow temperature at a given time, and the *initial* difference between the average model temperature at Column C1 and the inflow temperature.

$$\text{Relative Stagnation} = (T_{model} - T_{inflow}) / (T_{model} - T_{inflow})_{initial}$$

The value of relative stagnation at the start of the test will always be 1.00. Increasing stagnation over time will result in values greater than one and decreasing stagnation or good circulation will result in increasingly smaller values. The results of the comparison between the three outlet configurations can be seen in Chart 1.

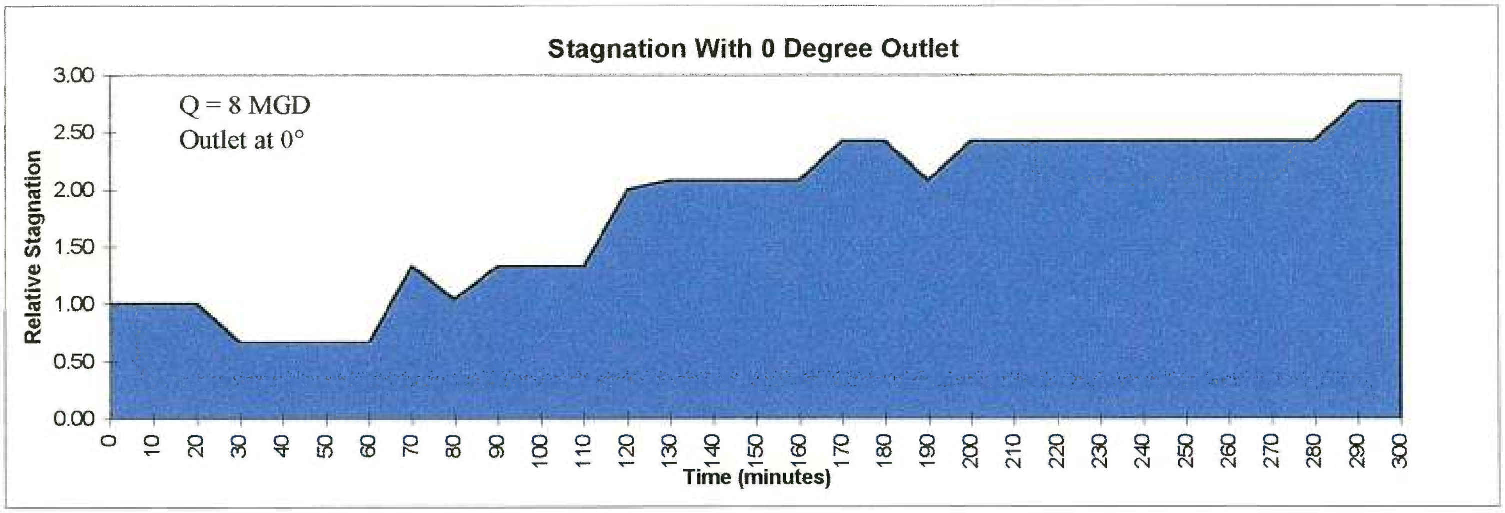
As can be seen, the single inlet/outlet results in the worst mixing especially with small reservoir fluctuations. Because the inflows and outflow hydrographs are physically tied to each other at the tee, only the *difference* between the inflow and outflow rate induces mixing (i.e. 2 MGD in the first 6 prototype hours, 1 MGD in the middle 12 hours and 0 in the last 6 hours). The 90° case is improved due to larger turnover of water; however stagnant areas still can develop at 180° from the outlet. The best case is 180° separation. Theoretical mixing is symmetrical about a circular reservoir and the length is the longest flow line is minimized.

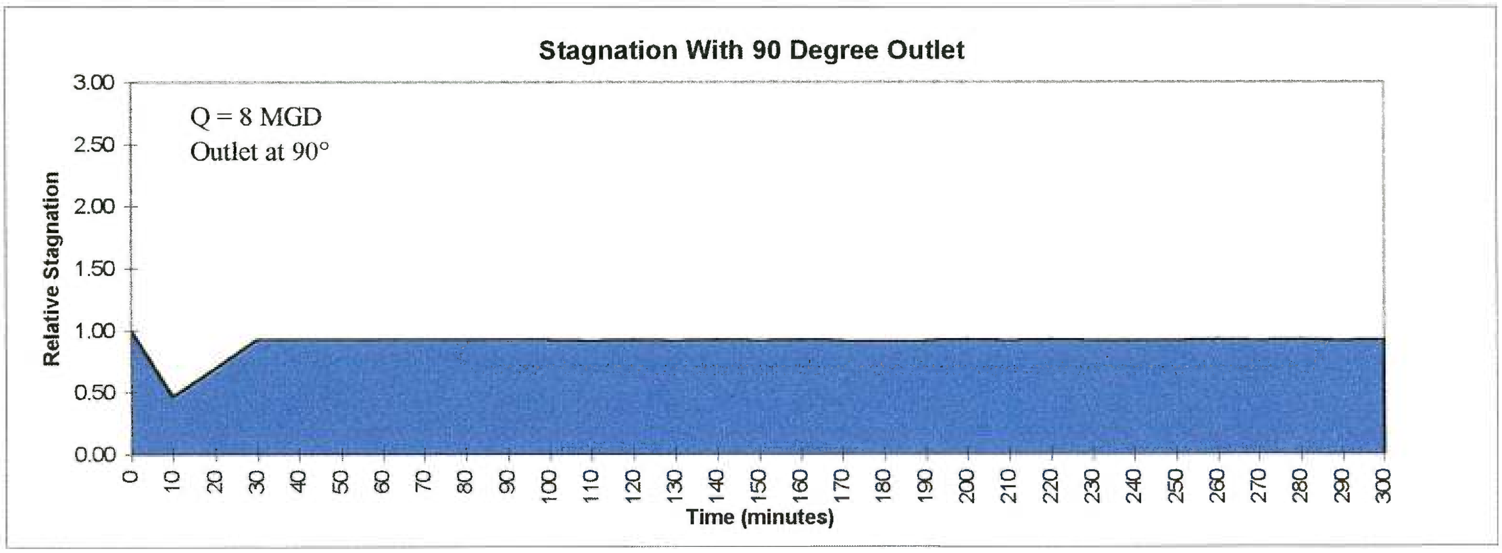
One benefit of the separate inlet/outlet configuration (90° and 180° cases) is that the inflow velocity head is much higher (a function of the velocity squared) resulting in greater turbulence and thus mixing in the area immediately surrounding the inlet. This, however, as was mentioned above, is only a local effect and the global mixing picture is more closely tied to other factors.

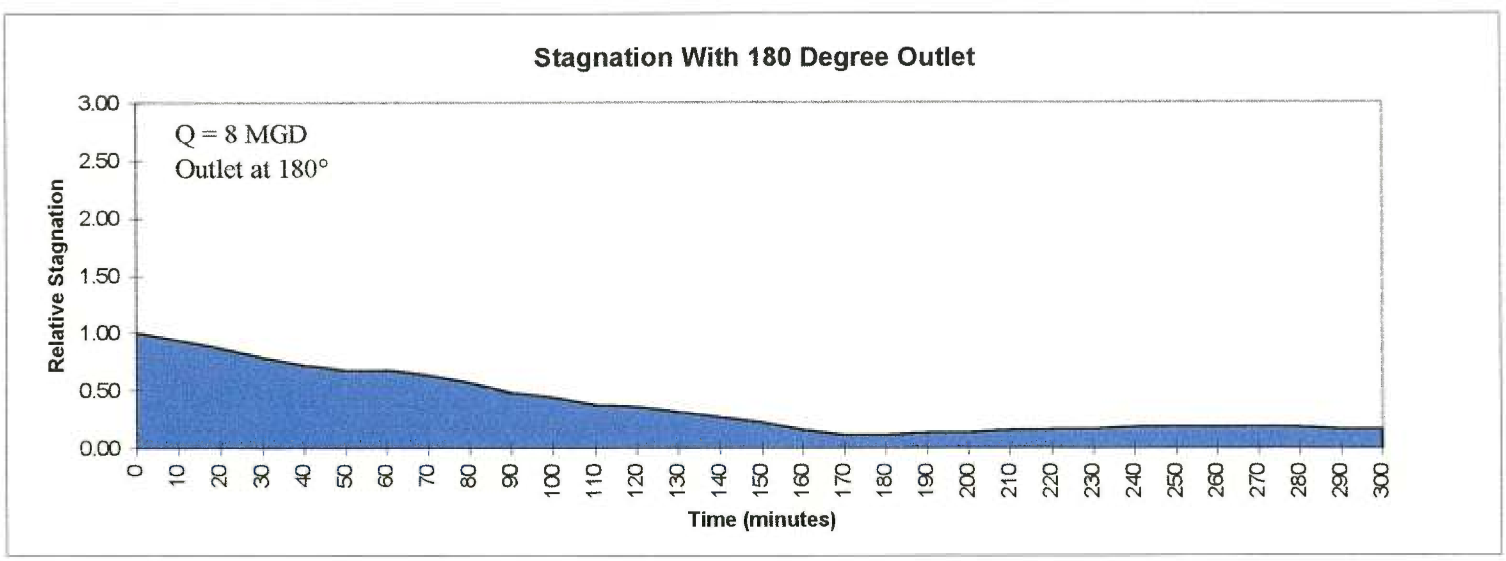
Vertical mixing tended to start at the top and work its way down for small temperature differences between the model and the inflow. This was consistent with tests performed for the City of Aurora.

In terms of horizontal mixing in the model, the last area to experience complete mixing of the dye for the 0° case was in the southeast corner of the model. Although one would have predicted that the last area would be the south corner due to symmetrical flow, uneven flow velocities in the model apparently favored mixing slightly on the west side. For the 90° case, the last area to experience horizontal mixing was the southeast corner of the model "behind" the outlet. For the 180° case, the last area was at the center of the model. The inlet appeared to establish flows which moved around the perimeter of the model. As was observed during the City of Aurora tests, the columns and column bases had an impact on the horizontal mixing. The columns tended to provide a "shadow" of poorer mixing away from the "sun" of the inflow.

Chart 1


Stagnation With 0 Degree Outlet
Q = 8 MGD
Outlet at 0°
Relative Stagnation
Time (minutes)


Stagnation With 90 Degree Outlet
Q = 8 MGD
Outlet at 90°
Relative Stagnation
Time (minutes)


Stagnation With 180 Degree Outlet
Q = 8 MGD
Outlet at 180°
Relative Stagnation
Time (minutes)

X. EFFECT OF TEMPERATURE DIFFERENCE BETWEEN MODEL AND INFLOW

The effect of a temperature difference between the model and the inflowing water was examined by comparing conductivity data from Test 3 and Test 4. Both tests had the same flow rates and the 180° outlet configuration. However, in Test 3 a temperature difference between the model and the inflow was intentionally introduced where it was not in Test 4. Due to factors discussed above, temperature differences were difficult to obtain and maintain in the laboratory. For Test 3, the initial temperature difference between the inflow and the model was 3.1°C, while for Test 4 the initial difference was 2.2°C. At the end of Test 3, the temperature difference was still about 1.1°C, while the temperature difference was negligible at the end of Test 4.

In order to evaluate the effects of an initial temperature difference in the model, a "percent stratification" term was defined as the difference in conductivity between the bottom of the model and the surface divided by the average model conductivity.

$$\text{Percent Stratification} = (C_{floor} - C_{surface}) / C_{average}$$

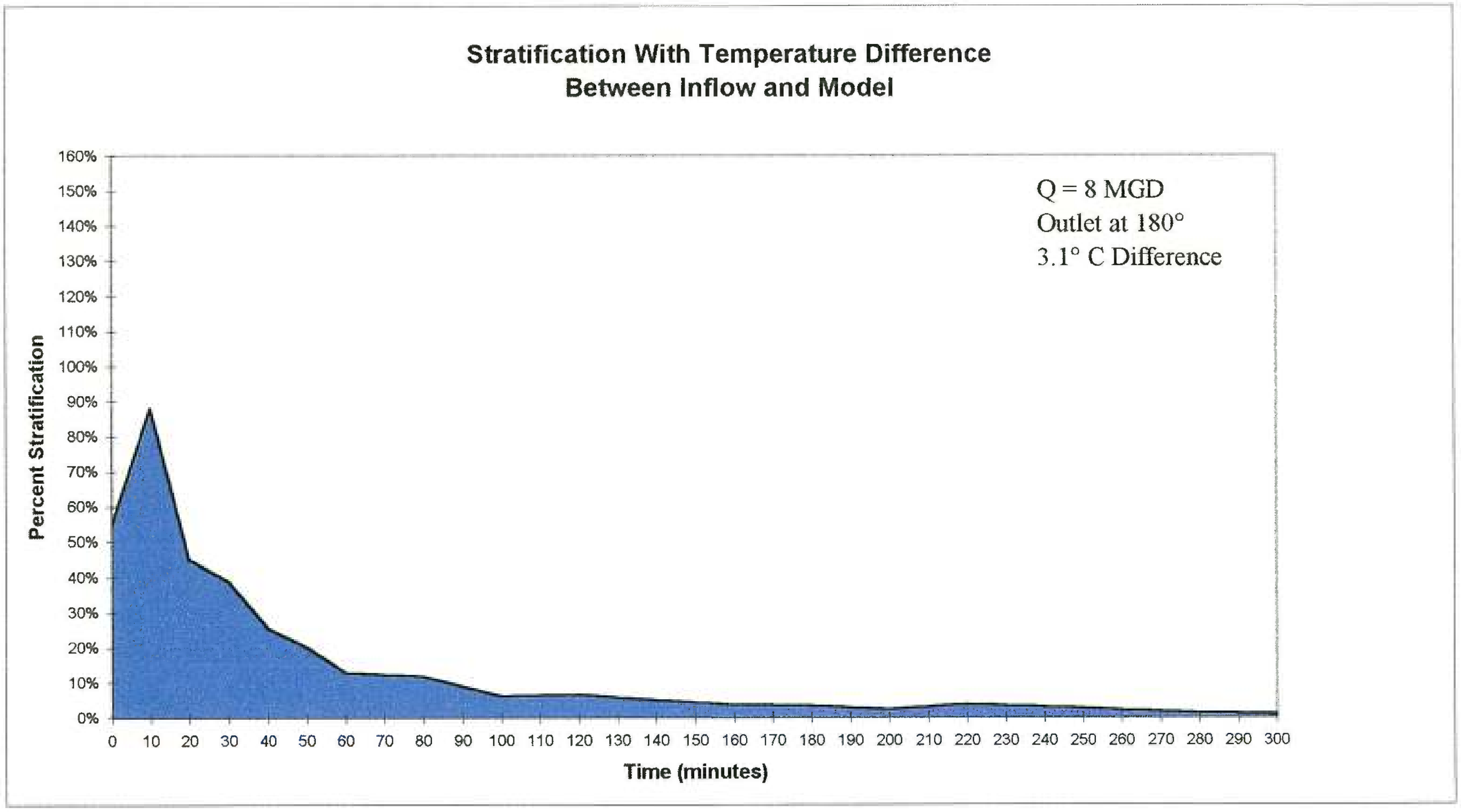
For the C_{floor} and $C_{surface}$ terms, conductivity data were averaged from the four columns at the surface and at the floor. The $C_{average}$ term is derived from the average of all eight readings. The higher the value of percent stratification, the worse the problem of stratification. Naturally this value decreased over time due to the increasing weight of average conductivity. If longer tests were performed an additional measurement parameter would be required.

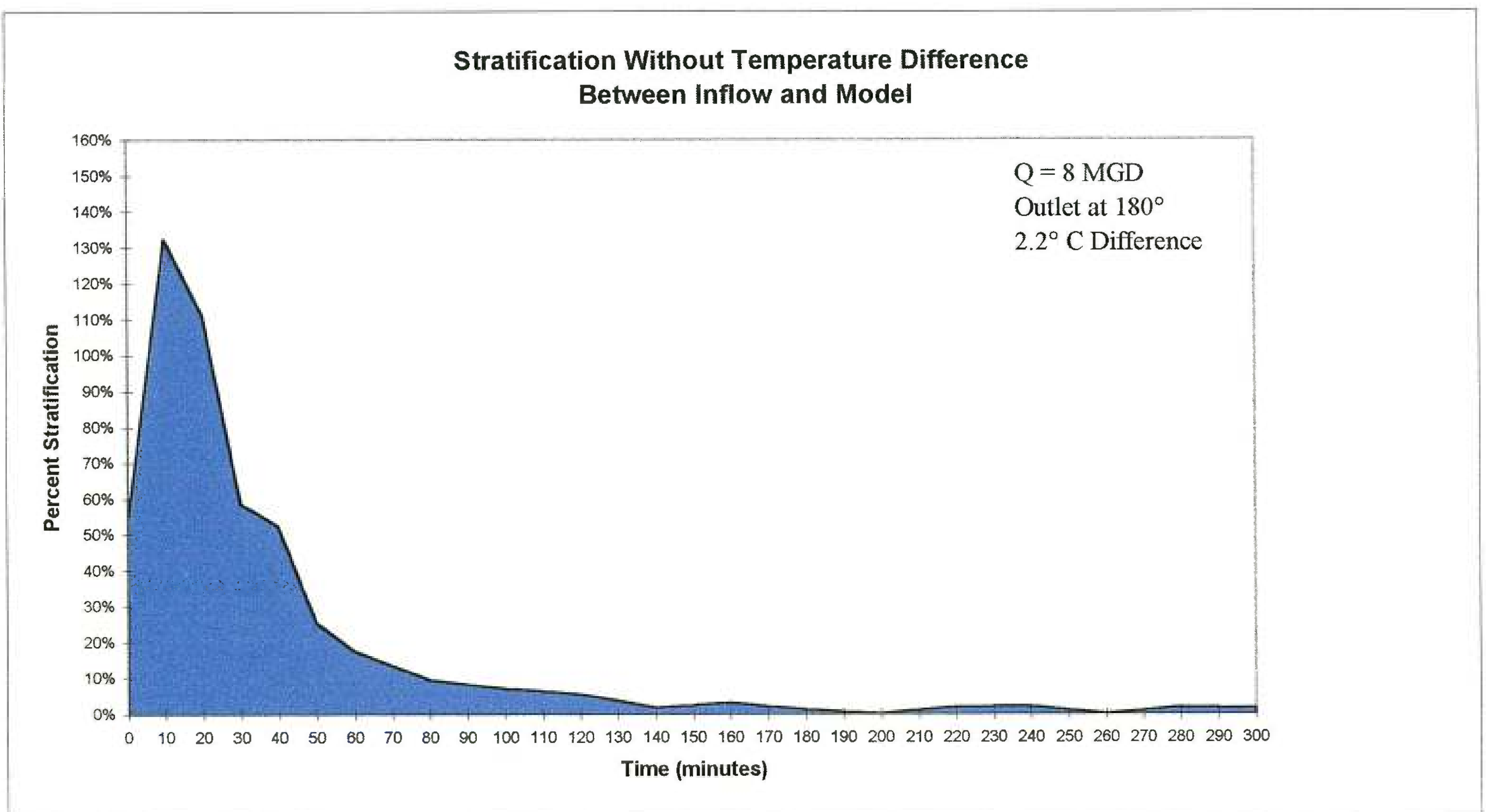
The results of the comparison can be seen in Chart 2. The test with the initial temperature difference actually had about 40% percent lower maximum stratification than the test where inflows more closely matched model temperatures. This is contrary to what one would expect. The effects of laboratory temperature fluctuations may partly account for this anomaly. Test 3 was performed on a very warm day where air temperatures rose constantly during the test up to 25.5°C at the end of the test, while Test 4 was performed on a rainy day when air temperatures bounced around between 19.9°C and 22.8°C. The effects of varying laboratory temperatures on mixing would have been reduced if lower flow rates had been used during the tests. Additional tests which compare a *range* of temperature differences versus percent stratification would also further clarify the effects of temperature differences.

At least one other observation can be made based on these two tests. The further one moves away from the inlet (i.e. the closer one moves towards the outlet), the less stratification was observed early in the tests. For example in Test 3, at t=30 minutes, there is a 14 μS/cm difference in conductivity between the floor and surface near the inlet (Column A2), an average difference of 7 μS/cm in conductivity between the floor and surface at columns B4 and C1, and a 5 μS/cm difference in conductivity between the floor and surface near the outlet (Column D3). This observation is contrary to what one might expect especially since the zone of greatest turbulence (and thus one would think mixing) is in the area immediately around the inlet. One may surmise that the effect of dispersion across the model is more effective in "breaking up" the stratification than the turbulence produced at the inlet. There is some theoretical basis for the poorest mixing occurring between the inlet or outlet and the wall behind them.[9]

---

[9] Falvey, Henry T., "Potential Flow Solution Flow in a Water Supply Tank," Report prepared for Bates Engineering, August 19, 1996, p. 3.


Stratification With Temperature Difference
Between Inflow and Model
Q = 8 MGD
Outlet at 180°
3.1° C Difference
Percent Stratification
Time (minutes)
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100% 110% 120% 130% 140% 150% 160%
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300


Stratification Without Temperature Difference
Between Inflow and Model
Q = 8 MGD
Outlet at 180°
2.2° C Difference
Percent Stratification
Time (minutes)
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100% 110% 120% 130% 140% 150% 160%
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300

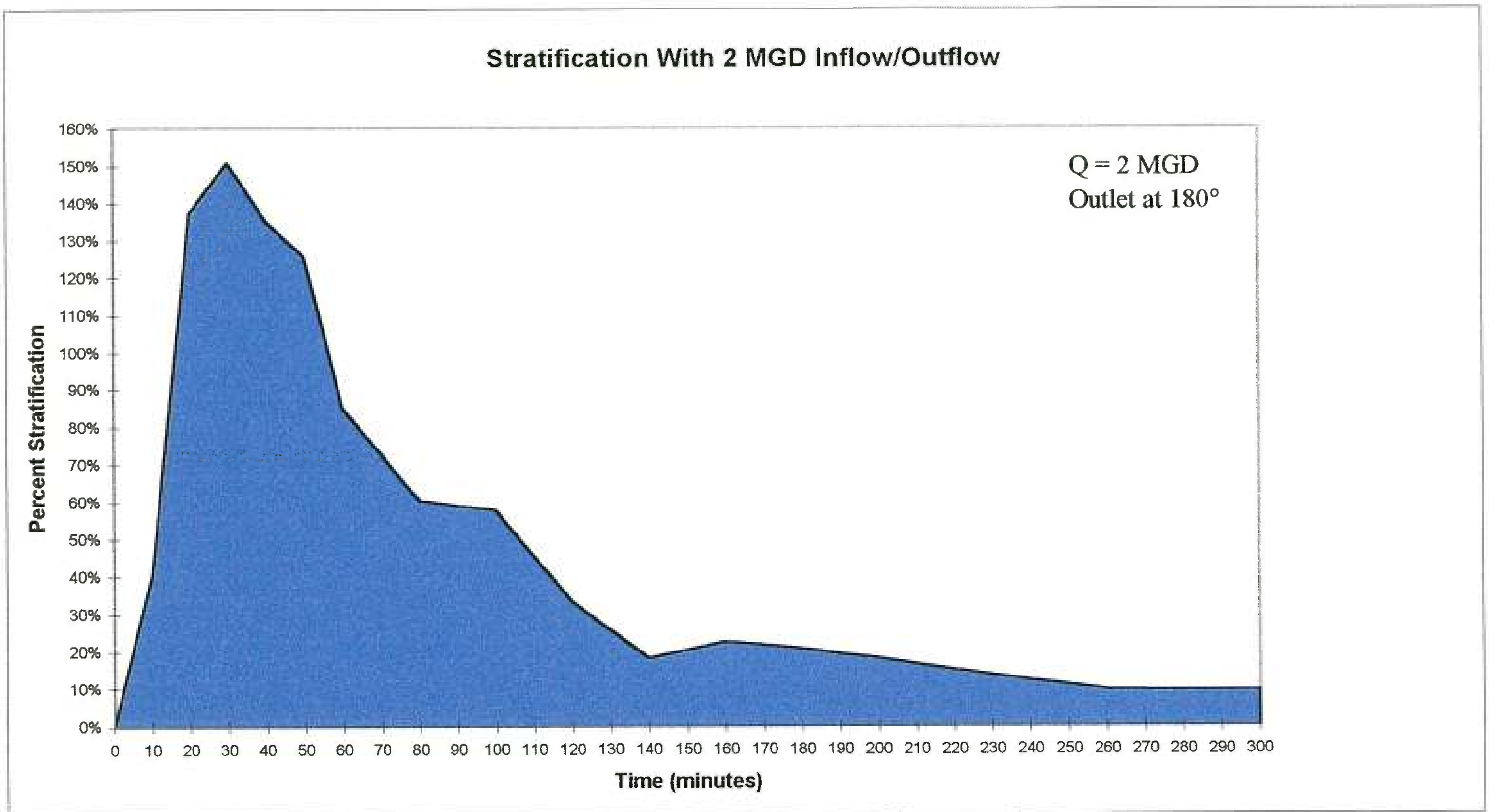
XI. EFFECT OF FLOW RATE

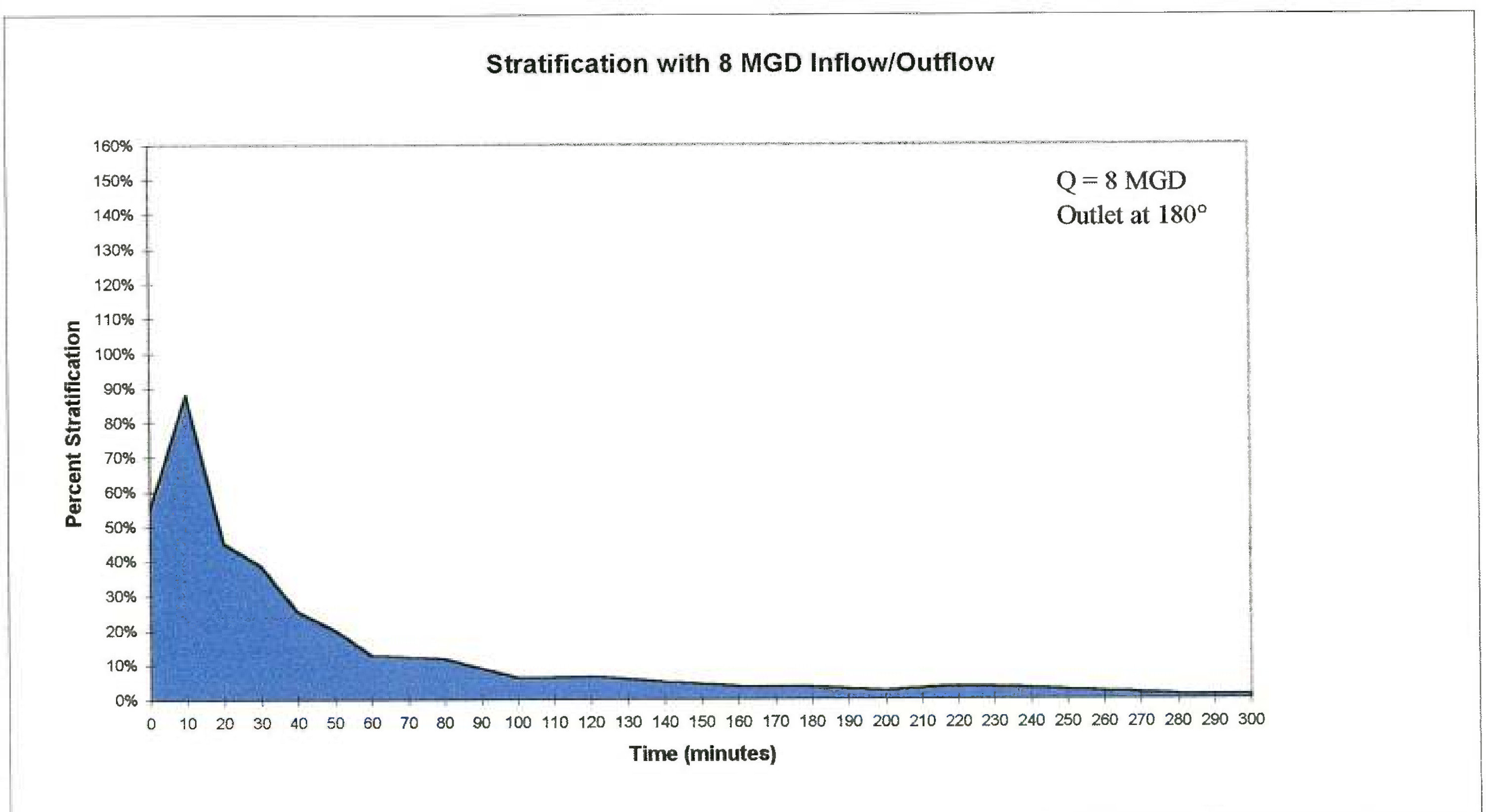
The effect of inflow and outflow rates was examined by comparing conductivity data from Test 3 and Test 5. Both tests had a temperature difference between the inflow and the model and well as the same 180° outlet configuration, but Test 3 had an 8 MGD average flow rate while Test 5 had an average of only 2 MGD.

Percent stratification (defined above) for the two tests over time was plotted. The results of the comparison can be seen in Chart 3. The percent stratification was 65% higher for the lower flow rate than the higher. Low flow rates lead to stratification as would be expected. This appears to be a more significant effect than the temperature difference between the model and the inflow.

It is also interesting to compare the absolute values of mixing between Test 3 and Test 5. The average model conductivity level for the 2 MGD test only reached about 60% of the mixing with 8 MGD. The effect of higher flow rates is obvious. With another series of tests a relationship could be plotted between the average flow rate and the extent of mixing. It appears that extent of mixing is approximately proportional to the square root of the flow rate.

Chart 3


Stratification With 2 MGD Inflow/Outflow
Q = 2 MGD
Outlet at 180°
Percent Stratification
160%
150%
140%
130%
120%
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300
Time (minutes)


Stratification with 8 MGD Inflow/Outflow
Q = 8 MGD
Outlet at 180°
Percent Stratification
160%
150%
140%
130%
120%
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300
Time (minutes)

XII. EFFECT OF AIR BUBBLER MIXING SYSTEM

The effectiveness of an air bubbler mixing system was examined by comparing conductivity values from Test 5 and Test 6. The outlet configuration was set at 180°. The low flow rate (2 MGD) was used because stratification was accentuated due to the lack of turnover in the model.

Releasing air from the bottom of a reservoir in the form of bubbles encourages vertical mixing by lifting cold water from the floor to the surface.[10] This discourages temperature stratification. If the bubblers are configured in specific arrangements based on water depth, the circulation patterns between bubblers can reinforce each other to promote more efficient turnover. For the model, Dr. Hank Falvey recommended two bubbler rings with two and six-foot diameters. Porous aquarium "wands" 1/8-inch in diameter were used to create the rings. Air was provided from the Bureau of Reclamation lab house compressed air line. The air was throttled through a regulator, passed through an air rotameter and then split into two before entering each bubbler ring at a single point. The far end of each ring was plugged. This resulted in somewhat uneven flow along the ring, but nonetheless the overall effect of the bubbler mixing system could be observed.

The air flow rate for the bubbler mixing system was based on the temperature difference from Test 5. A spreadsheet by Dr. Hank Falvey gives theoretical air flow rates to turn water over based on the buoyant force of the bubbles (see Appendix C). Dr. Falvey suggested using three to four times the theoretical value to account for inefficiencies in the bubbler mixing system, but due to limited compressed air pressures and volumes in the Bureau of Reclamation lab, only the theoretical value of 1.66 scfm was obtained.

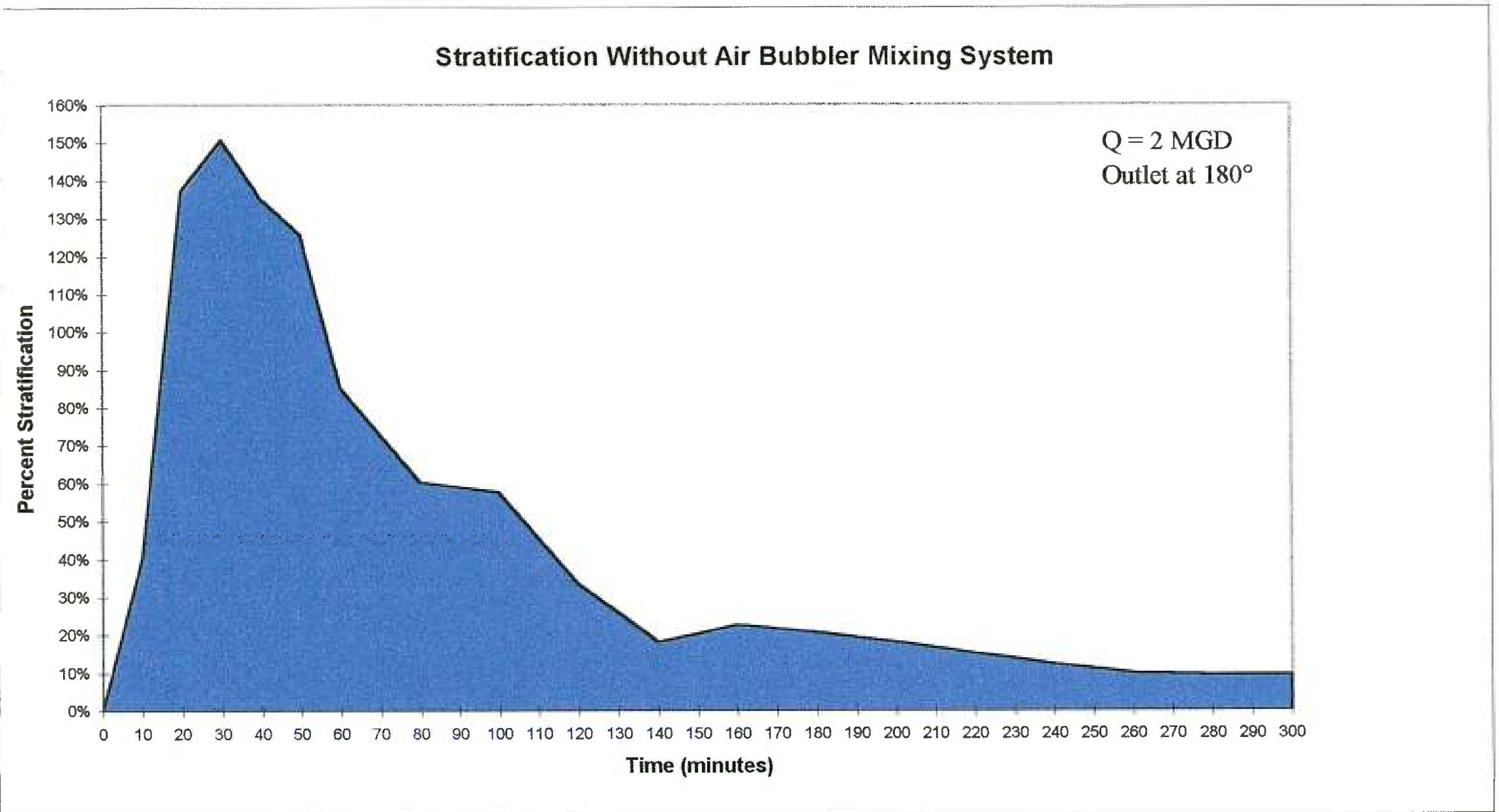
Percent stratification was again used as a basis for comparing the tests. The results can be seen in Chart 4. Almost no stratification was observed even for low water flow rates. The conclusion is that complete mixing of the model was achieved at the theoretical air flow rate. As a check, the air flows rates were reduced to approximately 40% of the theoretical for about one hour without any observed stratification. However, when the rates were reduced to about 20% at t=240 minutes, slight conductivity differences between the surface and the floor were evidenced, indicating stratification.

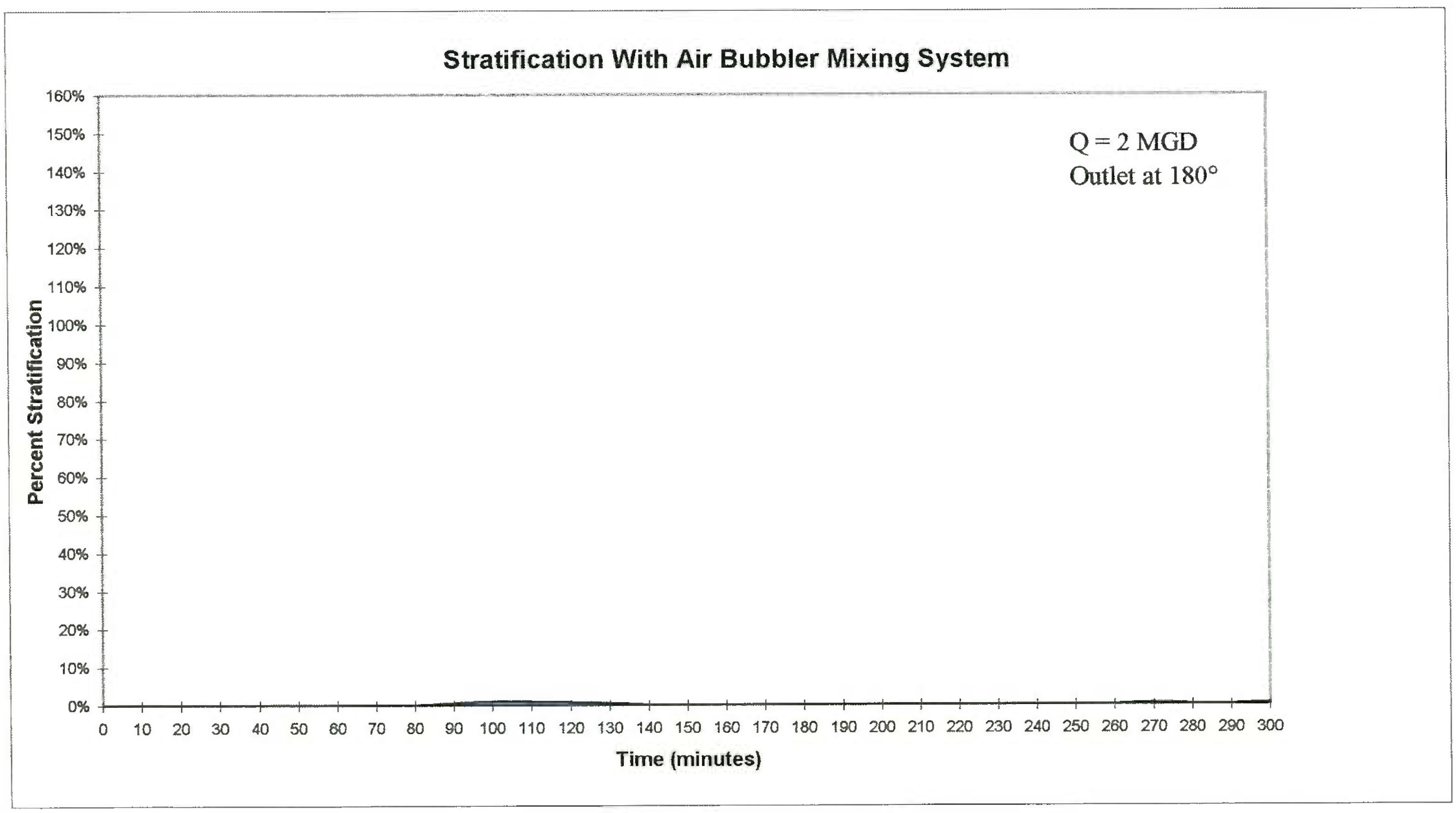
From the data, it may also be observed that complete horizontal mixing also occurred. Conductivity measurements were consistent in each quadrant of the model. Thus, it appears that an air bubbler mixing system may be sized to achieve complete vertical *and* horizontal mixing in a reservoir. However, some practical considerations may limit the usefulness of air bubbler mixing systems. The initial system and ongoing pumping costs may be prohibitive. In addition the bubbler mixing system requires additional maintenance and may complicate annual reservoir washdown. Concern has also been expressed that "dirty" air circulated through a reservoir may actually increase the chlorine demand of the water requiring a separate chlorine disinfection system at the reservoir. Oxygen in the water can also precipitate out iron and manganese from the water source causing unwanted residues.

---

[10] Falvey, Henry T., "Estimation of Destratification with a Bubbler," Report prepared for Bates Engineering, September 9, 1996.

Chart 4


Stratification Without Air Bubbler Mixing System
Q = 2 MGD
Outlet at 180°
Percent Stratification
160%
150%
140%
130%
120%
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300
Time (minutes)


Stratification With Air Bubbler Mixing System
Q = 2 MGD
Outlet at 180°
Percent Stratification
160%
150%
140%
130%
120%
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300
Time (minutes)

XIII. CONCLUSIONS

Improving Mixing in Reservoirs

Six tests were run to compare four factors affecting mixing in treated water storage reservoirs. A summary of these four comparisons is shown below:

Table 2. Summary of Mixing Factor Comparisons

Factor	Measurement	Test Nos.	Best Mixing
Outlet Configuration	Temperature	1,2,4	180° separation
Temperature Difference	Conductivity	3,4	No temp. difference
Flow Rate	Conductivity	3,5	High flow rates
Air Bubbler Mixing System	Conductivity	5,6	Yes

A single inlet/outlet results in the worst mixing especially with small reservoir fluctuations. The 90° case is improved due to larger turnover of water; but stagnant areas still can develop at 180 degrees from the outlet. The ideal case is 180° separation. However, the geometric relationship between the inlet and outlet does not appear to be as significant as the fact that the inlet and outlet are separately piped.

The smaller the temperature differences between the inflow and the reservoir the better the mixing. Lower temperature differentials permit less temperature stratification to develop.

High flow rates result in better horizontal and vertical mixing in reservoirs.

Although there is no direct quantitative correlation between the test results it appears that, in order of importance, the following parameters have an influence on mixing:

1. Outlet Configuration
2. Flow Rate
3. Temperature Difference Between Inflow and Reservoir

An air bubbler mixing system can be sized to eliminate the effects of temperature stratification in a reservoir by "turning over" the water. The cost of this may be prohibitive however, and new problems may be created such as increased maintenance, chlorine stripping and mineral precipitation.

Other observations include that higher inlet velocities caused by higher flow rates stimulate local mixing, but not reservoir-wide mixing. In general vertical mixing actually tends to be better towards the outlet than at the inlet.

Improving Future Model Studies

Dye is only effective for tests of short duration but does not provide any quantitative information on mixing. Although temperature measurements clarify the driving temperature differentials which drive vertical mixing, conductivity is generally more useful for quantitative assessment of mixing because it is only affected by the incoming and outflowing water and not by other factors such as ambient air temperature and changes in tap water temperature. The range of conductivity values varies from 0 to 100 μS/cm versus approximately 15 to 20°C giving a better "feel" for the results. However, we do not know of any direct means of comparing conductivity stratification with temperature stratification. This could be the focus of a future study.

Perhaps an ideal means of evaluating mixing in reservoirs would involve using a "tracer" which had a half life similar to that of chlorine, so that stagnant areas within the model would begin to lose their tracer over time similarly to chlorine. Fluoride has been used for this purpose for prototype testing.[11] One would still be a step away from the advantage of prototype testing even if this were the case, however, because the half-life relationship would not scale in the same Froude time relationship as the mixing of the water.

In our opinion, the most effective means of evaluating mixing in reservoirs in order of increasing effectiveness are:

1. Model - Tracer Dye
2. Model - Temperature
3. Model - Conductivity
4. Model - Tracer with Half-Life
5. Prototype - Chlorine monitoring

Any modeling of air bubbler mixing systems should use several ports and similar "wands" to produce uniform flow throughout the model.

[11] Grayman, Walter M., et. al., "Water quality and mixing models for tanks and reservoirs," *Journal of the American Water Works Association,* Vol. 88, No. 7 (July 1996), p. 63.

XIV. RECOMMENDATIONS

General Recommendations for Reservoir Design

1. **Separate the inlet and outlet**, preferably 180 degrees. This, however, does not imply that a single inlet/outlet will necessarily result in poor mixing, especially if the operational recommendations below are pursued.

2. **Evaluate the insulating properties of the reservoir materials**. Because temperature differences between the inflowing water and the reservoir can lead to thermal stratification of the reservoir, the better the reservoir is insulated, the less likely it will stratify. Certain materials, such as concrete, tend to be better insulators, discouraging temperature differences. Reservoirs that are partially or fully buried will also be less susceptible to temperature stratification due to the insulating properties of the soil.

3. **Size inlet and outlet piping to allow high flow rates**. The size of the inlet and outlet piping should not be the limiting factor in the rate at which water fills or drains a reservoir. Future pumping capacity or demands should be the basis for sizing the piping.

4. **Provide flanged fittings for the inlet and outlet piping** so that modifications based on further research can easily be implemented.

5. **Provide water sampling lines**. The lines should enable stored water to be sampled at various depths and locations in the reservoir. The water could be tested for chlorine residual, heterotropic plate count or some other indicator of quality.

6. **Provide temperature thermistors** for reservoirs believed to be susceptible to thermal stratification. The thermistors should enable temperatures to be measured at various depths and locations in the reservoir.

Recommendations for Design of Chatfield and Colorow Reservoirs

1. **Separate the inlet and outlet by 180 degrees**.

2. **Use buried concrete reservoirs**.

3. **Size inlet and outlet piping for maximum future pumping and demand flow rates**.

4. **Provide flanged fittings for the inlet and outlet piping**.

5. **Provide water sampling lines**.

Recommendations for Reservoir Operation

Although there are certain design parameters which can improve water quality by encouraging mixing such as separation of inlets and outlets, this study implies that a good means of improving water quality is by filling and emptying reservoirs to produce frequent turnover of water. This requires greater operator awareness because reservoir levels will necessarily fluctuate through a wider range. For effective reservoir operation, operators should:

1. **Operate the reservoir on a fill/draw cycle**. Instead of operating to keep the reservoir as full as possible, use fill and draw cycles to turn over water as often as possible. For example, instead of pumping water into the reservoir at a constant rate over a 24-hour period, consider filling the reservoir overnight and allowing the reservoir to be drawn down to an acceptable minimum level during the day. This will maximize flow rates and minimize temperature differences between the reservoir and the inflow. We believe it is reasonable for an operator to attempt to turn over a minimum of one third of a reservoir's contents each day. Some authors believe the entire reservoir volume should be displaced in one day.[12]

2. **Use only storage capacity which can be effectively turned over** given system limitations and variabilities in demand. During periods of low demand such as wintertime or before communities have been "built out", purposely limit the maximum water depth in a reservoir so that the corresponding volume can be effectively turned over in a day. Or, actually remove reservoirs from the system during low demand periods. If reservoirs are removed from the system, however, attention should be given to possible negative side effects such as a reduction in emergency storage, freezing inside the reservoir, buoyancy or ground swell due to expansive clays.

Recommendations for System Design

Some implications can be drawn from these tests for water system design.

1. **Consider pipe lengths when locating reservoir sites**. Long pipe lengths between the source of treated water and the reservoir or between the reservoir and the users can act as reservoirs themselves. These "reservoirs" can inhibit complete mixing in reservoirs and exacerbate temperature differences between inflowing water and the reservoir.

2. **Attempt to loop system components**. Reservoirs found at a dead end of a system will tend to experience little turnover.[13] It is possible that a quantity of water will merely move back and forth in the line. This is known as plug flow.

3. **Size system components with turnover in mind**. Sizing components with the maximum day demand in mind may result in storage and other component sizes which inhibit water turnover in reservoirs. Consider building two or more reservoirs at a particular storage site so that one or more reservoirs can be removed from the system during periods of low demand.

---

[12] Pizzi, Nick, "Optimizing Distribution System Operations", published in *Opflow* of the American Water Works Association, Vol. 22, No. 11 (Nov. 1996), p. 3.

[13] ibid., p. 2.

Recommendations for Further Investigation of Existing Facilities

1. **Review existing reservoirs** in the Denver Water system in terms of their ability to turn over water. This should include a survey of the location within the system, the inlet/outlet configuration, the mode of operation, the range of flow rates and any available temperature data. The reservoirs should be assessed for the need of additional information which could be gathered by retrofitting the reservoirs with water sampling lines or thermistors.

Recommendations for Further Research

1. **Develop empirical relationships which predict mixing**. Run additional tests to obtain more complete data on outlet configuration, temperature difference and flow rate versus mixing. Use lower flow rates to evaluate the effects of outlet configuration and temperature differences between the model and the inflow. Develop graphs based on this data to predict prototype performance.

2. **Develop a relationship between conductivity stratification and temperature stratification**. In order to use conductivity measurements to predict temperature stratification in a prototype, examine the ways in which conductivity varies temperature differences over water depth.

3. **Evaluate the effect of inlet piping configuration below the reservoir on mixing**. Examine the effects of inlet piping geometry underneath the reservoir floor with respect to mixing. Experiment with various bend configurations, approach angles and distances from the wall. (This would supplement the work done for the City of Aurora examining the effects of inlet piping *above* the floor).

4. **Investigate the effects of plug flow**. Use a common inlet/outlet and operate the model with very slow flow rates and a temperature differential between the inflows and the model.

5. **Further evaluate external means of promoting reservoir mixing**. Further investigate the configuration and flow rates on the effectiveness of air bubbler mixing systems in eliminating temperature stratification. Also investigate other means of promoting mixing such as recirculation pumps.

6. **Consider alternative measurement devises**. Experiment which other means of quantitatively evaluating mixing in reservoirs such as tracers with a half-life.

7. **Calibrate models with prototype data**. Use chlorine and temperature monitoring data gathered from prototype reservoirs to calibrate laboratory models. This will extend the usefulness of models and allow extrapolation to different geometries and flow conditions.

REFERENCES

Bates, Robert T., *Zone 10E Reservoir Site Evaluation and Capacity Study*, prepared for the Southgate Water District, August 1995.

Daugherty, Robert L. and Joseph B. Franzini. *Fluid Mechanics with Engineering Applications*, 7th ed., McGraw Hill, 1977.

Falvey, Henry T., "Estimation of Destratification with a Bubbler," Report prepared for Bates Engineering, September 9, 1996.

Falvey, Henry T., "Potential Flow Solution Flow in a Water Supply Tank," Report prepared for Bates Engineering, August 19, 1996.

Grayman, Walter M., et. al., "Water quality and mixing models for tanks and reservoirs," *Journal of the American Water Works Association,* Vol. 88, No. 7 (July 1996), pp. 60-73.

Hydraulic Laboratory Techniques, U.S. Bureau of Reclamation, Denver, 1980.

Pizzi, Nick, "Optimizing Distribution System Operations", published in *Opflow* of the American Water Works Association, Vol. 22, No. 11 (Nov. 1996).

Telephone conversation with Lewis Rossman, U.S. Environmental Protection Agency National Risk Management Research Laboratory, Cincinnati, October 22, 1996.

APPENDIX A - POTENTIAL FLOW SOLUTION FOR CIRCULAR RESERVOIRS

Henry T. Falvey & Associates

August 21, 1996

Robert Bates
Bates Engineering Inc.
7333 W. Jefferson Ave, Suite 155
Lakewood, CO 80235-2017

Dear Bob,

Enclosed is a report on the potential flow solution to predict the velocity distribution and stream lines in a water storage tank. As I mentioned to you on our June 5 meeting, the potential flow solution approximated the actual flow velocities that were observed in the model study that I conducted in Switzerland. The Excel spread sheet programs can be used to investigate the placement of the intake and outlet on the velocity distribution and stream lines in the tank.

I have also included a diskette for you to use in your simulations and an invoice for my services.

Sincerely,

Henry T. Falvey
President

P.O. Box 4 11624 Blackfoot Rd
Conifer CO 80433
Tel & FAX: (303) 838-4920
e-mail: falvey@lamar.ColoState.edu

POTENTIAL FLOW SOLUTION
FLOW IN A WATER SUPPLY TANK

HENRY T. FALVEY

August 19, 1996

INTRODUCTION

Two types of mathematical models can be used to predict the flow patterns in a water supply tank. These are a systems model[1][2] and a hydrodynamic model. A systems model is analogous to a "black box" in which the processes in the tank are simulated with relatively simple mathematical relationships. Actually, the systems model does not determine flow patterns per se. Instead, a flow pattern is assumed and the interaction of the flow pattern with the chemical constituents is described with coefficients. The magnitude of the coefficients is determined from field observations. The coefficients are constant for a given tank geometry and chemical concentration. However, if the tank geometry or the chemical concentration varies from the tested conditions, a new set of coefficients must be determined.

A hydrodynamic model can be very complex[2] or relatively simple. With a complex model, the tank is divided up into small volumes. The equations of motion (Navier-Stokes) and the chemical concentrations are simplified into algebraic relationships between the volume elements. Then the algebraic equations are solved with a computer. Theoretically, this model could include thermodynamic effects within the supply tank.

In tanks that have a large aspect (diameter to height) ratio, a much simpler hydrodynamic model can be formulated that will give a good approximation to the flow patterns within the tank with steady flow. This model is known as the potential flow model. The potential flow model is only used to determine the flow patterns and velocities in a tank. It cannot be used to predict water quality or chemical concentrations.

Potential or irrotational flow model is often used in hydraulics practice to obtain the approximate streamline pattern of the flow. This pattern is commonly known as a *flow net*. The technique has been used to calculate pressure distributions on sluice gates and bends, as well as the lift on air foils.

---

[1]Mau, R.E., Boulos, P.F., Clark, R.M., Grayman, W.M., Tekippe, R.J, and Trussell, R.R., 1995, "Explicit Mathematical Models of Distribution Storage Water Quality," American Society of Civil Engineers, *Journal of Hydraulic Engineering*, Oct., Vol. 121, No. 10. pp 699 - 709.

[2]Grayman, W.M., Deininger, R.A., Green, A., Boulos, P.F., Bowcock, R.W., and Godwin, C.C., 1996, "Water Quality and Mixing Models for Tanks and Reservoirs," *Journal of the American Water Works Association*, July, pp. 60 - 73.

P.O. Box 4 11624 Blackfoot Rd
Conifer CO 80433
Tel & FAX: (303) 838-4920
e-mail: falvey@lamar.ColoState.edu

With a potential flow model, the Navier-Stokes equations are written in a simplified form by neglecting the viscous terms. The advantage of the potential flow model is that it can be written for a spread sheet application that takes seconds to solve. On the other hand, solving the compete equation with the viscous terms and the chemical constituents requires hours to solve on a personal computer.

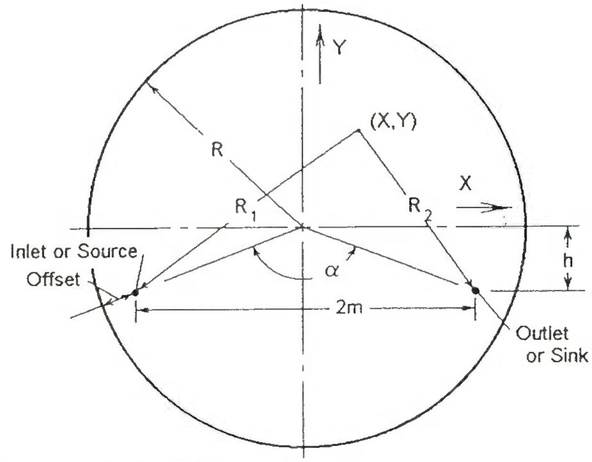


Figure 1. Definition Sketch

EQUATIONS

The equations for potential flow are written in terms of the parameters shown in figure 1. The input variables are the distance from the wall to the inlet (Source), the tank diameter (2R), the height of the tank (H), the included angle between the inlet and the outlet (α), and the discharge (Q). The discharge is given in million gallons per day. All linear dimensions are expressed in feet.

The value m is given by

$$m = R \sin\left(\frac{\alpha}{2}\right)$$

and h is given by

$$h = R \cos\left(\frac{\alpha}{2}\right)$$

If the inlet and outlet flows are equal, that is steady state, Rouse[3] expresses the velocity for the potential flow at any point by

$$V = \frac{m\,q}{\pi\, R_1\, R_2}$$

where R_1 and R_2 are the distances from any point in the field to the inlet and the outlet respectively, and q is the discharge per unit depth.

[3]Rouse, H., 1961, *Fluid Mechanics for Hydraulic Engineers*, Dover Publications, Inc., New York.

To be an accurate simulation, the inlet and outlet pipes would have to oriented perpendicular to the bottom of the tank. In practice, the flow enters and exits from a port on the floor of the tank. However, for large aspect ratios the approximation does not introduce large errors in the computed velocities and streamlines at several entrance pipe diameters from the intake.

The streamlines are determined by the circle that is formed when the angle between the two radii, R_1 and R_2, is constant. If the angle is acute, the centerline of the circles is above the line that joins the inlet to the outlet. If the angle is obtuse, the centerline is below the line. Each circle must pass through the inlet and outlet locations.

SPREADSHEET

The Excel 5.0 version spreadsheet entitled **velocity.xls** calculates the velocities at evenly distributed points within the tank. The Excel 5.0 version spreadsheet entitled **stream.xls** calculates the streamlines at given values of streamline potential within the tank. As noted above the input variables are the tank diameter, the tank height, the included angle between the inlet and the outlet, the distance the source is from the tank wall, and the discharge.

The output of the **velocity.xls** spreadsheet is the velocity in ft/sec at each of the points. Two three dimensional plots are available to view the output. One plot is a string diagram of the velocities and is presented on sheet two of the output. The second plot is a colored surface plot of the velocities and is presented on chart 2. The colored plot is useful in investigating the effect of variations to the included angle between the inlet and outlet and of variations of distance of the inlet from the tank wall. A more uniform velocity distribution can be quickly detected by observing the extent of a constant color. Stagnation zones are reduced when the distribution is uniform.

The output of the **stream.xls** spreadsheet is the streamlines for given values of the stream potential. The streamlines for a source and a sink, as in a water supply tank are circular in shape. The values are based on stream potential equal to unity. For potentials less than unity, the center of the circles is above the line that connects the source to the sink. For potentials greater than unit, the center of the circles is below the line. The streamlines give an indication of stagnation zones within the tank. These zones are delineated by the streamlines that intersect the tank walls as shown approximately by the hatched area in figure 2. Actually, the flow will probably not stagnate, but become three

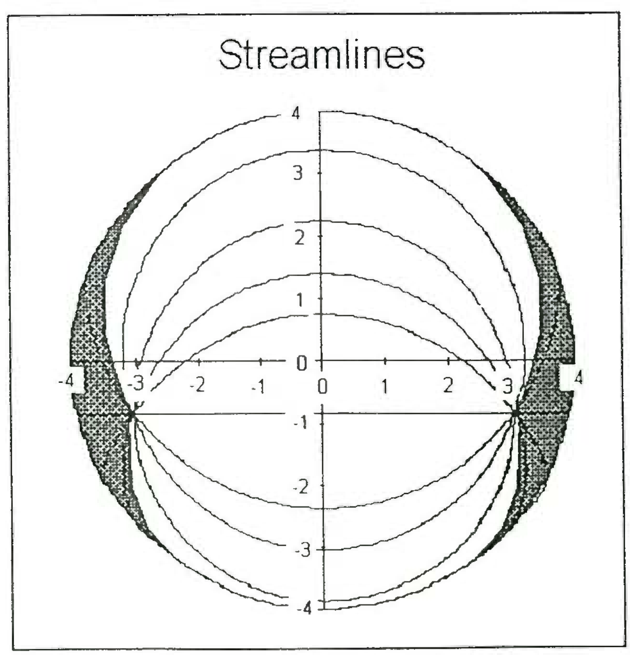


Figure 2 Streamlines for Offset = 10 inches

P.O. Box 4 11624 Blackfoot Rd
Conifer CO 80433
Tel & FAX: (303) 838-4920
e-mail: falvey@lamar.ColoState.edu

dimensional. That is, in the hatched area, the water will flow toward the wall and then be turned to flow vertically at the wall. The longitudinal flow in the hatched zone will then cause the water to follow a spiral pattern.

PRACTICAL CONSIDERATIONS

Predictions from the spreadsheet can be verified with the physical model investigations. The potential flow solution should reproduce values measured on the physical model closely at distances further than about 4 to 5 pipe diameters from the inlet and the outlet. Two factors make the agreement poor as the inlet or the outlet is approached. First, the potential flow solution assumes that all the flow exits and enters from points that have a zero diameter. Therefore, the velocities are infinite directly over the inlet and the outlet locations. At about 5 pipe diameters from the inlet or outlet, this effect is negligible. Secondly, the potential flow solution assumes that the inflow and the outflow are distributed uniformly over the depth of the tank. The inflow and outflow enter the tank through a port on the floor. Some distance is required for the flow to become distributed over the entire depth of the tank. This redistribution can be misinterpreted as a thermal gradient effect.

Thermal gradients can form in the tank if the inlet flows are at a different temperature than the general temperature of the tank. If the inflow equals the outflow for a long time, the thermal gradients will be eliminated and the simulations presented in the two spread sheets should yield qualitative, if not quantitative, estimates of the actual flow velocities and directions.. In practice this steady state operation rarely occurs. Thus, the spreadsheets are of limited usefulness in predicting the actual flow patterns that will be established in the field.

P.O. Box 4 11624 Blackfoot Rd
Conifer CO 80433
Tel & FAX: (303) 838-4920
e-mail: falvey@lamar.ColoState.edu

VELOCITIES IN TANK

Diameter	8.00	ft			
Height	0.88	ft	h	0.82	ft
Angle	150.00	deg	2m	6.12	ft
Offset	0.83	ft			
Q	1.00	mgd			

R_1

Y, ft

X, ft	-4.00	-3.60	-3.20	-2.80	-2.40	-2.00	-1.60	-1.20	-0.80	-0.40	0.00	0.40	0.80	1.20	1.60	2.00	2.40	2.80	3.20	3.60	4.00
-4.00	3.29	2.90	2.52	2.15	1.79	1.44	1.14	0.92	0.83	0.93	1.17	1.48	1.82	2.18	2.56	2.94	3.33	3.71	4.11	4.50	4.89
-3.60	3.21	2.81	2.42	2.03	1.64	1.26	0.89	0.58	0.43	0.60	0.93	1.29	1.68	2.07	2.46	2.85	3.25	3.65	4.04	4.44	4.84
-3.20	3.18	2.78	2.38	1.98	1.58	1.18	0.78	0.38	0.04	0.42	0.82	1.22	1.62	2.02	2.42	2.82	3.22	3.62	4.02	4.42	4.82
-2.80	3.20	2.80	2.41	2.01	1.62	1.24	0.86	0.53	0.37	0.56	0.90	1.27	1.66	2.05	2.45	2.84	3.24	3.64	4.04	4.43	4.83
-2.40	3.27	2.88	2.50	2.12	1.76	1.41	1.09	0.86	0.77	0.87	1.12	1.44	1.79	2.16	2.54	2.92	3.31	3.70	4.09	4.49	4.88
-2.00	3.39	3.02	2.65	2.30	1.96	1.66	1.40	1.23	1.17	1.24	1.43	1.69	2.00	2.33	2.69	3.05	3.42	3.80	4.19	4.57	4.96
-1.60	3.55	3.19	2.85	2.53	2.23	1.96	1.75	1.61	1.57	1.62	1.77	1.99	2.25	2.56	2.88	3.23	3.58	3.94	4.31	4.69	5.07
-1.20	3.74	3.41	3.09	2.79	2.52	2.29	2.12	2.00	1.97	2.01	2.13	2.31	2.55	2.82	3.12	3.44	3.77	4.12	4.48	4.84	5.21
-0.80	3.96	3.65	3.36	3.09	2.85	2.64	2.49	2.40	2.37	2.40	2.50	2.66	2.87	3.11	3.38	3.68	4.00	4.32	4.66	5.01	5.37
-0.40	4.22	3.92	3.65	3.40	3.19	3.01	2.87	2.79	2.77	2.80	2.89	3.02	3.21	3.43	3.68	3.95	4.25	4.56	4.88	5.21	5.56
0.00	4.49	4.21	3.96	3.74	3.54	3.38	3.26	3.19	3.17	3.19	3.27	3.39	3.56	3.76	3.99	4.24	4.52	4.81	5.12	5.44	5.77
0.40	4.78	4.52	4.29	4.08	3.90	3.76	3.65	3.59	3.57	3.59	3.66	3.77	3.92	4.10	4.31	4.55	4.81	5.08	5.37	5.68	6.00
0.80	5.08	4.84	4.63	4.43	4.27	4.14	4.04	3.99	3.97	3.99	4.05	4.15	4.28	4.45	4.65	4.87	5.11	5.37	5.65	5.94	6.24
1.20	5.40	5.18	4.97	4.80	4.64	4.52	4.44	4.38	4.37	4.39	4.44	4.53	4.66	4.81	4.99	5.20	5.43	5.67	5.94	6.21	6.50
1.60	5.73	5.52	5.33	5.16	5.02	4.91	4.83	4.78	4.77	4.79	4.84	4.92	5.03	5.18	5.35	5.54	5.75	5.99	6.24	6.50	6.78
2.00	6.07	5.87	5.69	5.53	5.40	5.30	5.23	5.18	5.17	5.18	5.23	5.31	5.41	5.55	5.71	5.89	6.09	6.31	6.55	6.80	7.07
2.40	6.41	6.22	6.05	5.91	5.79	5.69	5.62	5.58	5.57	5.58	5.63	5.70	5.80	5.92	6.07	6.24	6.43	6.64	6.87	7.11	7.36
2.80	6.76	6.58	6.42	6.29	6.17	6.08	6.02	5.98	5.97	5.98	6.02	6.09	6.18	6.30	6.44	6.60	6.78	6.98	7.19	7.43	7.67
3.20	7.12	6.95	6.80	6.67	6.56	6.48	6.41	6.38	6.37	6.38	6.42	6.48	6.57	6.68	6.81	6.96	7.13	7.32	7.53	7.75	7.99
3.60	7.48	7.32	7.17	7.05	6.95	6.87	6.81	6.78	6.77	6.78	6.82	6.88	6.96	7.06	7.19	7.33	7.49	7.67	7.87	8.08	8.31
4.00	7.84	7.69	7.55	7.44	7.34	7.26	7.21	7.18	7.17	7.18	7.21	7.27	7.35	7.45	7.56	7.70	7.86	8.03	8.22	8.42	8.64

R_2

Y, ft

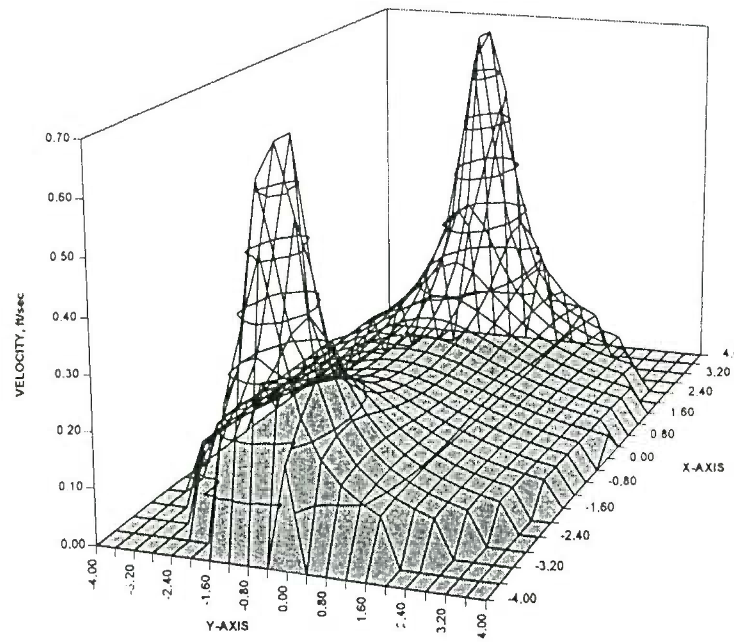
X, ft	-4.00	-3.60	-3.20	-2.80	-2.40	-2.00	-1.60	-1.20	-0.80	-0.40	0.00	0.40	0.80	1.20	1.60	2.00	2.40	2.80	3.20	3.60	4.00
-4.00	7.84	7.69	7.55	7.44	7.34	7.26	7.21	7.18	7.17	7.18	7.21	7.27	7.35	7.45	7.56	7.70	7.86	8.03	8.22	8.42	8.64
-3.60	7.48	7.32	7.17	7.05	6.95	6.87	6.81	6.78	6.77	6.78	6.82	6.88	6.96	7.06	7.19	7.33	7.49	7.67	7.87	8.08	8.31
-3.20	7.12	6.95	6.80	6.67	6.56	6.48	6.41	6.38	6.37	6.38	6.42	6.48	6.57	6.68	6.81	6.96	7.13	7.32	7.53	7.75	7.99
-2.80	6.76	6.58	6.42	6.29	6.17	6.08	6.02	5.98	5.97	5.98	6.02	6.09	6.18	6.30	6.44	6.60	6.78	6.98	7.19	7.43	7.67
-2.40	6.41	6.22	6.05	5.91	5.79	5.69	5.62	5.58	5.57	5.58	5.63	5.70	5.80	5.92	6.07	6.24	6.43	6.64	6.87	7.11	7.36
-2.00	6.07	5.87	5.69	5.53	5.40	5.30	5.23	5.18	5.17	5.18	5.23	5.31	5.41	5.55	5.71	5.89	6.09	6.31	6.55	6.80	7.07
-1.60	5.73	5.52	5.33	5.16	5.02	4.91	4.83	4.78	4.77	4.79	4.84	4.92	5.03	5.18	5.35	5.54	5.75	5.99	6.24	6.50	6.78
-1.20	5.40	5.18	4.97	4.80	4.64	4.52	4.44	4.38	4.37	4.39	4.44	4.53	4.66	4.81	4.99	5.20	5.43	5.67	5.94	6.21	6.50
-0.80	5.08	4.84	4.63	4.43	4.27	4.14	4.04	3.99	3.97	3.99	4.05	4.15	4.28	4.45	4.65	4.87	5.11	5.37	5.65	5.94	6.24
-0.40	4.78	4.52	4.29	4.08	3.90	3.76	3.65	3.59	3.57	3.59	3.66	3.77	3.92	4.10	4.31	4.55	4.81	5.08	5.37	5.68	6.00
0.00	4.49	4.21	3.96	3.74	3.54	3.38	3.26	3.19	3.17	3.19	3.27	3.39	3.56	3.76	3.99	4.24	4.52	4.81	5.12	5.44	5.77
0.40	4.22	3.92	3.65	3.40	3.19	3.01	2.87	2.79	2.77	2.80	2.89	3.02	3.21	3.43	3.68	3.95	4.25	4.56	4.88	5.21	5.56
0.80	3.96	3.65	3.36	3.09	2.85	2.64	2.49	2.40	2.37	2.40	2.50	2.66	2.87	3.11	3.38	3.68	4.00	4.32	4.66	5.01	5.37
1.20	3.74	3.41	3.09	2.79	2.52	2.29	2.12	2.00	1.97	2.01	2.13	2.31	2.55	2.82	3.12	3.44	3.77	4.12	4.48	4.84	5.21
1.60	3.55	3.19	2.85	2.53	2.23	1.96	1.75	1.61	1.57	1.62	1.77	1.99	2.25	2.56	2.88	3.23	3.58	3.94	4.31	4.69	5.07
2.00	3.39	3.02	2.65	2.30	1.96	1.66	1.40	1.23	1.17	1.24	1.43	1.69	2.00	2.33	2.69	3.05	3.42	3.80	4.19	4.57	4.96
2.40	3.27	2.88	2.50	2.12	1.76	1.41	1.09	0.86	0.77	0.87	1.12	1.44	1.79	2.16	2.54	2.92	3.31	3.70	4.09	4.49	4.88
2.80	3.20	2.80	2.41	2.01	1.62	1.24	0.86	0.53	0.37	0.56	0.90	1.27	1.66	2.05	2.45	2.84	3.24	3.64	4.04	4.43	4.83
3.20	3.18	2.78	2.38	1.98	1.58	1.18	0.78	0.38	0.04	0.42	0.82	1.22	1.62	2.02	2.42	2.82	3.22	3.62	4.02	4.42	4.82
3.60	3.21	2.81	2.42	2.03	1.64	1.26	0.89	0.58	0.43	0.60	0.93	1.29	1.68	2.07	2.46	2.85	3.25	3.65	4.04	4.44	4.84
4.00	3.29	2.90	2.52	2.15	1.79	1.44	1.14	0.92	0.83	0.93	1.17	1.48	1.82	2.18	2.56	2.94	3.33	3.71	4.11	4.50	4.89

					Stream Lines						
			Diameter	8	ft						
			Height	0.875	ft			h	0.82	ft	
			Angle	150	deg			2m	6.12	ft	
			Offset	0.833	ft			S	3.17	ft	
			Q	1	mgd			γ_o	0.26	rad	
	1.00	ζ_{max}							0.80	ζ_{max}	
Diameter	6.12	ft						Diameter	6.66	ft	
h'	0.00	ft						h'	1.32	ft	
γ	0.00	rad	0.00	deg				γ	0.41	rad	23.27 deg
ζ	1.57	rad	90.00	deg				ζ	1.26	rad	72.00 deg
ϕ_{equal}	0.79	rad	45.00	deg				ϕ_{equal}	1.03	rad	59.27 deg
ϕ	R1	R2	α	X	Y	ϕ	R1	R2	α	X	Y
rad	ft	ft	rad			rad	ft	ft	rad		
0	6.12	0.00	-0.21	3.06	-0.82	0	6.12	0.00	-0.21	3.06	-0.82
0.16	6.04	0.96	-0.08	2.91	0.13	0.16	6.35	1.01	-0.08	3.22	0.17
0.31	5.82	1.89	0.04	2.47	0.98	0.31	6.43	1.99	0.04	3.06	1.17
0.47	5.45	2.78	0.17	1.80	1.66	0.47	6.35	2.92	0.17	2.60	2.06
0.63	4.95	3.60	0.29	0.95	2.09	0.63	6.12	3.78	0.29	1.89	2.78
0.79	4.33	4.33	0.41	0.00	2.24	0.79	5.73	4.55	0.41	0.99	3.23
0.94	3.60	4.95	0.52	-0.95	2.09	0.94	5.20	5.20	0.52	0.00	3.39
1.10	2.78	5.45	0.63	-1.80	1.66	1.10	4.55	5.73	0.63	-0.99	3.23
1.26	1.89	5.82	0.73	-2.47	0.98	1.26	3.78	6.12	0.73	-1.89	2.78
1.41	0.96	6.04	0.81	-2.91	0.13	1.41	2.92	6.35	0.81	-2.60	2.06
1.57	0.00	6.12	0.87	-3.06	-0.82	1.57	1.99	6.43	0.87	-3.06	1.17
1.73	-0.96	6.04	0.91	-2.91	-1.76	1.73	1.01	6.35	0.91	-3.22	0.17
1.88	-1.89	5.82	0.91	-2.47	-2.62	1.88	0.00	6.12	0.91	-3.06	-0.82
2.04	-2.78	5.45	0.89	-1.80	-3.29	2.04	-1.01	5.73	0.89	-2.60	-1.72
2.20	-3.60	4.95	0.83	-0.95	-3.73	2.20	-1.99	5.20	0.83	-1.89	-2.43
2.36	-4.33	4.33	0.76	0.00	-3.88	2.36	-2.92	4.55	0.76	-0.99	-2.88
2.51	-4.95	3.60	0.66	0.95	-3.73	2.51	-3.78	3.78	0.66	0.00	-3.04
2.67	-5.45	2.78	0.56	1.80	-3.29	2.67	-4.55	2.92	0.56	0.99	-2.88
2.83	-5.82	1.89	0.45	2.47	-2.62	2.83	-5.20	1.99	0.45	1.89	-2.43
2.98	-6.04	0.96	0.33	2.91	-1.76	2.98	-5.73	1.01	0.33	2.60	-1.72
3.14	-6.12	0.00	0.21	3.06	-0.82	3.14	-6.12	0.00	0.21	3.06	-0.82
								Mirror Image			
	0.60	ζ_{max}							1.20	ζ_{max}	
Diameter	7.83	ft						Diameter	6.66	ft	
h'	2.44	ft						h'	1.32	ft	
γ	0.67	rad	38.61	deg				γ	0.41	rad	23.27 deg
ζ	0.94	rad	54.00	deg				ζ	1.88	rad	108.00 deg
ϕ_{equal}	1.15	rad	65.61	deg				ϕ_{equal}	1.35	rad	77.27 deg
ϕ	R1	R2	α	X	Y	ϕ	R1	R2	α	X	Y
rad	ft	ft	rad			rad	ft	ft	rad		
0	6.12	0.00	-0.21	3.06	-0.82	0	6.12	0.00	-0.21	3.06	-0.82
0.16	6.74	1.18	-0.08	3.60	0.23	0.16	5.73	1.01	-0.08	2.60	0.08
0.31	7.19	2.34	0.04	3.78	1.40	0.31	5.20	1.99	0.04	1.89	0.79
0.47	7.47	3.43	0.17	3.60	2.57	0.47	4.55	2.92	0.17	0.99	1.25
0.63	7.56	4.45	0.29	3.06	3.63	0.63	3.78	3.78	0.29	0.00	1.40
0.79	7.47	5.35	0.41	2.22	4.46	0.79	2.92	4.55	0.41	-0.99	1.25
0.94	7.19	6.12	0.52	1.17	5.00	0.94	1.99	5.20	0.52	-1.89	0.79
1.10	6.74	6.74	0.63	0.00	5.18	1.10	1.01	5.73	0.63	-2.60	0.08
1.26	6.12	7.19	0.73	-1.17	5.00	1.26	0.00	6.12	0.73	-3.06	-0.82

					Stream Lines						
			Diameter	8	**ft**						
			Height	0.875	**ft**			h	0.82	ft	
			Angle	150	**deg**			2m	6.12	ft	
			Offset	0.833	**ft**			S	3.17	ft	
			Q	1	**mgd**			γ_o	0.26	rad	
	1.00	ζ_{max}							0.80	ζ_{max}	
Diameter	6.12	ft					Diameter	6.66	ft		
h'	0.00	ft					h'	1.32	ft		
γ	0.00	rad	0.00	deg			γ	0.41	rad	23.27	deg
ζ	1.57	rad	90.00	deg			ζ	1.26	rad	72.00	deg
ϕ_{equal}	0.79	rad	45.00	deg			ϕ_{equal}	1.03	rad	59.27	deg
ϕ	R1	R2	α	X	Y	ϕ	R1	R2	α	X	Y
rad	ft	ft	rad			rad	ft	ft	rad		
0	6.12	0.00	-0.21	3.06	-0.82	0	6.12	0.00	-0.21	3.06	-0.82
0.16	6.04	0.96	-0.08	2.91	0.13	0.16	6.35	1.01	-0.08	3.22	0.17
0.31	5.82	1.89	0.04	2.47	0.98	0.31	6.43	1.99	0.04	3.06	1.17
0.47	5.45	2.78	0.17	1.80	1.66	0.47	6.35	2.92	0.17	2.60	2.06
0.63	4.95	3.60	0.29	0.95	2.09	0.63	6.12	3.78	0.29	1.89	2.78
0.79	4.33	4.33	0.41	0.00	2.24	0.79	5.73	4.55	0.41	0.99	3.23
0.94	3.60	4.95	0.52	-0.95	2.09	0.94	5.20	5.20	0.52	0.00	3.39
1.10	2.78	5.45	0.63	-1.80	1.66	1.10	4.55	5.73	0.63	-0.99	3.23
1.26	1.89	5.82	0.73	-2.47	0.98	1.26	3.78	6.12	0.73	-1.89	2.78
1.41	0.96	6.04	0.81	-2.91	0.13	1.41	2.92	6.35	0.81	-2.60	2.06
1.57	0.00	6.12	0.87	-3.06	-0.82	1.57	1.99	6.43	0.87	-3.06	1.17
1.73	-0.96	6.04	0.91	-2.91	-1.76	1.73	1.01	6.35	0.91	-3.22	0.17
1.88	-1.89	5.82	0.91	-2.47	-2.62	1.88	0.00	6.12	0.91	-3.06	-0.82
2.04	-2.78	5.45	0.89	-1.80	-3.29	2.04	-1.01	5.73	0.89	-2.60	-1.72
2.20	-3.60	4.95	0.83	-0.95	-3.73	2.20	-1.99	5.20	0.83	-1.89	-2.43
2.36	-4.33	4.33	0.76	0.00	-3.88	2.36	-2.92	4.55	0.76	-0.99	-2.88
2.51	-4.95	3.60	0.66	0.95	-3.73	2.51	-3.78	3.78	0.66	0.00	-3.04
2.67	-5.45	2.78	0.56	1.80	-3.29	2.67	-4.55	2.92	0.56	0.99	-2.88
2.83	-5.82	1.89	0.45	2.47	-2.62	2.83	-5.20	1.99	0.45	1.89	-2.43
2.98	-6.04	0.96	0.33	2.91	-1.76	2.98	-5.73	1.01	0.33	2.60	-1.72
3.14	-6.12	0.00	0.21	3.06	-0.82	3.14	-6.12	0.00	0.21	3.06	-0.82
								Mirror Image			
	0.60	ζ_{max}							1.20	ζ_{max}	
Diameter	7.83	ft					Diameter	6.66	ft		
h'	2.44	ft					h'	1.32	ft		
γ	0.67	rad	38.61	deg			γ	0.41	rad	23.27	deg
ζ	0.94	rad	54.00	deg			ζ	1.88	rad	108.00	deg
ϕ_{equal}	1.15	rad	65.61	deg			ϕ_{equal}	1.35	rad	77.27	deg
ϕ	R1	R2	α	X	Y	ϕ	R1	R2	α	X	Y
rad	ft	ft	rad			rad	ft	ft	rad		
0	6.12	0.00	-0.21	3.06	-0.82	0	6.12	0.00	-0.21	3.06	-0.82
0.16	6.74	1.18	-0.08	3.60	0.23	0.16	5.73	1.01	-0.08	2.60	0.08
0.31	7.19	2.34	0.04	3.78	1.40	0.31	5.20	1.99	0.04	1.89	0.79
0.47	7.47	3.43	0.17	3.60	2.57	0.47	4.55	2.92	0.17	0.99	1.25
0.63	7.56	4.45	0.29	3.06	3.63	0.63	3.78	3.78	0.29	0.00	1.40
0.79	7.47	5.35	0.41	2.22	4.46	0.79	2.92	4.55	0.41	-0.99	1.25
0.94	7.19	6.12	0.52	1.17	5.00	0.94	1.99	5.20	0.52	-1.89	0.79
1.10	6.74	6.74	0.63	0.00	5.18	1.10	1.01	5.73	0.63	-2.60	0.08
1.26	6.12	7.19	0.73	-1.17	5.00	1.26	0.00	6.12	0.73	-3.06	-0.82

										V										
										Y, ft										
X, ft	-4.00	-3.60	-3.20	-2.80	-2.40	-2.00	-1.60	-1.20	-0.80	-0.40	0.00	0.40	0.80	1.20	1.60	2.00	2.40	2.80	3.20	3.60	4.00
-4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-3.60	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.39	0.51	0.37	0.24	0.17	0.13	0.10	0.09	0.00	0.00	0.00	0.00	0.00	0.00
-3.20	0.00	0.00	0.00	0.00	0.15	0.20	0.30	0.62	0.69	0.56	0.29	0.19	0.14	0.11	0.09	0.08	0.07	0.00	0.00	0.00	0.00
-2.80	0.00	0.00	0.00	0.12	0.15	0.20	0.29	0.48	0.69	0.45	0.28	0.19	0.15	0.12	0.10	0.08	0.07	0.06	0.00	0.00	0.00
-2.40	0.00	0.00	0.10	0.12	0.15	0.19	0.24	0.32	0.35	0.31	0.24	0.18	0.14	0.12	0.10	0.08	0.07	0.06	0.05	0.00	0.00
-2.00	0.00	0.00	0.10	0.12	0.14	0.17	0.21	0.24	0.25	0.23	0.20	0.17	0.14	0.12	0.10	0.08	0.07	0.06	0.05	0.00	0.00
-1.60	0.00	0.09	0.10	0.12	0.13	0.16	0.18	0.20	0.20	0.19	0.18	0.15	0.13	0.11	0.10	0.08	0.07	0.06	0.06	0.05	0.00
-1.20	0.00	0.09	0.10	0.11	0.13	0.15	0.16	0.17	0.18	0.17	0.16	0.14	0.13	0.11	0.10	0.08	0.07	0.06	0.06	0.05	0.00
-0.80	0.00	0.09	0.10	0.11	0.12	0.14	0.15	0.16	0.16	0.16	0.15	0.14	0.12	0.11	0.10	0.08	0.07	0.06	0.06	0.05	0.00
-0.40	0.00	0.08	0.10	0.11	0.12	0.13	0.14	0.15	0.15	0.15	0.14	0.13	0.12	0.11	0.10	0.08	0.07	0.07	0.06	0.05	0.00
0.00	0.07	0.08	0.10	0.11	0.12	0.13	0.14	0.15	0.15	0.15	0.14	0.13	0.12	0.11	0.09	0.08	0.07	0.07	0.06	0.05	0.05
0.40	0.00	0.08	0.10	0.11	0.12	0.13	0.14	0.15	0.15	0.15	0.14	0.13	0.12	0.11	0.10	0.08	0.07	0.07	0.06	0.05	0.00
0.80	0.00	0.09	0.10	0.11	0.12	0.14	0.15	0.16	0.16	0.16	0.15	0.14	0.12	0.11	0.10	0.08	0.07	0.06	0.06	0.05	0.00
1.20	0.00	0.09	0.10	0.11	0.13	0.15	0.16	0.17	0.18	0.17	0.16	0.14	0.13	0.11	0.10	0.08	0.07	0.06	0.06	0.05	0.00
1.60	0.00	0.09	0.10	0.12	0.13	0.16	0.18	0.20	0.20	0.19	0.18	0.15	0.13	0.11	0.10	0.08	0.07	0.06	0.06	0.05	0.00
2.00	0.00	0.00	0.10	0.12	0.14	0.17	0.21	0.24	0.25	0.23	0.20	0.17	0.14	0.12	0.10	0.08	0.07	0.06	0.05	0.00	0.00
2.40	0.00	0.00	0.10	0.12	0.15	0.19	0.24	0.32	0.35	0.31	0.24	0.18	0.14	0.12	0.10	0.08	0.07	0.06	0.05	0.00	0.00
2.80	0.00	0.00	0.00	0.12	0.15	0.20	0.29	0.48	0.69	0.45	0.28	0.19	0.15	0.12	0.10	0.08	0.07	0.06	0.00	0.00	0.00
3.20	0.00	0.00	0.00	0.00	0.15	0.20	0.30	0.62	0.69	0.56	0.29	0.19	0.14	0.11	0.09	0.08	0.07	0.00	0.00	0.00	0.00
3.60	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.39	0.51	0.37	0.24	0.17	0.13	0.10	0.09	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

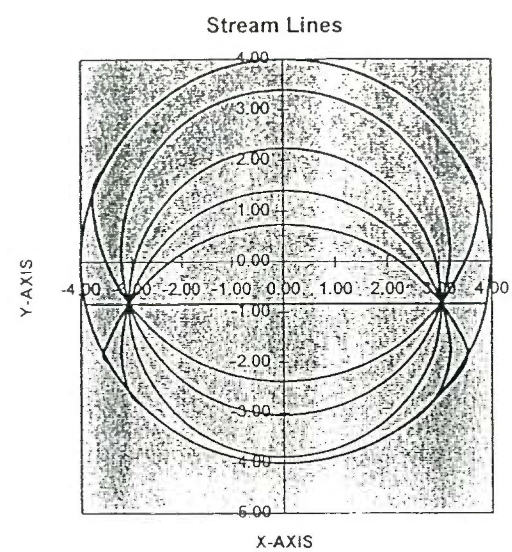
POTENTIAL FLOW



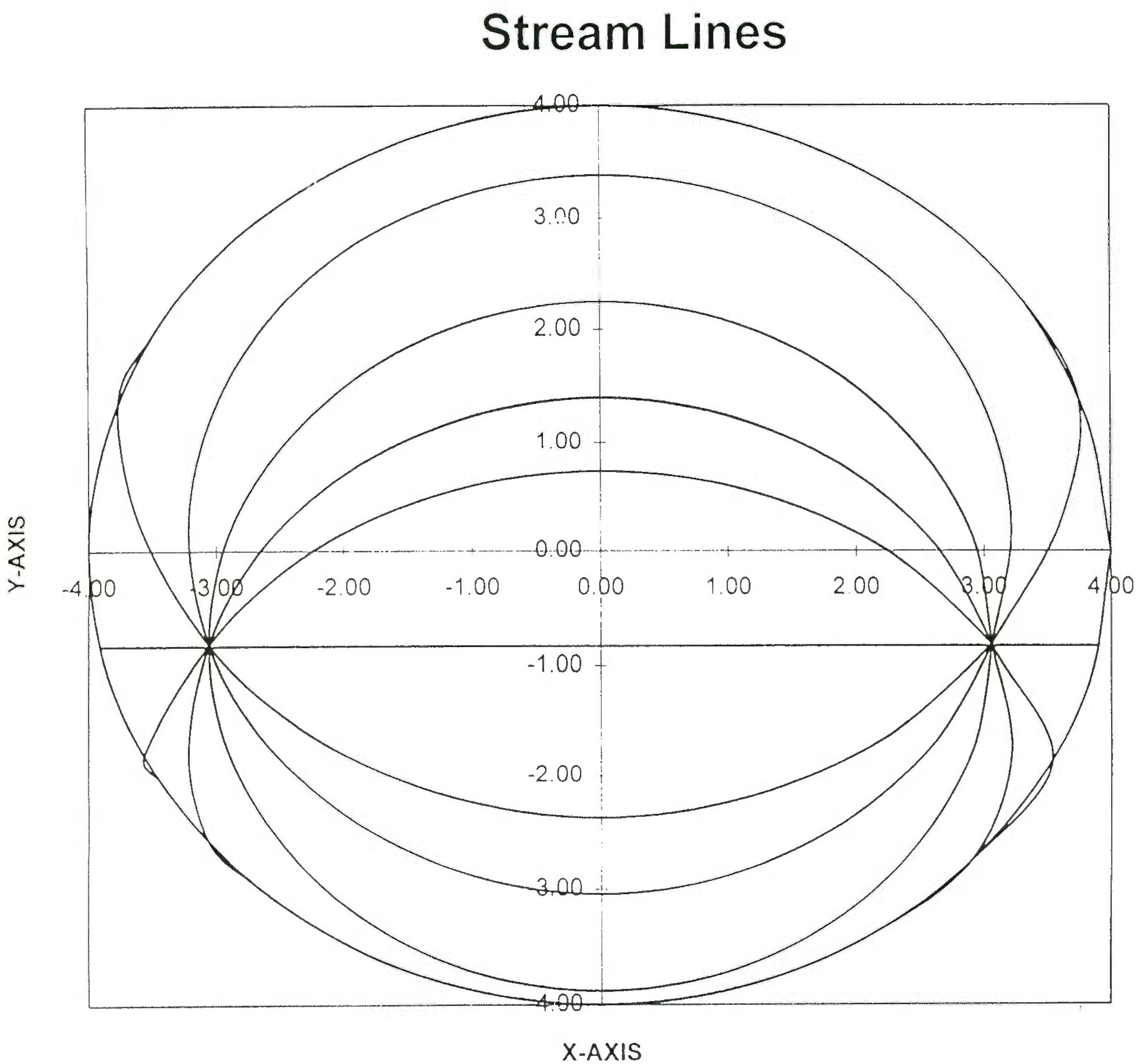
1.41	5.35	7.47	0.81	-2.22	4.46	1.41	-1.01	6.35	0.81	-3.22	-1.81
1.57	4.45	7.56	0.87	-3.06	3.63	1.57	-1.99	6.43	0.87	-3.06	-2.81
1.73	3.43	7.47	0.91	-3.60	2.57	1.73	-2.92	6.35	0.91	-2.60	-3.70
1.88	2.34	7.19	0.91	-3.78	1.40	1.88	-3.78	6.12	0.91	-1.89	-4.42
2.04	1.18	6.74	0.89	-3.60	0.23	2.04	-4.55	5.73	0.89	-0.99	-4.87
2.20	0.00	6.12	0.83	-3.06	-0.82	2.20	-5.20	5.20	0.83	0.00	-5.03
2.36	-1.18	5.35	0.76	-2.22	-1.66	2.36	-5.73	4.55	0.76	0.99	-4.87
2.51	-2.34	4.45	0.66	-1.17	-2.19	2.51	-6.12	3.78	0.66	1.89	-4.42
2.67	-3.43	3.43	0.56	0.00	-2.38	2.67	-6.35	2.92	0.56	2.60	-3.70
2.83	-4.45	2.34	0.45	1.17	-2.19	2.83	-6.43	1.99	0.45	3.06	-2.81
2.98	-5.35	1.18	0.33	2.22	-1.66	2.98	-6.35	1.01	0.33	3.22	-1.81
3.14	-6.12	0.00	0.21	3.06	-0.82	3.14	-6.12	0.00	0.21	3.06	-0.82

Mirror Image

	1.40	ζ_{max}		
Diameter	7.83	ft		
h'	2.44	ft		
γ	0.67	rad	38.61	deg
ζ	2.20	rad	126.00	deg
ϕ_{equal}	1.77	rad	101.61	deg



ϕ	R1	R2	α	X	Y
rad	ft	ft	rad		
0	6.12	0.00	-0.21	3.06	-0.82
0.16	5.35	1.18	-0.08	2.22	0.02
0.31	4.45	2.34	0.04	1.17	0.55
0.47	3.43	3.43	0.17	0.00	0.74
0.63	2.34	4.45	0.29	-1.17	0.55
0.79	1.18	5.35	0.41	-2.22	0.02
0.94	0.00	6.12	0.52	-3.06	-0.82
1.10	-1.18	6.74	0.63	-3.60	-1.87
1.26	-2.34	7.19	0.73	-3.78	-3.04
1.41	-3.43	7.47	0.81	-3.60	-4.21
1.57	-4.45	7.56	0.87	-3.06	-5.26
1.73	-5.35	7.47	0.91	-2.22	-6.10
1.88	-6.12	7.19	0.91	-1.17	-6.64
2.04	-6.74	6.74	0.89	0.00	-6.82
2.20	-7.19	6.12	0.83	1.17	-6.64
2.36	-7.47	5.35	0.76	2.22	-6.10
2.51	-7.56	4.45	0.66	3.06	-5.26
2.67	-7.47	3.43	0.56	3.60	-4.21
2.83	-7.19	2.34	0.45	3.78	-3.04
2.98	-6.74	1.18	0.33	3.60	-1.87
3.14	-6.12	0.00	0.21	3.06	-0.82

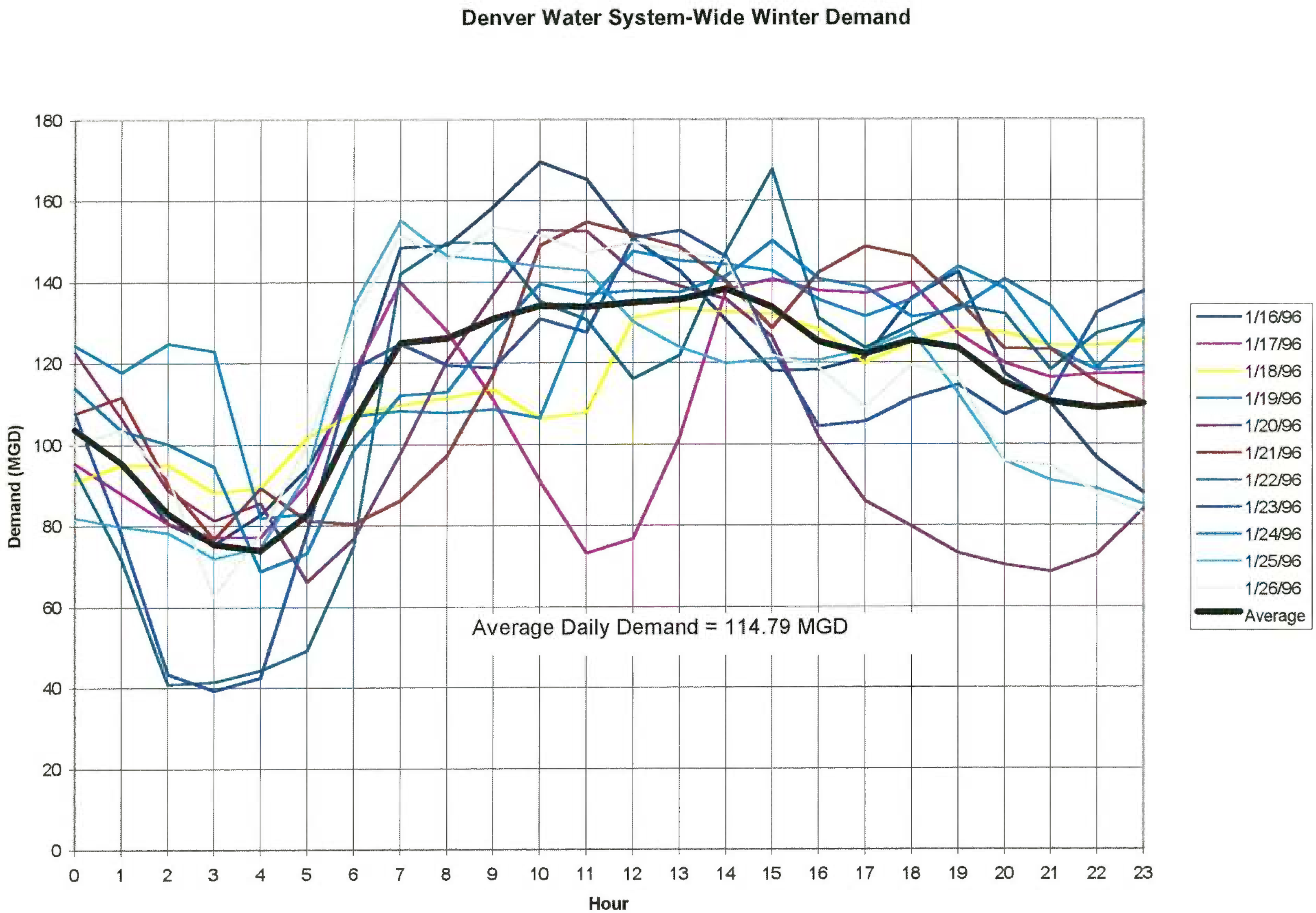

Stream Lines
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-4.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00
Y-AXIS
X-AXIS

APPENDIX B - MODEL INFLOW AND OUTFLOW HYDROGRAPHS

Appendix B

DENVER WATER
SYSTEM-WIDE WINTER DEMAND (MGD)

Hour	1/16/96	1/17/96	1/18/96	1/19/96	1/20/96	1/21/96	1/22/96	1/23/96	1/24/96	1/25/96	1/26/96	Average
0	103.32	95.28	90.85	124.25	122.70	107.75	93.80	107.80	113.82	82.00	100.15	103.79
1	95.95	87.88	94.93	117.68	106.53	111.70	71.82	77.82	103.47	79.75	103.60	95.56
2	80.55	80.57	94.90	124.75	88.72	90.30	40.80	43.35	100.15	78.25	92.03	83.12
3	75.45	77.15	88.10	122.85	81.30	76.67	41.38	39.30	94.38	71.95	62.65	75.56
4	82.70	77.25	89.30	81.80	85.53	89.32	44.22	42.45	68.70	74.65	78.15	74.01
5	94.02	90.43	101.83	82.93	66.07	81.13	49.10	78.50	73.18	92.98	100.10	82.75
6	114.63	117.63	107.38	106.88	76.80	80.40	74.88	118.60	98.72	134.38	131.48	105.62
7	148.50	139.80	109.63	108.20	97.75	86.20	142.02	124.63	112.07	155.23	151.57	125.05
8	149.15	127.80	111.43	107.67	120.60	97.23	149.70	119.38	112.90	146.48	145.42	126.16
9	158.45	110.93	113.50	108.53	137.02	117.20	149.68	118.80	127.38	145.45	153.65	130.96
10	169.55	90.92	106.30	106.35	152.85	149.05	135.20	130.90	139.45	143.88	151.68	134.19
11	165.25	73.10	107.82	134.52	152.60	154.83	130.55	127.52	136.93	142.68	147.10	133.90
12	150.52	76.72	130.95	147.57	142.75	151.77	116.00	150.88	137.75	130.13	149.85	134.99
13	142.65	101.60	133.43	145.25	138.92	148.55	121.82	152.73	137.35	123.73	147.35	135.76
14	130.35	138.02	132.48	144.33	135.63	139.95	147.57	146.20	141.38	119.75	145.55	138.29
15	117.93	140.60	132.07	142.65	126.35	128.50	167.73	123.20	150.10	121.00	121.82	133.81
16	118.25	137.85	128.13	135.52	101.73	142.30	130.93	104.38	140.65	120.50	118.78	125.37
17	121.23	137.13	119.95	131.38	86.00	148.75	123.62	105.53	138.63	123.03	109.10	122.21
18	136.00	139.78	124.95	135.63	79.70	146.30	129.22	111.12	131.27	127.57	119.47	125.55
19	142.38	127.02	128.10	143.77	73.10	135.18	134.07	114.50	132.98	112.30	116.25	123.60
20	117.22	119.82	127.43	138.18	70.15	123.38	132.00	107.12	140.45	95.67	95.78	115.20
21	109.95	116.25	124.13	123.22	68.47	123.28	118.30	112.15	133.80	90.92	94.58	110.46
22	96.40	117.15	124.18	118.08	72.65	114.85	127.25	132.43	118.65	88.95	87.97	108.96
23	87.87	117.38	125.53	119.10	84.03	110.30	130.50	137.50	129.73	85.03	82.68	109.97
Average	121.18	109.92	114.47	122.96	102.83	118.95	112.59	109.45	121.41	111.93	116.95	114.79


Denver Water System-Wide Winter Demand
Demand (MGD)
180
160
140
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Hour
Average Daily Demand = 114.79 MGD
1/16/96
1/17/96
1/18/96
1/19/96
1/20/96
1/21/96
1/22/96
1/23/96
1/24/96
1/25/96
1/26/96
Average

Appendix B

Hydraulic Model Mixing Study
Inflow and Outflow Hydrographs
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Flow (gpm)
2.53
2.25
2.25
1.69
0 13 25 38 50 63 75 88 101 113 126 138 151 164 176 189 201 214 226 239 252 264 277 289
Time (minutes)
Model Inflow
Scaled Prototype Demand
Model Outflow

APPENDIX C - THEORETICAL BASIS FOR AIR BUBBLER MIXING SYSTEM

Henry T. Falvey & Associates

September 9, 1996

Robert Bates
Bates Engineering Inc.
7333 W. Jefferson Ave, Suite 155
Lakewood, CO 80235-2017

Dear Bob,

Decided to just fax this to you anyway, just in case you couldn't retrieve it on your e-mail. You should be able to read the excel file with no trouble. If you do have trouble, please let me know. Dave Woodward asked me about the effect of depth. That comes in as an energy term. The energy determines how rapidly the stratification is destroyed. The more energy that is input, the faster the gradient will disappear. However, the air flow quantity needed in this equation is determined only from force considerations due to buoyancy (the strength of the gradient) and drag (the bubble size and orifice hole distribution). Can discuss this further if the concept isn't explained clearly.

Sincerely,

Henry T. Falvey
President

P.O. Box 4 11624 Blackfoot Rd
Conifer CO 80433
Tel & FAX: (303) 838-4920
e-mail: falvey@lamar.ColoState.edu

ESTIMATION OF DESTRATIFICATION
WITH A BUBBLER

Baines and Leitch[1] give the momentum for uniform flow as

$$-\int_{s} g\, \Delta\rho\, dA = \frac{gQ_b}{V_b}$$

where g is the acceleration of gravity, $\Delta\rho$ is the relative density, A is the cross sectional area of the water surface, Q_b is the air flow rate, and V_b is the rise velocity of a bubble. The relative density is given by

$$\Delta\rho = \frac{\rho - \rho_o}{\rho_o}$$

where ρ_o is the density at the bottom of the tank. The momentum equation states that the downward buoyant force of the displace liquid is exactly balanced by the upward drag of the bubbles. Solving the momentum equation for the air discharge with a two layer stratified fluid gives

$$Q_a = \frac{\rho_1 - \rho_o}{\rho_o} A\, V_b$$

where ρ_1 is the density of the top fluid.

Zic, Stefan and Ellis[2] indicate that the destratification efficiency for a bubble plume from a single source located in the middle of a circular tank is roughly 1 % for thermally stratified liquids and 3 % for salinity stratified liquid. The efficiency is defined by

---

[1]Baines, W.D., and Leitch, A.M., 1992, "Destruction of Stratification by Bubble Plume," *Journal of Hydraulic Engineering*, American Society of Civil Engineers, Vol. 118., No. 4, April, pp. 559-577.

[2]Zic, K., Stefan, H.G., and Ellis, C., 1992, "Laboratory Study of Water Destratification by a Bubble Plume," *Journal of Hydraulic Research*, International Association for Hydraulic Research, Vol. 30, No. 1, pp. 7-28.

P.O. Box 4 11624 Blackfoot Rd
Conifer CO 80433
Tel & FAX: (303) 838-4920
e-mail: falvey@lamar.ColoState.edu

$$\eta = \frac{A \int_0^H \rho(z)\, g\, z\, dz}{\rho_a\, Q_a\, g\, H}$$

where H is the depth of the tank. They plotted the results as a function of a plume number defined as

This efficiency equation is essentially the same as that used by Stephens and Imberger[3] for a propeller in a tank. They found efficiencies as high as 12 % for a propeller located in the center of a large tank. Their results are plotted versus an impeller number defined as

$$I = \frac{\varpi}{\sqrt{-\frac{g}{\rho_o}\frac{d\rho}{dz}}}$$

where ω is the angular speed of the impeller and the denominator is equivalent to the buoyant frequency of the stratification. For a two layer stratification the impeller number is defined as

$$I = 100 \left(\frac{\varpi^2 D}{g'}\right) \left(\frac{D}{H_u}\right) \left(\frac{D}{z}\right)^2$$

where D is the impeller diameter, H_u is the upper layer depth, and g' is the reduced gravity defined as

$$g' = g \left(\frac{\rho_1 - \rho_o}{\rho_o}\right)$$

[3]Stephens, R., and Imberger, J, 1993, "Reservoir Destratificaton via Mechanical Mixers," *Journal of Hydraulic Engineering*, American Society of Civil Engineers, Vol. 119, No. 4., April, pp. 438-457.

Henry T. Falvey & Associates

September 6, 1996

Robert Bates
Bates Engineering Inc.
7333 W. Jefferson Ave, Suite 155
Lakewood, CO 80235-2017

Dear Bob,

Dave Woodward called yesterday requesting an estimate of the air flow rate that would be necessary to destratify the tank. Enclosed is a spread sheet that gives the theoretical total inflow air flow rate for various tank and inflow temperatures. The values I used should cover the range of temperatures that will be observed in the model. Experiments indicate that the maximum efficiency for a single source located at the center of the tank is only 1 %. However, with the dual ring system that you are considering, the efficiencies could be as high as 30 to 50%. The model tests can be used to determine the actual efficiencies. I would recommend that the theoretical air flow rates be increased by a factor of 3 or 4 to account for the efficiency. This will give you some latitude in the model investigation.

The spread sheet can also be used to predict the air flow rates necessary to destratify a prototype installation. Do you want the file sent to you on disk or should I e-mail it to you? It is in Excel format.

Sincerely,

Henry T. Falvey
President

P.O. Box 4 11624 Blackfoot Rd
Conifer CO 80433
Tel & FAX: (303) 838-4920
e-mail: falvey@lamar.ColoState.edu

		Theoretical Air Flow Rate Required to Destratify Tank							
Diameter	2.438	m	A	4.67	m^2	V_b	0.25	m/s	
				Downward Buoyant Force (N)					
Temp °C		0	5	10	15	20	20.5	25	30
	Density kg/m^3	999.868	999.992	999.726	999.125	998.228	998.112	997.069	995.671
0	999.868	0.000	-0.001	0.001	0.003	0.008	0.008	0.013	0.020
5	999.992	0.001	0.000	0.001	0.004	0.008	0.009	0.014	0.020
10	999.726	-0.001	-0.001	0.000	0.003	0.007	0.008	0.012	0.019
15	999.125	-0.003	-0.004	-0.003	0.000	0.004	0.005	0.010	0.016
16.9	998.784	-0.005	-0.006	-0.004	-0.002	0.003	0.003	0.008	0.015
20	998.228	-0.008	-0.008	-0.007	-0.004	0.000	0.001	0.005	0.012
25	997.069	-0.013	-0.014	-0.012	-0.010	-0.005	-0.005	0.000	0.007
30	995.671	-0.020	-0.020	-0.019	-0.016	-0.012	-0.011	-0.007	0.000
		Note: Negative values mean stratification is unstable							
				Air Discharge (L/s)					
				Temp °C in Tank					
		0	5	10	15	20	20.5	25	30
	0	0.00	0.00	0.17	0.87	1.91	2.05	3.27	4.90
	5	0.14	0.00	0.31	1.01	2.06	2.19	3.41	5.04
Temp °C	10	0.00	0.00	0.00	0.70	1.75	1.88	3.10	4.73
Of Inflow	15	0.00	0.00	0.00	0.00	1.05	1.18	2.40	4.03
	16.9	0.00	0.00	0.00	0.00	0.65	0.79	2.00	3.64
	20	0.00	0.00	0.00	0.00	0.00	0.14	1.36	2.99
	25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.64
	30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX D - TEMPERATURE AND CONDUCTIVITY DATA

BATES ENGINEERING

DENVER WATER TANK MIXING HYDRAULIC MODEL STUDY

TEMPERATURE DATA

Test #1

Outlet Condition: 0

Bubblers: None

Date: 8/21/96

Recorder: Dave Woodward

Thermometer:

Time	Water	Inlet	Outlet	Air	Column A2				Column B4				Column C1				Column D3			
(min)	Ht. (in.)				Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface
0	7.875		58		60	60	60	60	60	59	59	61	61	60	60	60	60	59	59	61
10			59		60	59	59	60	60	59	60	60	60	60	60	61	60	59	59	60
20		59	59		60	60	60	60	61	60	60	60	61	60	60	60	60	60	60	61
30		59	59		60	60	60	60	60	59	60	60	60	60	60	60	60	59	60	60
40		59	59		60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
50		59	59		60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
60		59	59		60	60	60	60	60	60	60	61	60	60	60	60	60	60	60	61
70		59	59		60	60	60	60	61	60	60	61	60	60	60	60	61	60	60	61
80	9.375	58	59		61	60	60	61	61	61	61	62	60	60	60	61	62	61	61	62
90		59	59		61	60	60	61	61	61	61	62	61	60	60	61	61	61	61	62
100		59	59		61	61	60	61	61	61	61	62	61	60	60	61	62	61	61	62
110		59	59		61	61	60	61	62	61	61	62	61	61	61	61	62	61	61	62
120		59	60		61	61	61	61	62	61	61	62	61	60	61	61	61	61	61	62
130		58	60		61	61	61	61	62	62	61	62	61	61	61	61	62	61	61	62
140		58	59		61	61	61	61	62	61	62	62	61	61	61	61	62	61	61	62
150		58	60		61	61	61	61	62	61	61	62	61	61	61	61	62	61	61	62
160		58	60		61	61	61	61	62	62	61	62	61	61	61	61	62	62	62	63
170		58	60		61	61	61	61	62	62	62	62	61	61	61	62	62	62	62	63
180		58	60		61	61	61	62	62	62	62	62	61	61	61	62	62	62	62	63
190		58	60	74	61	61	61	62	63	62	62	63	61	61	61	61	62	62	62	63
200	9.375	58	60		61	61	61	62	62	62	62	63	61	61	61	62	62	62	62	63
210		58	61		61	61	61	62	63	62	62	64	61	61	61	62	63	62	62	63
220	9.312	58	61		61	61	61	62	62	62	62	64	61	61	61	62	64	62	62	64
230		58	60	75	61	61	61	62	63	62	62	63	61	61	61	62	62	62	62	64
240		58	60		61	61	61	62	63	62	62	64	61	61	61	62	63	62	63	63
250	9.562	58	61	75	61	61	61	62	63	62	62	64	61	61	61	62	63	62	62	64
260		58	60		61	61	61	62	62	62	62	64	61	61	61	62	63	62	62	64
270	9.75	58	60		62	61	61	62	64	63	62	64	61	61	61	62	63	62	62	64
280	9.875	58	60		62	61	61	62	63	62	62	64	61	61	61	62	63	62	62	64
290		58	60		62	61	61	62	63	63	63	64	62	61	61	62	63	62	62	64
300		58		75	62	61	61	62	64	63	63	64	62	61	61	62	63	62	62	64

BATES ENGINEERING

DENVER WATER TANK MIXING HYDRAULIC MODEL STUDY

TEMPERATURE DATA

Test #2

Outlet Condition: 90 from inlet near column C4

Bubblers: None

Date: 8/23/96

Recorder: Jim Light

Thermometer: Based on the outlet thermometer, my thermometer reads one degree higher (ex outlet 60 mine 61)
the inlet thermometer reads one degree lower (ex. outlet 60 inlet59)

Time	Water	Inlet	Outlet	Air	Column A2				Column B4				Column C1				Column D3			
(min)	Ht. (in.)				Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface
0	7.875	58	60		62			61	62			62					61			61
10		59	60	70	60	61	61	61	61	61	61	61	60	61	61	60	61	61	61	61
20	8.437	59	60	70	60	61	61	61	61	61	61	61	60	61	61	61	61	61	61	61
30	8.500	59	60	70	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61	62
40	8.687	59	60	70	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61
50	8.937	59	60	70	61	61	61	61	62	62	62	62	61	61	61	61	62	61	61	62
60	9.187	59	60	74	61	61	61	61	62	62	62	62	61	61	61	61	61	61	61	62
70	9.375	59	60	74	61	61	61	61	62	62	62	62	61	61	61	61	62	62	62	62
80	9.437	59	61	72	61	61	61	61	62	62	62	62	61	61	61	61	62	62	62	62
90	9.500	59	61	72	61	61	61	61	62	62	62	62	61	61	61	61	62	62	62	62
100	9.437	59	61	72	61	61	61	61	62.5	62	62	62	61	61	61	61	62	62	62	62
110																				
120	9.312	59	61	72	61	61	61	61	62	62	62	62	61	61	61	61	62	62	62	62
130																				
140	9.125	59	61	72	61	61	61	61	62.5	62.5	62.5	62.5	61	61	61	61	62.5	62	62	62.5
150																				
160	9.000	59	61	75	61	61	61	61	63	62	62.5	62.5	61	61	61	61	62.5	62	62	63
170																				
180	8.875	59	61	74	61	61	61	61	63	62.5	62.5	63	61	61	61	61	63	62.5	62.5	63
190																				
200	8.875	59	61	74	61	61	61	61	63	62.5	62.5	63	61	61	61	61	63	62.5	63	63
210																				
220	8.562	59	61	75	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61
230																				
240	8.500	59	61	74	62	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61
250																				
260	8.500	59	61	73	62	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61
270																				
280	**8.562**	**59**	**61**	**76**	**62**	**61**	**61**	**61**	**61**	**61**	**61**	**61**	**61**	**61**	**61**	**61**	**61**	**61**	**61**	**61**
290																				
300	8.562	59	61	76	62	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61

BATES ENGINEERING
DENVER WATER TANK MIXING HYDRAULIC MODEL STUDY

CONDUCTIVITY DATA
Test #3
Outlet Condition: 180
Bubblers: None

Inlet flow 2.05 gpm
up to 2.10 gpm 150 min
up to 2.15 gpm 180 min

Date: 9/4/96
Recorder: Dave Woodward
Probe: Orion Conductivity Meter Model 160 (SN 24022021)

Time	Water	Inlet	Outlet	Column A2				Column B4				Column C1				Column D3			
(min)	Ht. (in.)			Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface
0	7.875	100	2	12			6	5			2	2			2	2			2
10		105	12	11			4	9			2	3			2	13			6
20	8.125			18			15	20			8	20			12	18			13
30	8.250		27	26			12	26			18	24			18	26			21
40	8.375	104	36	37			21	34			29	29			27	33			26
50		104	41	38			27	39			33	38			31	38			34
60	8.650		44	43			37	43			39	44			37	44			40
70			49	52			44	48			44	48			40	49			44
80	8.825		53	53			44	51			44	51			47	53			50
90	8.750		57	59			52	55			52	57			52	57			50
100	8.650	104	60	59			56	59			57	58			55	59			53
110	8.500		63	64			59	64			60	63			57	63			57
120			66	70			65	68			63	65			62	66			62
130			69	70			64	69			65	69			63	70			68
140	8.188		71	71			68	71			69	73			66	72			70
150	8.125	104	74	78			72	74			71	74			70	73			70
160	8.000		76	77			80	78			74	77			72	77			72
170																			
180	7.750	103	81	83			83	82			77	81			78	81			78
190																			
200	7.750		85	86			86	85			83	86			82	85			83
210																			
220	7.562		87	90			87	88			85	89			85	88			85
230																			
240	7.438		91	92			90	91			88	92			88	90			88
250																			
260	7.438		92	94			92	93			92	94			91	93			91
270																			
280	7.625		95	95			93	95			94	95			93	94			94
290																			
300	7.625	103	96	97			96	96			95	96			95	96			95

BATES ENGINEERING
DENVER WATER TANK MIXING HYDRAULIC MODEL STUDY
TEMPERATURE DATA
Test #3
Outlet Condition: 180
Bubblers: None

Date: 9/4/96
Recorder: Jim Light
Thermometer: Orion

Time	Water	Inlet	Outlet	Air	Column A2				Column B4				Column C1				Column D3			
(min)	Ht. (in.)				Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface
0																				
10																				
20																				
30																				
40		16.5			19.6			20.0	19.6			19.8	19.7			20.0	19.8			20.2
50																				
60																				
70			19.2																	
80																				
90			18.9		18.9			19.1	18.9			19.2	18.9			19.1	18.9			19.3
100																	18.8			
110																				
120																				
130			18.5																	
140																				
150																				
160																				
170																				
180		17.2	18.3		18.2			18.2	18.2			18.4	18.2			18.4	18.3			18.4
190																				
200			18.3																	
210																				
220																				
230																				
240		17.1	18.2		18.0			18.2	18.0			18.2	18.0			18.3	18.2			18.3
250																				
260																				
270																				
280																				
290												18.0								
300	16.9		18.0	25.5	17.9			17.9	17.9			18.0	17.9			18.0	18.0			18.0

*Therm I = 18.5 C

TEST 3

TIME	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	INFLOW	OUTFLOW
0	68.2	68.3	68.6	68.2	67.8	68.2	68.3	68.4	68.2	68.8	68.7	68.4	68.3	68.2	68.4	68.3	68.2	68.2	68.1	67.0	62.8	71.6
209	67.5	67.6	67.6	67.7	68.3	67.7	68.1	68.4	68.2	69.3	67.9	67.8	68.2	68.2	69.0	68.3	68.3	68.2	68.4	68.8	63.8	73.4
419	67.4	67.2	67.8	68.0	68.6	67.4	68.0	68.0	68.1	69.5	67.8	67.6	68.1	68.1	69.1	67.8	67.6	68.1	68.1	69.1	63.4	73.4
630	67.4	67.2	67.8	68.0	68.5	67.3	67.5	67.9	68.1	69.5	67.4	67.4	68.1	67.9	69.0	67.4	67.6	67.4	67.6	68.8	62.8	74.0
853	66.6	66.6	67.0	67.3	67.7	67.2	67.3	67.4	67.5	68.8	67.3	66.9	67.5	67.9	68.2	67.5	67.2	67.4	67.6	68.1	62.6	74.0
1274	66.6	66.4	66.9	66.7	67.5	66.7	66.8	67.1	67.4	68.6	67.0	66.8	67.3	67.3	67.5	67.3	66.9	67.0	67.6	67.9	62.3	66.7
1484	66.1	66.4	66.6	66.5	66.8	66.5	66.6	67.0	66.8	67.9	66.3	66.4	66.6	67.2	67.5	66.8	66.8	66.6	66.9	67.9	62.1	66.2
1691	65.6	65.6	66.1	65.8	66.0	65.7	65.8	66.3	66.5	66.5	66.3	65.9	66.2	66.4	66.8	66.6	66.0	65.8	66.0	66.9	61.7	65.3
1902	65.0	64.9	65.4	65.1	65.4	65.1	65.4	65.5	65.8	66.2	65.5	65.2	65.6	65.6	66.1	65.9	65.2	65.6	65.3	66.3	61.4	65.3
2299	64.7	64.3	64.7	65.1	65.2	64.8	64.8	65.2	65.2	65.5	65.1	64.9	65.1	65.2	65.9	65.1	65.0	65.0	64.9	65.5	61.3	64.5
2509	64.2	64.0	64.2	64.3	64.4	64.3	64.4	64.6	64.9	65.0	64.6	64.4	64.7	56.8	65.1	65.1	64.3	64.4	64.5	65.5	61.3	64.4
2720	64.1	63.9	64.1	64.2	64.5	64.1	64.1	64.2	64.4	64.6	64.3	64.4	64.3	64.7	65.0	64.4	64.3	64.2	64.4	64.6	61.3	63.7
2942	63.6	63.4	63.7	64.3	64.2	63.8	63.8	63.9	64.3	64.1	63.9	63.6	64.0	64.0	64.3	64.2	63.4	64.2	64.0	64.7	61.3	63.5
3336	63.5	63.2	63.8	63.7	63.9	63.6	63.6	63.7	63.9	64.0	63.9	63.6	63.6	63.9	64.3	64.2	63.4	63.4	63.6	64.0	61.3	63.3
3546	63.2	63.2	63.1	63.3	63.7	63.3	63.4	63.5	63.5	63.8	63.8	63.6	63.6	63.6	64.1	63.7	63.4	63.2	63.6	63.7	61.3	63.2
3941	62.9	63.0	63.0	63.4	63.7	63.3	63.3	63.2	63.5	63.7	63.4	63.2	63.5	63.5	63.9	63.3	63.0	63.4	63.5	63.8	61.3	63.0
4330	62.6	62.7	63.0	63.1	63.5	63.1	63.3	63.1	63.4	63.1	63.3	63.0	63.3	63.1	63.5	63.3	62.8	63.5	63.3	63.8	61.4	62.8
4540	62.7	62.5	62.9	63.0	63.5	63.0	63.0	63.1	63.3	63.3	63.2	62.7	63.2	63.2	63.7	63.4	62.6	63.1	62.9	63.8	61.4	62.8

BATES ENGINEERING

DENVER WATER TANK MIXING HYDRAULIC MODEL STUDY

CONDUCTIVITY DATA

Test #4

Outlet Condition: 180

Bubblers: None

Date: 9/6/96

Recorder: Jim Light

Probe: Orion

Inlet Q = 2.15 gpm (dropped below this due to debris)
= 2.25 gpm at 75 min
2.20 gpm at 180 min
Took no pictures at 70 min
2 pictures at 80 min (one without lights)

Stopped flows at 30 min to remove air from inlet line - flows were too low. Stopped again at 35 min for 5 min to clean out hoses from the dye tank to the model. Apparently debris was caught in inlet line.

Time	Water	Inlet	Outlet	Column A2				Column B4				Column C1				Column D3			
(min)	Ht. (in.)			Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface
0	7.875	107	2	13			5	2			2	2			2	2			2
10			7	25			4	7			2	15			2	2			2
20	7.937		23	21			4	22			10	21			7	20			3
30			27	26			7	27			19	26			10	27			22
40	8.125		27	36			29	35			19	36			22	33			12
50	8.25		38	40			29	39			34	40			28	40			32
60	8.5	106	43	48			37	48			41	48			38	43			41
70																			
80			52	58			52	53			50	55			47	54			51
90																			
100	8.687		60	65			59	62			58	63			57	61			60
110																			
120	8.625	106	69	70			66	68			66	70			64	69			66
130																			
140	8.562		74	73			76	74			71	75			71	74			73
150																			
160			79	80			79	78			77	80			75	78			75
170																			
180	8.687	106	82	86			80	83			91	84			80	82			80
190																			
200	8.687		86	88			85	86			94	87			84	86			85
210																			
220	8.5		88	90			89	89			87	89			85	88			88
230																			
240	8.437	104	91	93			92	91			89	92			88	91			90
250																			
260			92	94			95	93			91	93			94	92			92
270																			
280	8.5		94	96			94	95			93	95			93	94			93
290																			
300	8.375		95	97			95	95			94	96			94	96			95

BATES ENGINEERING

DENVER WATER TANK MIXING HYDRAULIC MODEL STUDY

TEMPERATURE DATA

Test #4

Outlet Condition: 180

Bubblers: None

Temp. Probe #22 (outlet) was not in water until 50 min.

Both die tank and model were filled last night.

Date: 9/6/96

Recorder:

Thermometer: Orion, Thermometer "I" for air

Time	Water	Inlet	Outlet	Air	Column A2				Column B4				Column C1				Column D3			
(min)	Ht. (in.)				Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface
0		18.7																		
10			20.9		20.6			21.0	20.9			21.1	20.7			21.0	21.1			21.1
20																				
30																				
40				22.8																
50																				
60		18.6	20.1	19.9				20.3	19.9			20.0	20.0			20.3	20.1			20.2
70																				
80																				
90																				
100																				
110																				
120		18.4	19.1		19.1			19.2	19.1			19.2	19.1			19.3	19.2			19.2
130																				
140																				
150																				
160				21.0																
170																				
180		18.3	18.6		18.4			18.6	18.5			18.6	18.5			18.6	18.6			18.6
190																				
200				20.9																
210																				
220																				
230																				
240		17.7	18.2	20.6	18.0			18.0	18.0			18.2	18.0			18.2	18.2			18.2
250																				
260																				
270																				
280																				
290																				
300			18.0	21.6	17.9			18.0	17.9			18.0	17.9			18.2	18.0			18.0

Lab not cooled, reflects outside temperatures , cool and rainy.

TEST 4

TIME	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	INFLOW	OUTFLOW
0	65.0	64.7	64.7	65.0	65.2	64.9	65.0	64.8	65.1	65.9	64.8	64.7	64.8	64.8	65.5	64.6	64.3	64.7	65.0	64.9	56.2	64.4
360	65.0	64.8	64.6	65.0	65.4	64.9	65.0	64.8	65.1	66.3	65.0	65.0	65.0	64.8	65.1	65.1	64.7	65.1	65.1	65.2	56.4	64.4
751	63.8	63.9	64.8	65.1	66.0	63.9	64.1	64.7	65.1	66.9	63.8	64.4	65.0	64.8	65.8	64.6	64.3	64.0	64.4	65.5	56.5	63.5
1110	63.2	63.5	64.2	65.1	66.0	63.4	63.8	64.0	65.1	66.3	63.7	63.6	64.3	64.8	65.9	64.2	63.6	64.1	64.4	65.7	56.5	63.5
1321	63.4	63.2	63.9	64.3	65.4	63.2	63.4	63.9	64.3	66.3	63.3	63.6	63.9	64.3	65.5	64.2	63.5	63.3	63.9	65.5	57.1	62.8
1645	62.8	63.1	63.6	64.2	65.2	62.8	63.2	63.5	63.8	65.5	63.1	62.8	63.6	63.9	65.1	63.4	63.2	63.3	63.6	65.5	57.1	62.6
1855	62.6	62.4	63.0	63.5	64.4	62.5	62.7	63.1	63.5	65.1	62.9	62.7	63.5	63.3	64.4	63.4	62.7	62.7	63.1	64.8	57.1	62.4
2072	62.6	62.4	62.8	62.8	63.9	62.4	62.6	62.9	63.2	64.6	62.5	62.1	62.7	63.2	63.9	63.0	62.6	62.5	62.8	64.3	57.1	62.0
2281	62.1	62.2	62.2	62.7	63.7	61.9	62.3	62.4	62.7	63.8	62.3	61.9	62.7	62.6	63.5	62.8	61.9	62.2	62.3	63.6	57.1	61.7
2491	61.8	61.6	62.2	62.4	62.9	61.8	61.9	62.3	62.6	63.4	62.1	61.9	62.4	62.4	63.3	62.6	61.9	61.9	61.8	62.9	57.2	61.5
2799	61.4	61.5	62.2	62.1	62.9	61.7	61.8	62.1	62.5	63.3	62.0	61.6	62.0	62.3	63.5	62.2	61.8	61.7	61.9	63.0	57.1	61.3
3007	61.4	61.5	61.7	62.1	62.9	61.7	61.7	61.8	61.9	63.0	61.7	61.3	61.9	62.1	62.8	61.8	61.3	61.8	62.0	62.9	57.3	61.3
3217	61.2	61.1	61.4	61.9	62.9	61.1	61.4	61.5	61.9	63.0	61.6	61.2	61.8	61.7	62.7	61.8	60.9	61.8	61.5	62.6	57.9	61.4
3427	61.0	60.8	61.4	61.4	62.3	61.0	61.3	61.5	61.8	62.9	61.4	61.2	61.7	61.6	62.7	61.8	61.1	61.1	61.3	62.3	57.8	61.2
3908	61.0	60.7	61.3	61.4	62.4	61.0	61.0	61.5	61.8	63.0	61.5	61.1	61.2	61.6	62.6	61.8	61.1	61.0	61.3	62.2	58.1	60.9
4117	61.0	60.8	60.8	61.2	62.5	61.0	61.0	61.3	61.7	63.0	61.5	60.7	61.1	61.6	62.7	61.8	61.0	61.1	61.3	62.2	58.0	60.8
4325	61.0	60.7	60.6	61.2	62.0	61.0	61.0	61.0	61.3	63.0	61.2	60.7	61.0	61.4	62.7	61.7	61.0	60.9	61.3	62.7	58.0	60.5
4534	60.8	60.5	60.8	61.2	62.8	61.0	60.8	60.7	61.3	63.1	61.2	60.4	61.0	61.3	62.8	61.7	60.8	61.0	61.3	62.6	58.4	60.5
4744	60.4	60.4	60.6	61.1	64.0	60.6	60.7	60.7	61.1	64.2	61.0	60.3	60.8	61.0	65.1	61.0	60.3	60.7	61.3	64.5	58.4	60.4
5446	60.7	60.1	60.5	61.0	65.2	60.4	60.5	60.7	61.2	64.8	60.7	60.3	60.9	61.2	65.9	61.0	60.1	60.6	61.3	65.4	58.7	60.4
5657	60.4	60.1	60.6	60.8	65.4	60.3	60.3	60.7	61.2	64.6	60.8	60.3	60.5	61.1	65.8	61.0	60.2	60.4	61.3	65.5	58.8	60.2
5868	60.3	60.1	60.6	61.1	66.0	60.4	60.2	60.5	61.0	64.7	60.7	60.3	60.5	61.1	66.5	61.0	60.2	60.4	61.2	65.8	58.4	60.4
6078	60.2	60.1	60.4	60.7	66.0	60.2	60.2	60.5	61.1	65.4	60.7	60.3	60.4	60.9	66.7	61.0	60.1	60.3	61.0	66.2	58.0	60.4
6288	60.1	60.0	60.5	60.4	66.0	60.2	60.2	60.3	61.0	65.4	60.5	60.2	60.3	60.8	67.5	61.1	60.2	60.2	60.8	66.2	58.0	60.0
6905	60.0	60.0	60.2	60.5	66.8	60.1	60.0	60.2	61.1	66.3	60.4	60.1	60.3	60.8	67.7	60.7	60.0	60.2	60.4	66.3	57.9	59.6

BATES ENGINEERING

DENVER WATER TANK MIXING HYDRAULIC MODEL STUDY

CONDUCTIVITY DATA

Test #5

Outlet Condition: 180

Bubblers: None

Date: 9/10/96

Recorder: Jim Light

Probe: Orion

Time	Water	Inlet	Outlet	Column A2				Column B4				Column C1				Column D3			
(min)	Ht. (in.)			Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface
0	7.75	104	1	2			2	1			1	1			1	1			1
10	7.812		1	3			2	3			1	2			2	1			1
20	7.875		13	9			2	10			2	12			2	12			2
30	7.875		14	13			2	14			2	16			2	14			2
40	7.875		16	15			2	16			4	16			3	15			3
50	7.937		17	19			3	18			4	17			7	16			2
60	8	104	19	18			4	21			12	19			6	19			9
70																			
80			22	23			10	26			17	23			10	23			14
90																			
100	8.125		28	29			13	29			15	28			13	28			22
110																			
120	8	104	31	30			14	33			25	31			27	32			24
130																			
140	7.937		35	33			24	37			28	34			30	35			34
150																			
160			37	39			28	39			31	38			26	37			37
170																			
180	7.875	104	41	43			32	40			35	40			30	43			38
190																			
200	7.875		44	46			35	46			37	44			37	46			43
210																			
220			48	48			36	48			41	48			42	49			47
230																			
240	7.875	103	50	49			45	51			38	49			45	51			49
250																			
260	7.812		54	53			49	53			43	54			50	55			53
270																			
280	7.812		56	57			52	56			46	55			52	57			55
290																			
300	7.812	103	58	60			53	58			49	59			56	59			57

BATES ENGINEERING

DENVER WATER TANK MIXING HYDRAULIC MODEL STUDY

TEMPERATURE DATA

Test #5

Outlet Condition: 180

Bubblers: None

Hydrograph .25 Q standard

Date: 9/10/96

Recorder: Jim Light

Thermome er Orion Thermometer "I"

Bureau Temperature data file and time corrected at t=30 min

At 80 min, full dye mixing

Time	Water	Inlet	Outlet	Air	Column A2				Column B4				Column C1				Column D3			
(min)	Ht. (in.)				Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface
0		16.9	20.5	24.2	20.2			20.0	20.1			20.2	20.2			20.2	20.3			20.4
10																				
20																				
30																				
40																				
50																				
60		17.2	19.9	23.9	19.9			20.0	19.7			20.1	19.9			20.0	19.9			20.1
70																				
80			19.6																	
90																				
100																				
110																				
120		17.6		23.8	19.6			19.7	19.7			19.9	19.6			19.7	19.7			19.9
130																				
140																				
150																				
160																				
170																				
180		18.0	19.6	24.2	19.7			19.7	19.5			19.6	19.6			19.7	19.6			19.7
190																				
200																				
210																				
220																				
230																				
240		18.0	19.5		19.6			19.7	19.5			19.6	19.6			19.6	19.6			19.6
250																				
260																				
270																				
280																				
290																				
300		18.4	19.6	24.4	19.6			19.6	19.5			19.6	19.5			19.6	19.6			19.6

TEST 5

TIME	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	INFLOW	OUTFLOW
0	66.0	66.4	67.0	66.6	68.8	66.3	66.5	66.8	66.9	68.8	66.5	66.6	66.6	66.8	69.1	66.6	66.2	66.6	66.8	68.5	60.4	66.4
392	66.0	66.3	67.0	66.6	69.0	66.5	66.3	66.5	66.8	69.0	66.4	66.5	66.6	66.4	69.1	66.6	66.5	66.6	66.5	68.7	60.6	66.2
976	66.4	66.3	66.8	66.6	67.6	66.0	66.5	66.7	66.6	68.9	66.2	66.2	66.5	66.6	68.5	66.6	66.0	66.6	66.8	67.9	60.4	66.1
5058	65.8	65.6	66.2	66.3	66.8	65.7	65.7	66.0	66.5	67.1	66.2	65.9	66.0	66.3	66.7	66.1	65.9	65.7	66.0	67.0	60.8	65.7
5267	65.7	65.6	66.2	66.1	66.8	65.7	65.8	66.2	66.5	67.6	66.2	66.0	66.0	66.3	66.7	66.1	65.9	65.8	66.0	66.8	60.8	65.9
5476	65.6	65.6	66.2	66.2	66.8	65.7	65.7	66.0	66.4	68.0	66.2	66.0	65.9	66.1	66.8	66.1	65.9	65.7	66.0	67.0	60.9	65.7
5685	65.6	65.5	66.1	65.9	66.8	65.7	65.7	65.9	66.1	68.0	65.8	65.7	65.9	66.4	67.5	66.0	65.6	65.9	66.0	67.0	61.2	65.5
5894	65.8	65.6	66.2	65.8	66.8	65.6	65.7	65.9	66.0	68.0	66.0	65.5	65.9	66.2	68.3	65.9	65.6	65.6	66.2	67.0	60.9	65.8
6103	65.7	65.6	66.2	65.8	66.9	65.7	65.7	65.6	65.9	68.9	66.2	65.9	65.9	66.1	68.6	65.9	65.2	65.9	66.0	67.9	61.9	65.5
6312	65.8	65.5	66.0	65.8	68.3	65.6	65.7	65.7	66.0	68.9	65.9	65.7	65.9	65.7	68.4	65.9	65.6	65.8	66.0	68.5	61.8	65.3
6524	65.8	65.5	66.0	65.8	68.3	65.7	65.7	65.9	65.9	68.8	65.9	65.7	65.9	65.9	69.1	65.9	65.5	65.8	66.0	68.8	62.1	65.6
6736	65.8	65.6	65.8	65.8	68.4	65.7	65.7	65.8	65.9	68.7	66.3	65.9	65.8	66.0	69.1	65.9	65.6	65.7	66.0	68.7	62.1	65.6
6944	65.7	65.5	66.2	65.8	68.3	65.6	65.7	65.5	65.9	68.7	66.0	65.7	65.9	65.8	68.9	66.2	65.4	65.7	66.0	68.7	62.0	65.6
7312	65.7	65.6	66.0	65.8	68.3	65.7	65.7	65.7	66.0	68.5	65.9	65.7	65.9	66.1	68.4	65.9	65.3	65.7	66.0	68.7	62.4	65.5

BATES ENGINEERING

DENVER WATER TANK MIXING HYDRAULIC MODEL STUDY

CONDUCTIVITY DATA

Test #6 Start time = 10:35 Stop time = 3:35

Outlet Condition: 180 Use 1/4 of standard hydrograph

Bubblers: Yes Q = 1.66 scfm (39 psiat gage turned down at 180 min. to 40% at 240 nin. cut to 20% at 270 to 40%)

Flows directed to West due to uneven bubbling

Date: 9/20/96

Recorder: Steve Lovato

Probe:

Time	Water	Inlet	Outlet	Column A2				Column B4				Column C1				Column D3			
(min)	Ht. (in.)			Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface
0	7.75	101	2	3			3	2			2	2			2	2			2
10			4	4			5	3			4	4			4	3			4
20			6	7			7	6			6	6			6	6			6
30			9	10			10	8			9	9			9	8			8
40	8		11	11			11	11			11	11			11	11			11
50			13	13				13			13	14			14	13			13
60		101	15	17			17	15			15	15			15	15			15
70																			
80	8.25		20	21			21	20			20	20			20	20			20
90																			
100			24	25			24	24			24	24			24	24			24
110																			
120	8.062	100	28	29			28	28			28	28			28	28			28
130																			
140	8		32	32			32	32			32	32			32	32			32
150																			
160			36	37			37	36			36	36			36	36			
170																			
180	7.937	101	39	39			39	39			39	39			39	38			38
190																			
200																			
210			44	44			44	43			43	44			44	43			43
220																			
230																			
240	7.875	100	48	48			48	48			48	48			48	48			48
250																			
260																			
270			52	54			52	52			52	52			53	51			51
280																			
290																			
300		100		56			56	56			55	55			55	55			55

BATES ENGINEERING

DENVER WATER TANK MIXING HYDRAULIC MODEL STUDY

TEMPERATURE DATA

Test #6

Outlet Condition: 180

Bubblers: Yes

Date: 9/20/96

Recorder:

Thermometer:

Time	Water	Inlet	Outlet	Air	Column A2				Column B4				Column C1				Column D3			
(min)	Ht. (in.)				Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface	Floor	25%	50%	Surface
0		16	18.2	20.5	18.2			18.2	18.2			18.2	18.2			18.2	18.2			18.2
10																				
20																				
30								18								18				
40																				
50																				
60		16.4	18		17.9			18	18			18	18			18	18			18
70																				
80																				
90																				
100																				
110																				
120		16.6	17.9	21.9	17.9			17.9	17.9			17.9	17.9			17.9	17.9			17.9
130																				
140																				
150																				
160																				
170																				
180		16.9	17.9	22.7	17.9			17.9	17.9			17.9	17.9			17.9	17.9			17.9
190																				
200																				
210																				
220																				
230																				
240		17.2	17.9		18			18	17.9			18	18			18	18			18
250																				
260				23.2																
270																				
280																				
290																				
300		17.4	18		17.9			18	17.9			18	18			18	18			18.1

TEST 6

TIME	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	INFLOW	OUTFLOW
0	63.4	63.3	46.2	63.5	63.7	63.2	63.4	63.2	63.4	63.7	63.3	63.5	63.5	58.0	63.2	63.3	63.2	63.4	63.6	63.5	59.3	63.2
209	63.2	63.3	46.2	63.5	63.7	63.3	63.4	63.3	63.5	63.8	63.2	63.4	63.5	63.2	63.1	63.3	62.8	63.4	63.2	63.4	59.0	62.9
420	63.4	63.2	45.5	63.3	63.7	63.3	63.3	63.1	63.3	63.3	63.2	63.4	63.2	63.1	63.4	62.9	62.8	63.4	62.9	63.1	59.5	63.1
628	63.0	63.1	45.4	63.3	63.7	63.2	63.4	63.1	63.4	63.5	63.1	63.1	63.2	63.2	63.4	62.6	62.7	62.9	62.8	63.0	59.3	62.8
839	62.6	63.1	45.2	63.0	63.7	63.2	63.4	63.1	63.2	63.3	63.1	62.8	63.0	63.2	63.0	62.6	62.6	63.0	62.9	63.0	59.3	62.9
1072	62.9	62.9	45.1	63.1	63.3	63.2	63.3	63.1	63.1	63.0	63.1	62.7	63.0	63.1	63.2	62.6	62.7	62.9	62.8	62.9	59.7	62.8
1282	62.8	63.0	45.2	63.3	63.7	63.2	63.2	63.1	63.0	63.7	63.2	62.9	63.2	63.1	63.4	62.8	62.7	62.7	62.7	63.0	59.7	62.8
1493	62.9	62.7	45.4	63.0	63.6	63.2	63.1	63.1	63.1	63.0	62.8	62.8	62.8	63.1	63.3	62.8	62.7	62.6	62.9	63.1	59.7	62.8
1704	62.7	62.7	45.5	63.2	63.4	63.0	63.0	63.1	63.0	63.0	63.1	62.7	62.8	60.1	63.0	62.6	62.7	62.6	62.8	63.0	60.4	62.5
1914	62.7	62.5	46.2	63.0	63.5	62.9	63.0	62.9	62.8	62.9	63.1	62.7	62.8	60.8	63.0	62.7	62.8	62.5	62.8	62.9	60.4	62.6
2122	62.6	62.9	46.2	63.0	63.3	62.9	62.7	63.1	62.9	62.9	63.1	62.7	62.8	60.9	62.8	62.6	62.7	62.6	62.7	63.0	60.4	63.1
2333	62.6	62.4	45.8	62.9	63.4	62.8	63.0	62.9	62.8	63.0	63.1	62.7	62.7	62.9	62.8	62.7	62.6	62.5	62.8	62.9	60.3	62.7
2542	62.6	62.5	46.1	62.9	63.3	62.8	62.9	63.0	62.8	63.0	63.0	62.7	62.7	62.8	62.7	62.6	62.6	62.6	62.7	63.0	60.8	62.8
2753	62.6	62.8	45.5	63.0	63.5	62.8	63.0	62.8	62.9	63.0	63.1	62.7	62.7	62.9	63.2	62.7	62.7	62.6	62.7	63.0	61.3	62.5
2963	62.6	63.0	46.0	63.1	63.7	63.1	63.0	63.1	63.2	63.5	63.2	62.8	62.8	63.2	63.1	62.7	62.7	62.8	62.8	62.9	61.2	62.5
3253	62.6	62.9	46.1	63.2	63.7	63.0	63.0	63.1	63.2	63.7	63.1	62.9	62.9	63.1	63.5	62.8	62.4	62.7	62.8	63.0	61.3	62.8
3478	62.8	63.2	46.0	63.4	63.7	63.2	63.3	63.1	63.2	63.7	63.1	62.8	63.2	63.2	63.5	62.9	62.7	62.7	62.8	62.9	61.3	62.9
3688	63.0	63.1	46.1	63.4	63.8	63.3	63.3	63.1	63.3	63.0	63.1	63.2	63.2	63.2	63.3	62.6	62.8	63.0	62.9	63.0	61.5	62.8

APPENDIX E - SELECTED PHOTOGRAPHS

Photo Log

1. Overall view of the model looking from the north. 250-gallon plastic supply tank is at left, inlet pump at bottom left center, model at center and data temperature logger at right. White PVC stand above model held 35 mm camera with remote shutter release for visually assessing horizontal mixing.

2. Close-up of temperature data logger provided by the Bureau of Reclamation. In background, Jim Light of Denver Water is measuring conductivity values at column D3.

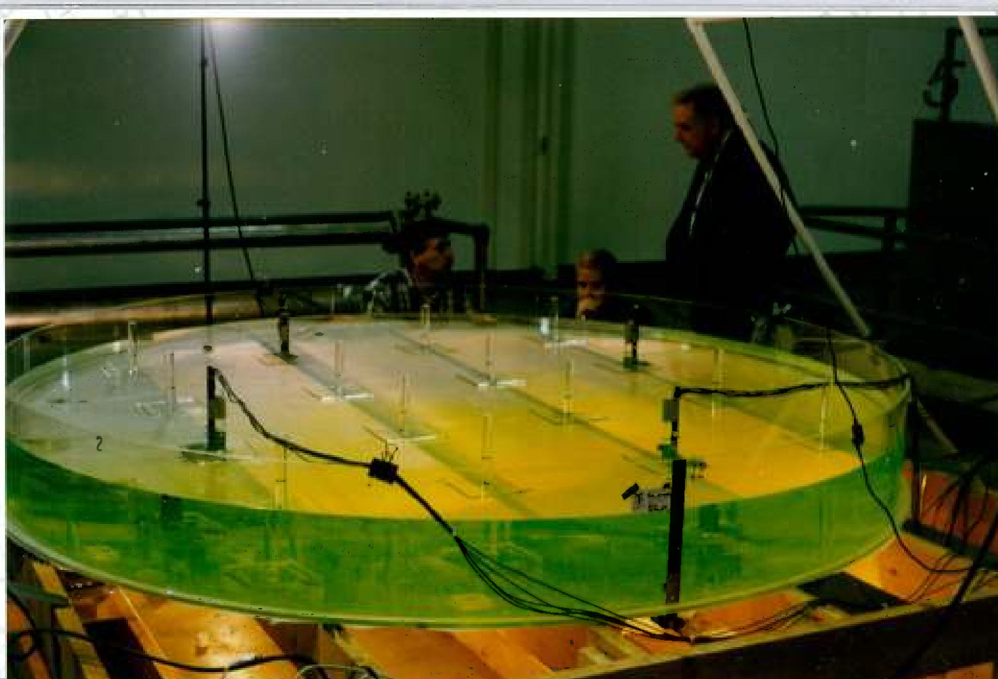
3. Effect of inlet dispersion shown here during Test 4. Cold water entering the model forms a plume immediately around the inlet due to high incoming velocities, but then dives towards the floor.

4. Vertical temperature stratification visible in Test 4 looking toward the east. Note that the effect of stratification decreases moving from the inlet (left) to the outlet (right).

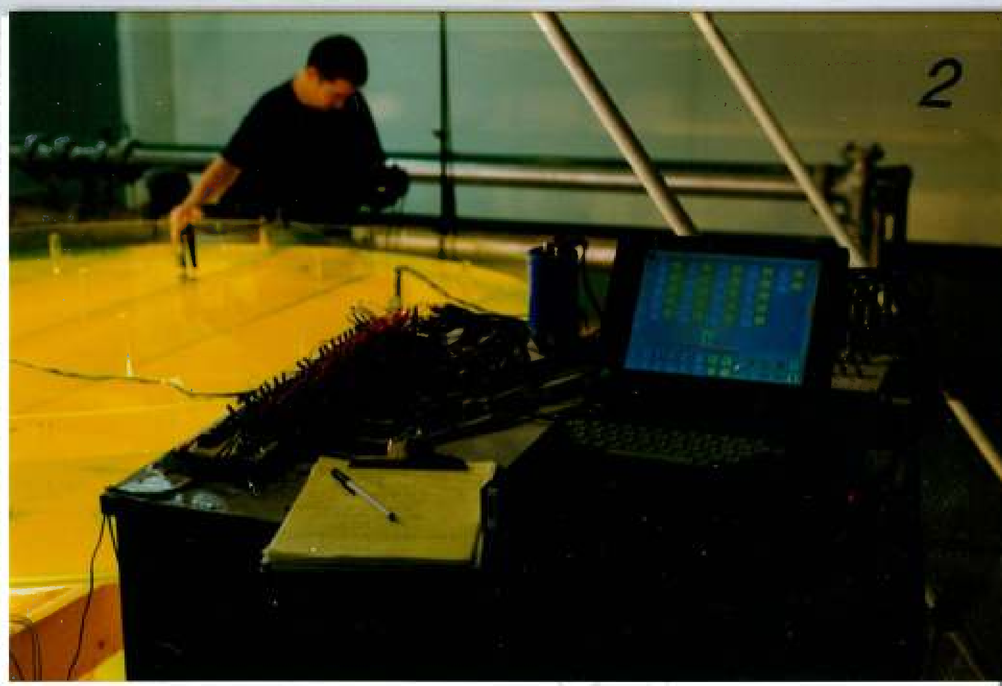
5. Effects of horizontal mixing seen in Test 4 looking to the south. Note clear areas behind columns indicating that the columns are acting as a mixing "shadow". The final stagnant area for the 180° outlet configuration was typically in the center of the model.

6. Air bubbler mixing system in Test 6 producing complete horizontal and vertical mixing.

Note: Photographs taken above the model at regular time intervals and miscellaneous photographs taken from other positions are included in a separate binder




12


2