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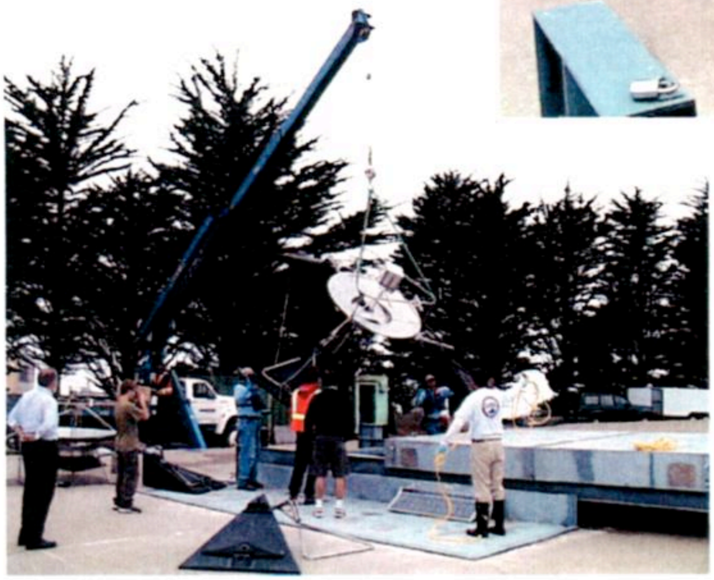
Solarbee Mixer Study

Sunset Reservoir South Basin



By
Water Quality Bureau
San Francisco PUC

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Foreword

While the San Francisco Public Utilities Commission (SFPUC) distribution system water quality has met regulatory standards, water regulations are becoming increasingly stringent with a focus on distribution system operations. With these new regulations, distribution operators must continually fine-tune and adjust operations to address water quality issues as well as supply issues.

The SFPUC chloramine conversion completed in February 2004, reflects these new regulations and the need for adjusting distribution system operations. While the bulk of funding was used for new ammoniating facilities at the treatment plants, a significant number of improvements are recommended for distribution system operations. These tasks include reservoir/tank cleaning and maintenance, distribution system flushing, reservoir/tank cycling and mixing improvements, evaluation of water age, chlorine boosting studies, increased water quality monitoring, and nitrification response.

This study evaluates the Solarbee Hydraulic Mixer as an operational tool that may assist operations to maintain water quality as necessitated by the chloramine conversion. Three major objectives can be accomplished by using these mixers in city reservoirs: eliminate short-circuiting and minimize water age in oversized distribution system reservoirs; minimize residual loss in reservoirs; and facilitate emergency disinfection or breakpoint chlorination in a reservoir (as in the case of a severe nitrification event).

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Water Quality Bureau (WQB)
Manouchehr Boozarpour
Katie Miller
Alan R. Wong
Brian Carlomagno
Charles Ozumba
Kenton Ngo
Carissa Clark
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Roberto (Bobby) Gonzales
Carrie Winters
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Pat Ford

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Charlotte Smith

Walter M. Grayman, Consulting Engineer

Solarbee
Joel Bleth
Sandy Walker
Harvey Hibl
Phil Pfeiffer
Solarbee Staff

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Executive Summary

Introduction

Several studies have been completed recommending deep cycling, routine draw down, mechanical mixers and/or inlet/outlet modifications to promote turnover within SFPUC terminal drinking water reservoirs. These tools for moving water more effectively are prompted by the long detention times associated with many SFPUC reservoirs, and are intended to prevent nitrification after the change to chloramines as a secondary disinfectant in February 2004. Mechanical mixing within the reservoirs was recommended as one potential method for decreasing maximum detention times and minimizing nitrification. To this end, the SFPUC's Water Quality Bureau (WQB), City Distribution Division (CDD), and Charlotte Smith and Associates (CS&A) investigated the use of the Solarbee SB10000F hydraulic mixer. This low energy 10,000 gpm (14.4 mgd) mixer is designed to improve mixing and break thermal stratification. The objectives of the study were to:

- Evaluate the mixer's ability to mix a reservoir, decrease maximum detention times (T_{max}), and minimize dead zones
- Determine the mixer's ability to assist with the dispersion and mixing of chemicals during breakpoint chlorination as a nitrification response.
- Evaluating the mixing effectiveness of new inlet modifications at Sunset South
- Document temperature conditions of Sunset South throughout the year
- Evaluate the Solarbee mixer's ability to break thermal stratification

Methodology

Two Solarbee units were delivered to Sunset Reservoir in August 2002 and were installed by SFPUC and Solarbee staff. Two parameters were measured to evaluate the Solarbee's mixing effectiveness: non-conservative tracer (chlorine) concentrations and temperature. Chlorine concentrations were measured at five different locations and at 3 different depths. Vertical temperature profiles were simultaneously measured at several of the same locations using temperature probes. The reservoir volume ranged between 69 MG and 75 MG for all tests, and the reservoir area is approximately 11 acres.

Tests 1 and 2 were conducted in Winter 2002 (November and December, respectively) and both mixers were used for the tests. Test 1 was termed the 'Mixers On' test and Test 2 the 'Mixers Off' (Baseline) test. The tests were run at near identical hydraulic conditions, with chlorine injected at the inlet during a fill and then discontinued once the reservoir reached a certain depth. The reservoir was then isolated.

Test 3 and 4 were designed to evaluate chlorine mixing and destratification capabilities of one Solarbee unit under isolated conditions with no inlet energies. For Test 3, a chlorine slug was injected into the reservoir while during Test 4 chlorine was metered onto the mixer's impeller.

Results and Discussion

The results for Tests 1 and 2 were virtually identical indicating mixing by inlet momentum was the dominant mixing factor during winter 2002, masking and outpacing any mixing improvement that could be attributed to the Solarbee. The observed complete dispersion time for both tests was roughly 15 hours, whereas the theoretical complete dispersion time of the Solarbee units at the manufacturer specified rate (2 @ 10,000 gpm) was approximately 60 hours (2.5 days). Thermal stratification was minimal to none during the winter tests.

The ability of one Solarbee Mixer to destratify Sunset South was quantified during Test 3 (May 2003), as well as evaluating a potential method for achieving breakpoint chlorination—slug injection. Test 3 showed that a chlorine slug injection should not be employed when breakpointing a reservoir with Solarbee. The dense chlorine slug moved down the floor slope and deposited itself near the drain and outlet valve. It took several days to locate the slug, move the mixer, and modify the testing protocol to disperse the slug. Once moved to the slug location at the reservoir outlet, the mixer was able to completely disperse the slug in <4.9 days, validating Solarbee claims. While the slug was being located, the mixer was still on. During this time, temperature measurements showed destratification occurring at 2.8 ft/day. The decrease in stratification by Solarbee facilitated complete chlorine dispersion once the slug was located and lifted. However, completely uniform chlorine concentrations and water temperatures were never observed after 12 days of intermittent mixing, a limited duration.

Test 4 (July 2003) assessed the Solarbee mixer in a similar fashion as Test 3, but chlorine was injected continuously onto the mixer impeller at the reservoir surface. Test 4 showed the limits of the Solarbee due to a high amount of initial stratified conditions existing in the reservoir at the start of the test. The reservoir was isolated for 10 days prior to chlorine injection, with no mixing, which exacerbated stratification by ~48C before the test began. The results indicated that this increase in stratification caused compartmentalization at the reservoir surface, which in turn resulted in surface recirculation, incomplete chlorine dispersion throughout the reservoir, and the mixer flowing at less than the specified rate. The observed complete dispersion time was >7.2 days, significantly longer than the theoretical complete dispersion time of ~5 days. Completely uniform chlorine concentrations and water temperatures were never observed after 8 days of continuous mixing (a limited duration), with the outermost middle and bottom sample locations receiving little to no chlorine. The data indicates that Solarbee can be significantly restricted by the degree of initial stratification and the presence of a thermocline; with theoretical dispersion occurring only after temperature conditions become more uniform. The addition of an additional mixing unit would likely offset the limitations seen.

Conclusions

The following tables summarize the conclusions of this Solarbee Study.

Solarbee Conclusions:

- If stratification exists, Solarbee mixes at a slower pace until stratification is sufficiently minimized.
- Mixing effectiveness and destratification depends on the number of mixing units used for a particular reservoir volume; the performance and number of mixers is expected to be optimum when $Q_{Solarbee} \langle Q_{ave}$ of a reservoir.
- The performance of Solarbee during in-service conditions may be limited by successive fill cycles.
- Solarbee provides effective surface dispersion.
- Employing Solarbee prior to chlorine injection reduces stratification and subsequently promotes faster and more efficient vertical and horizontal mixing.
- Solarbee is expected to compliment mixing at reservoirs when mixing by CIP strategies is deficient (i.e. summer stratification and no vertical inlet component).
- Solarbee appears reliable, cost-effective and low maintenance.
- Setup and installation can be completed in < 1 day, without taking the reservoir out of service.
- The draft tube makes moving the unit within a reservoir somewhat difficult.
- Solarbee has a good record (other utilities were contacted).

Breakpoint Conclusions:

- Breakpoint chlorination of Sunset South in winter can be achieved by inlet momentum and chlorine injection at the inlet; mechanical mixers are not necessary.
- During summer conditions at Sunset South, supplemental mechanical mixing would be beneficial.
- Breakpoint chlorination should be conducted with metered injection, either by rapid fill or by mechanical mixing.
- Slug injection should not be conducted when breakpoint chlorinating a reservoir.
- Breakpoint chlorination with Solarbee is optimal with metered injection occurring at the impeller.
- When breakpointing a reservoir, mixers should be employed several days prior to chlorine injection to maximize destratification and subsequent dispersion.
- Test 3 indicated that with one mixer and minimal stratification, breakpoint chlorination could be achieved at Sunset South in 5 days. Adding a second mixer, as recommended by Solarbee, would likely result in breakpoint chlorination being achieved in less time (~2.5 days).
- Test 4 indicated that with one mixer and prevalent stratification, breakpoint chlorination may be more difficult to achieve. Adding a second mixer would likely offset the limitations seen.

General Mixing and CIP Conclusions:

- Inlet momentum was the dominant mixing force at Sunset South during Tests 1 and 2.
- Sunset South is naturally well mixed during winter months. CIP inlet modifications were credited for good mixing seen.
- Stratification was not seen at Sunset South in winter months.
- Sunset South should not require supplemental mixing in winter.
- Stratification exists at Sunset South in summer months, despite new CIP inlet modifications.
- A vertical inlet component should be incorporated into reservoir upgrades (CIP or In-house) where possible, to combat stratification.
- Stratification similar to what was seen at Sunset South occurs at other oversized SFPUC reservoirs in summer months.
- Earlier free chlorine decay estimates of 0.17 to 0.18 mg/L/day were similar to Test 3 decay rates.
- Previous Physical Scale Modeling (PSM) results were similar to Test 1 and 2 results.

Recommendations

WQB recommends the use of Solarbee mixers at Sunset Reservoir South Basin and other select SFPUC terminal reservoirs. These recommendations are based on the positive results seen in the study, on previous San Francisco Water Team chloramine planning reports, and on a concurrent study evaluating alternative mixing technologies. Other select reservoirs with poor circulation and are candidates for Solarbee Mixers are identified in previous SFWT chloramine planning reports, and the Spatial Sampling Study, WQB & CS&A May 2003.

WQB believes that the Solarbee mixers provide cost effective supplemental mixing and destratification for oversized SFPUC terminal drinking water reservoirs with poor mixing and/or chronic stratification. They also provide the mixing conditions to assist breakpoint chlorination if nitrification occurs.

The mixing effectiveness of Solarbee is clearly identified in this report along with cost information. Given chloramine conversion was completed in February 2004, WQB should work with CDD to decide which reservoirs would benefit most by Solarbee. The number of Solarbees prescribed for a particular sized reservoir should be carefully evaluated. Under-sizing the number of units for a severely stratified reservoir will likely cause the mixer to run less efficiently and at less than its specified rate. The following table (Table ES-1) outlines useful information for making decisions and for comparing against other mixing technologies.

Table ES-1: General Comparison Information

Cost Per Unit	$27,000 – Mixer with draft tube.
Operating Cost	220W at 2A = $256/yr at 13.3¢/kW-hr. Replace brushes every 4 months ($10/set); gear motor every 2 to 4 years ($500).
Flow Rate	14.4 mgd or 10,000 gpm (3,000 gpm direct flow and 7,000 gpm induced flow)
Cost Per MG Mixed	At 13.3¢/kW-hr and 14.4 mgd = 5¢/MG
Expected Life	• Floats – 20 years • Structure / Distribution Dish – 20 years • Gear motor – 5 years • Solar Panels – 30 years • Wiring and Electrical Components – 20 years
Staff Requirement	Installation – 2 Divers (or boat operators), 2 Crane Operators, 1 Engineer O&M – 2 Divers

1 Introduction

1.1 Background

Several studies have been completed recommending deep cycling, routine draw down, and inlet/outlet modifications to promote mixing within SFPUC terminal drinking water reservoirs. These modifications are prompted by the long detention times within the reservoirs and are intended to prevent nitrification after changing to chloramines as a secondary disinfectant.

Nitrification results from the decay of chloramine, which prompts the release of free ammonia into the water. The decay of chloramine in a reservoir often occurs in unmixed dead zones and/or in areas of high disinfectant demand. The presence of dead zones and compartmentalization increases when layers (strata) of different temperatures exist in the water column. This layer cake effect is termed "stratification." Stratification is usually more prevalent in summer, when ambient temperatures are higher than source water temperatures.

Once free ammonia is released into the water, ammonia-oxidizing bacteria (AOB) "nitrifies" the free ammonia to nitrate, which causes other bacteria to grow, further residual loss, and so on. This process fuels a divergent cycle of further nitrification until the storage facility has difficulty maintaining residual and shows elevated levels of bacteria. If nitrification cannot be avoided, the reservoir must be taken out of service and/or breakpoint chlorinated.

Breakpoint chlorination is the process of adding sufficient free chlorine to oxidize all nitrogen species to gas, and killing all bacteria. The process requires the uniform dispersion of a defined concentration of free chlorine throughout the entire isolated reservoir. Reservoir mixing improvements are therefore necessary to 1.) Prevent nitrification from occurring in the first place, and 2.) Aid in completely mixing free chlorine if breakpoint chlorination is required.

While some reservoirs can incorporate or are scheduled for inlet/outlet modifications, other reservoirs may have limitations and the installation of mechanical equipment is more appropriate. For some reservoirs, recent inlet/outlet modifications may not be sufficient for mixing a reservoir, in which case supplemental mechanical mixing may be necessary. To this end, the SFPUC's Water Quality Bureau (WQB) and City Distribution Division (CDD) investigated the use of the Solarbee SB10000F hydraulic mixer. This high flow (10,000 gpm), low energy mixer is designed to improve reservoir mixing and to eliminate or decrease stratification.

Two Solarbee SB10000F units were delivered to Sunset Reservoir in August 2002 for a free-of-charge trial. Two back-to-back studies were completed with the Sunset Reservoir South Basin isolated from service – one with the mixer on (Test 1, November 19, 2002), and one with the mixer off (Baseline Test 2, December 16, 2002). Two additional studies were completed with different chlorine injection methods – one using a chlorine slug

(Test 3, April 29, 2003) and one using continuous injection (Test 4, July 21, 2003). The results of the four investigations are presented in this report.

1.2 The Need for Additional Mixing Devices

The San Francisco Water Team, overseen by Utilities Engineering Bureau (UEB) Project Management, detailed SFPUC City reservoirs which have a high potential for nitrification following conversion to chloramines in February 2004[1]. These reservoirs are candidates for installing hydraulic mixers such as the Solarbee SB10000F.

Various operational strategies and construction improvements were identified for some of these reservoirs to reduce water age and increase mixing. Installing hydraulic mixers was recommended as one strategy to reduce the maximum water age (T_{max})[2] by encouraging mixing, thereby deterring nitrification.

The Solarbee tests had two main goals: to evaluate the mixer's ability to mix a reservoir and decrease T_{max} and dead zones; and to determine its ability to assist with breakpoint chlorination for nitrification response.

> "Install permanent internal mixing equipment to select reservoirs if other SFPUC projects to improve reservoir hydraulics are scheduled for after the chloramine conversion. The select reservoirs include those that currently experience long detention time and/or high water ages (e.g., University Mound North)."
>
> -Recommendations from Chloramines CDR, 1999 SFWT

[1] Chloramines Conceptual Design Report (SFWT, 1999) and Operational and Mixing Strategies to Maintain Water Quality in CDD Reservoirs (SFWT, 2002)

[2] T_{max} is defined in this paper to mean the time required for an entire volume of water entering a reservoir to exit the reservoir.

2 Test Equipment, Site Location, and Installation

2.1 Test Equipment

SFPUC staff identified the Solarbee SB10000F Hydraulic Mixer during the AWWA Annual Conference in July 2002. It is a high flow, low energy, mechanical mixer with a rotating impeller that lifts water through a 3' diameter flexible draft tube and disperses[3] water in a laminar[4] fashion across the surface of the water (see Figure 1). The impeller rotates near the water surface and can be powered by solar energy, or hardwiring for enclosed reservoirs. The mixer's small gearbox is filled with food-grade NSF-61 approved oil for potable water applications.

The Solarbee SB10000F is specified at a total flow rate of 10,000 gpm (14.4 mgd) at 10' diameter[5]. Of the total flow rate of 10,000 gpm, 3,000 gpm is *direct flow* taken from the bottom through the draft tube, and 7,000 gpm is *induced flow* that is entrained around the exterior of the draft tube and the surrounding water column (see Appendix A). More information can be found at: http://www.solarbee.com/bulletin.shtml.

The above information is based on Solarbee claims and does not necessarily represent SFPUC findings. Typical Solarbee applications include aeration of open oxidation ponds, sludge lagoons, and raw water reservoirs, with limited applications in enclosed potable reservoirs. Therefore, some of the claims and experience of Solarbee must be further verified for potable water applications.

Marketing representatives discussed and ultimately agreed to loan a demo unit to the SFPUC in August 2002. The mixer was of interest to the SFPUC because of its claims of low energy usage and low maintenance requirements.

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[3] The term 'dispersion' is used generically throughout this report to mean the spatial property of being scattered about over an area or volume. The study assumes that molecular and thermal diffusion, though present, is negligible compared to the dispersion caused by Solarbee mixing energy and/or by inlet momentum.

[4] The term 'laminar' is used by Solarbee and throughout this report to mean 'non-turbulent' or 'low-energy'. It is unclear if the water movement by Solarbee is actually laminar, as defined in fluid mechanics as flow with parallel streamlines and a Reynold's Number < 2000.

[5] The reader should note that the units were hardwired during the tests and the rates may be less if only solar power is used (~8,125 gpm or 11.7 mgd). The diameters specified here are the theoretical external mixing diameters where the induced flow rates are believed to occur (see Appendix A).

Figure 1: Elevated View of Solarbee Mixer with Draft Tube

Specifications of the SB10000F include:

- Total Flow at 10' diameter: 10,000 gallons per minute (14.4 mgd) = 3,000 gpm direct flow and 7,000 gpm induced flow
- Inlet Hose Diameter: 36"
- Intake Depth Range: 3.5' to 100'
- Machine Diameter: 16'
- Machine Weight: 600lbs
- Construction Material: Stainless Steel
- Drive Train: Brush-style DC Motor[6]
- Power Source: Solar or 110VAC
- Warranty: 2 years, parts and labor

Additional manufacturer's literature and equipment diagrams are located in Appendix A of this report.

2.2 Test Site

Planning for the Solarbee Mixer evaluation included the selection of a SFPUC reservoir to accommodate testing. Sunset South Reservoir, the largest of the ten city reservoirs, was selected because its size and features could accommodate installation and monitoring. While this basin was not identified as having a high potential for nitrification, there was a consensus that if the mixer was effective at the largest SFPUC reservoir, it would likely

[6] Solarbee now offers a brushless version of the SB10000.

prove to be effective at many of the other comparable or smaller sized SFPUC reservoirs with similar aspect ratios (relative dimensions).

Sunset Reservoir recently received chlorine station upgrades and local water project improvements that included inlet chlorine injection capabilities, a boat access hatch for installing the mixers, and monitoring ports on the reservoir roof. These features facilitated the use of Sunset South for this study. Also, Sunset was extensively modeled to characterize mixing in previous studies.

Several temperature studies of Sunset South conducted by Charlotte Smith & Associates[7] and SFPUC WQB, indicated that stratification periodically exists in the reservoir under certain conditions, despite the presence of the new inlet designed to increase mixing and prevent stratification. WQB was interested in testing Solarbee's ability to eliminate or decrease stratification in Sunset South (Stratification is explained in Section 3.1.6, and Figure 4 provides an example of stratification existing in Sunset South).

Upon selection of the reservoir, recommendations were given by Solarbee representatives for selecting the placement and number of mixers. The representatives decided that two mixers were warranted due to the size of the reservoir. They recommended placement of the mixers in the center of two identical halves, if the reservoir were divided equally (See Figure 2; Appendix B includes more detailed schematics of Sunset South). PVC legs were installed on the draft tube bottom to minimize entrainment of sediment and debris, and resulting turbidity.

Considerations for Selecting Sunset South as the Solarbee Test Site:

- Largest SFPUC Reservoir, 87.4 MG
- Previously characterized reservoir mixing
- Sample ports exist to accommodate monitoring
- Upgraded chlorine station and injection facilities
- Access hatch sufficient size for preassembled mixer installation
- Local CIP improvements completed in 2000
- Ability to collect field measurements to evaluate efficacy of local CIP improvements
- Previously documented existence of stratification existing in the reservoir.

Manufacturer's Response to Selected Test Site

- Recommended installation of two units
- Recommended placement
- Provided theoretical mixing time

[7] Spatial Sampling Study (Charlotte Smith & Associates, 2003)

The Principle specifications for Sunset Reservoir South Basin include:

- Construction Date: 1960, Concrete; rectangular with partially sloped sides
- High Water Elevation: 385'
- Depth of Water at Spill: 30'
- Area: 11.5 Acres; approximately 500-ft by 1000-ft
- Capacity: 87.3 MG
- Supply Source 1) Sunset Supply Line (SSL) via Lake Merced PS (East Bay Blend)
- Supply Source 2) San Andreas Pipeline 2 (SA2) via Harry Tracy Water Treatment Plant (Peninsula Watershed)
- Typical Supply Flows[8]: 15 MGD Total
- [SSL: 13.5 MGD; SA2: 6.7 MGD; Sutro Pumps: –5.2 MGD]
- 42-inch inlet located at reservoir floor

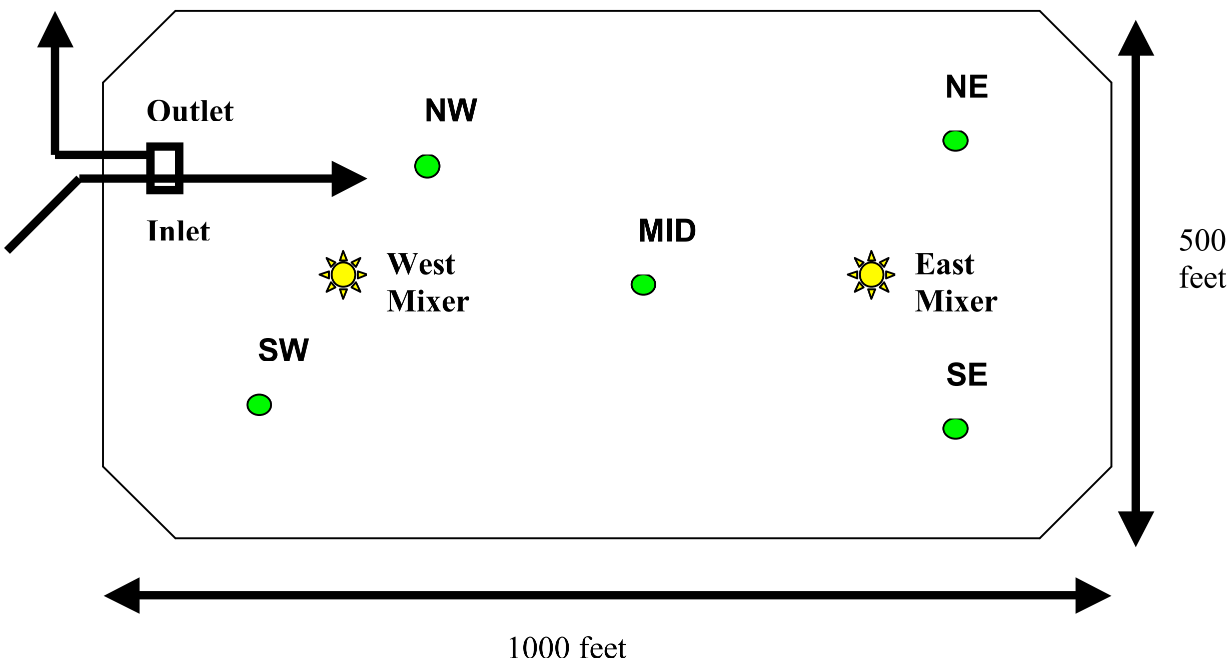

Figure 2: Diagram of Sunset Reservoir South with Sample Station Locations and Recommended Placement of Mixers by Solarbee.

2.3 Site Conditions

Several studies have been completed to evaluate mixing within SFPUC terminal distribution reservoirs. These studies helped identify mixing limitations and provided basis for design improvements:

[8] Sunset Reservoir North Physical Model Studies Project Report (Hydroconsult Engineers, 2001)

- Chloramine Conceptual Design Report (CDR) by San Francisco Water Team (SFWT), 1999
- Hydraulic (CFD) Analysis by Flow Science, 2000
- Physical Scale Modeling (PSM) by Hydroconsult, 2001
- Mixing Report by CDM, 2002
- Spatial Sampling Report by Charlotte Smith & Associates (CS&A), 2003

These studies provided estimates of average detention time (T_{avg}), 95% detention time (T_{95}), and the time required to reach completely mixed conditions. T_{avg} is the average residence time in a reservoir, often equal to the volume divided by the average flow rate (V/Q), or the time for 50% of a volume of water entering a reservoir to exit the reservoir. T_{95} is the time required for 95% of a water volume entering a reservoir to exit the reservoir. Completely mixed conditions are reached when a new water volume entering a reservoir is equally distributed throughout the entire reservoir volume (measured or estimated using tracer concentrations). These parameters are summarized in Table 1.

Table 1: Previous Study Findings for Sunset Reservoir South Basin

	CDR (1999)	**PSM (2001)**	**Mixing Report CFD (2002)[1]**	**Spatial Sampling (2003)**
$T_{average}$	12 days	N/A	12 days	N/A
T_{95}	60 days	N/A	16 days	N/A
Estimated Completely Mixed Time	N/A	0.6 days (15 hrs)	1.5 days (36 hrs)	3 days (72 hrs)
Assumptions and Conditions	Assumptions were: T_{ave} = V/Q; T_{95} = T_{ave} x 5, where 5 = “significant dead zone” factor	Conditions were: 15 MGD transient flow with 41” inlet and 1.3’ to 2.5’ below spill operating level.	Conditions were: 7.3 MGD steady-state flow with 36” inlet and a level of 1.3’ above spill.	Conditions were: 15 MGD supply flow (no outflow) filled from 6’ to 3’ below spill and isolated.

[1] The Mixing Report by CDM cited results from Flow Science CFD modeling (Flowscience, 2000) report for Sunset South

2.4 Mixer Installation and Setup

Solarbee representatives met CDD and WQB staff at Sunset Reservoir South on Thursday August 1, 2002 at 9 am. All parties worked together to assemble, disinfect, and install the two Solarbee mixers. More complete setup information and photographs are located in Appendix C.

2.4.1 Assembly

The two mixers were assembled onsite by Solarbee staff. The total assembly time (for 2 units) was approximately 2 hours. Three 1 ft PVC pipe segments were attached to the bottom of each draft tube on the strainer plate in order to elevate the intake off the floor and minimize the entrainment of sediments.

2.4.2 Disinfection

SFPUC divers proceeded to disinfect all mixer surfaces prior to placing the mixers into the reservoir. The divers sprayed all surfaces down, including the inside of the draft tube, with 2% sodium hypochlorite solution. The total disinfection time for both mixers required roughly 40 minutes.

2.4.3 Installation

A crane was parked adjacent to the reservoir and was used to lower the units into the reservoir through a large rolling hatch (~15' x 11' access hatch on reservoir roof with wheels originally designed for boats). SFPUC crane operators, Solarbee staff, and SFPUC divers worked together to direct and lower the mixers. The mixers were pulled by boat to their planned locations and fastened to the surrounding columns using steel cables. The entire installation time was approximately 2.5 hours.

The entire process (assembly, disinfection, installation, and testing) required approximately 7 hours for both mixers. The approximate number of staff required was as follows:

- 2 Crane Operators—1 controlling, 1 directing
- 2 Divers or Boat Operators—disinfection, safety, piloting, knowledge of reservoir
- 2 Assemblymen—assemble/test mixers, help divers secure units inside reservoir (Solarbee representatives)
- 1 Engineer—coordinate all of above, decide locations of mixers

3 Test Protocol and Evaluation Criteria

3.1 Test Protocol

3.1.1 Study Plan

In August 2002, Charlotte Smith & Associates (CS&A) and WQB submitted a planning document to CDD entitled "Plan for the Evaluation of the Mixing Behavior of Sunset South Reservoir." This plan outlined the preliminary study protocol and initiated coordination between WQB, CDD, and Buildings and Grounds (B&G), as well as detailing material and supply orders for the study. The test plan became more detailed as each test date was approached (see Appendix C for plans).

3.1.2 Test Goals

The goals of the four tests are outlined below:

- **Test 1, Continuous Chlorine Feed at Inlet – Mixers On**
  The goal of this test was to evaluate Solarbee's mixing effectiveness utilizing two mixers and inlet momentum during and after a fill.

- **Test 2, Continuous Chlorine Feed at Inlet – Mixers Off (Baseline)**
  The goal of this test was to evaluate reservoir mixing utilizing inlet momentum only with the mixers off, during and after a fill – baseline test for Test 1.

- **Test 3, Chlorine Slug – One Mixer**
  The goal of this test was to evaluate reservoir mixing using a one-time slug-dose of chlorine with one mixer and no inlet momentum – reservoir isolated, no fill.

- **Test 4, Continuous Chlorine Feed at Mixer – One Mixer**
  The goal of this test was to evaluate reservoir mixing using a continuous chlorine feed with one mixer and no inlet momentum – reservoir isolated, no fill.

3.1.3 Study Parameters

The non-conservative tracer, sodium hypochlorite (chlorine), was selected for this study. Other potable water compatible tracers considered were fluoride and sodium. Fluoride, which is already added to SFPUC water, could not be sufficiently increased or decreased to produce a marked change that could be measured. The amount of sodium required to produce a measurable quantity of tracer in Sunset South was too large due to the large volume of water in the reservoir. Chlorine was inexpensive and readily accessible onsite.

Also, the bulk water chlorine decay rate of Sunset South was well documented and understood from earlier studies[9].
Chlorine was injected into the inlet for Tests 1 and 2 and into the middle (MID) sample port for Tests 3 and 4 (See Figure 2). Temperature data was gathered at varying depths and locations during each test (outlined in Section 3.1.6). Chlorine concentrations were measured at each of the five sampling ports. Turbidity measurements were taken sporadically to ensure mixers were not stirring up sediment from the reservoir floor.

The study parameters were different for each of the four tests conducted. Table 2 summarizes the parameters of each test.

Table 2: Study Parameters for Each Mixer Test

Test	**Tracer Injection**	**Temperature Monitoring**	**Chlorine Measurement**	**Reservoir Conditions**	**Solarbee Condition**
1 Continuous Feed at Inlet Two Mixers On	810 gallons into inlet	NW, SE, and SW sample ports	All sample ports; SW using older pump and measured by hand.	Outlet closed prior to fill and inlet closed after fill cycle.	On at start of test.
2 Continuous Feed at Inlet Mixers Off (Baseline)	810 gallons into inlet	NW, SE, and SW sample ports	All sample ports; SW using older pump and measured by hand.	Outlet closed prior to fill and inlet closed after fill cycle.	Off
3 Slug Test – One Mixer	1000 gallons into MID sample port	NW, SE, and SW sample ports	Varied between start and finish of test. See Test 3 Discussion.	Completely isolated 15 days prior to chlorine slug lift.	On for 6 days prior to chlorine slug lift.
4 Continuous Feed at Mixer – One Mixer	1000 gallons into MID sample port	SW and MID sample ports	All sample ports; used Kemmerer for SE port.	Completely isolated 10 days prior to start.	On at start of test.

3.1.4 Chlorine Monitoring

Security cabinets were installed with pumps, chlorine analyzers, and data loggers, and placed at the five existing roof ports (Northwest=NW, Southwest=SW, Middle=MID, Northeast=NE, and Southeast=SE; see Figure 2). Three lengths of flexible sample tubing were individually valved and manifolded to the pump intake (Figure 3). These three lengths allowed samples to be taken from the top, middle, and bottom of each water column. A PVC sample pipe was installed inside the reservoir inlet for chlorine dosage confirmation measurements during Tests 1 and 2. Foot valves were placed on all sample-

[9] Charlotte Smith & Associates estimated bulk water decay to be 0.17 to 0.18 mg/L/day for Sunset South in the May 2003 "Spatial Sampling Report."

tubing ends[10]. The chlorine analyzer used for the study was the Dulcometer® Controller D1C series. Information sheets for sampling equipment used are provided in Appendix D.

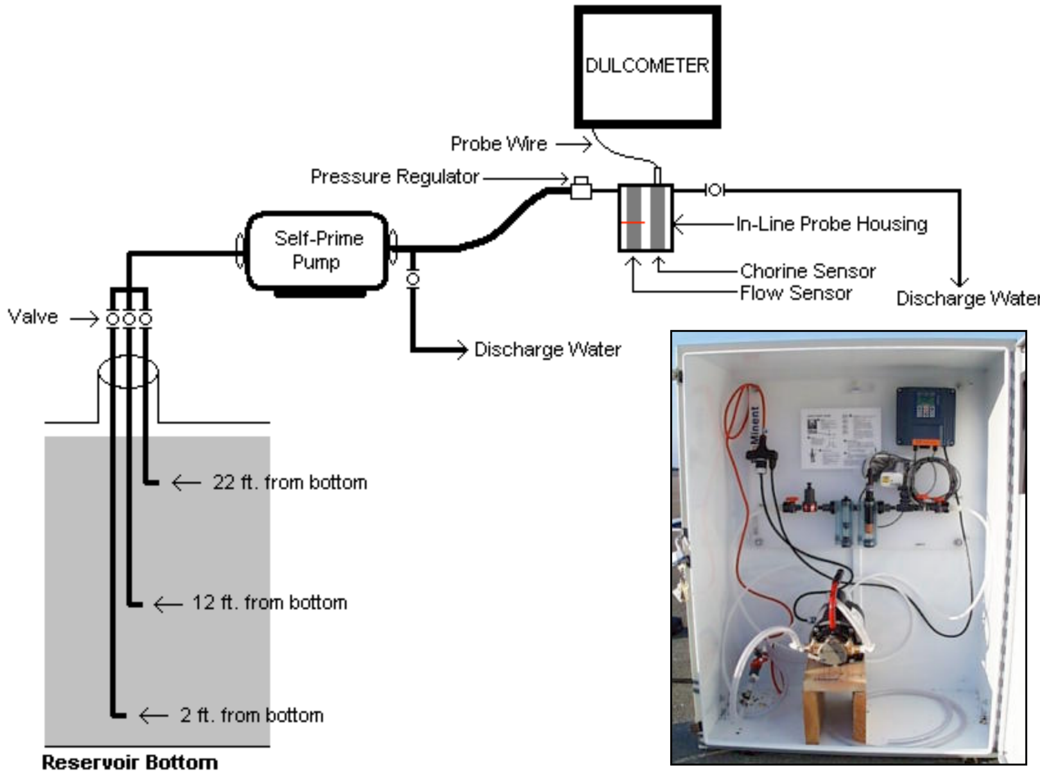

Figure 3: Example of Monitoring Station and Pump Setup Located on Reservoir Roof

3.1.5 Sampling Stations and Data Recording

Data recording was conducted both manually and automatically. Manual recording consisted of reading the chlorine concentrations from the Dulcometer® and writing them down on data sheets. Automatic recording consisted of recording chlorine concentrations from the Dulcometer onto a data logger.

Sampling rounds consisted of 15 measurements (5 locations, 3 depths) taken approximately every hour. All sample lines were flushed thoroughly before each test began. WQB staff waited a minimum of 2 minutes for a sample line to flush and stabilize before recording a measurement from the Dulcometer screen. After recording a chlorine residual at a specific site for a specific depth, the valves were adjusted to the next depth (Top→Middle, Middle→Bottom, Bottom→Top) before the technician moved to the next site. In this way, the newly adjusted sample stream would have ample time to flush and stabilize before the technician returned to take its measurement.

[10] A foot valve allows water to flow only in one direction, and when placed at the tubing's intake, keeps water from flowing out of the tubing when the monitoring station is not in use. This keeps the pump primed and prevents water from back flowing into the reservoir.

The Dulcometers were initially calibrated with water quality standards made up in the laboratory, and then validated by HACH DR-890s every 4 hours. HACH DR-890s were validated daily using HACH® Gelex™ standards. If a certain Dulcometer was found to have error (+/- 0.2 ppm), duplicate samples were taken. If the duplicates indicated the same error, parallel samples were taken with a different HACH DR-890. If the error still persisted, the Dulcometers were recalibrated from a validated DR-890.

3.1.6 Temperature Monitoring

Temperature monitoring probes (thermistors) were placed at various port locations, depending on the goals of each test, to monitor stratification and to measure destratification rates. Stratification is a layering of different temperature water in the water column, usually with colder water at the bottom and warmer water near the reservoir surface. Stratification can cause compartmentalization and high water age, conditions that promote nitrification. Destratification rates can be estimated by measuring the depth of destratification over time.

Previous temperature studies of Sunset South conducted by Charlotte Smith & Associates[11] and SFPUC WQB indicated that stratification periodically exists in the reservoir under certain conditions, despite the presence of a new inlet designed to increase mixing and prevent stratification. WQB was interested in testing Solarbee's ability to decrease or eliminate stratification in Sunset South. Figure 4 provides an example of in-service stratification existing in Sunset South in mid-September and then returning to mixed conditions in late-September to early-October (with no mixing).

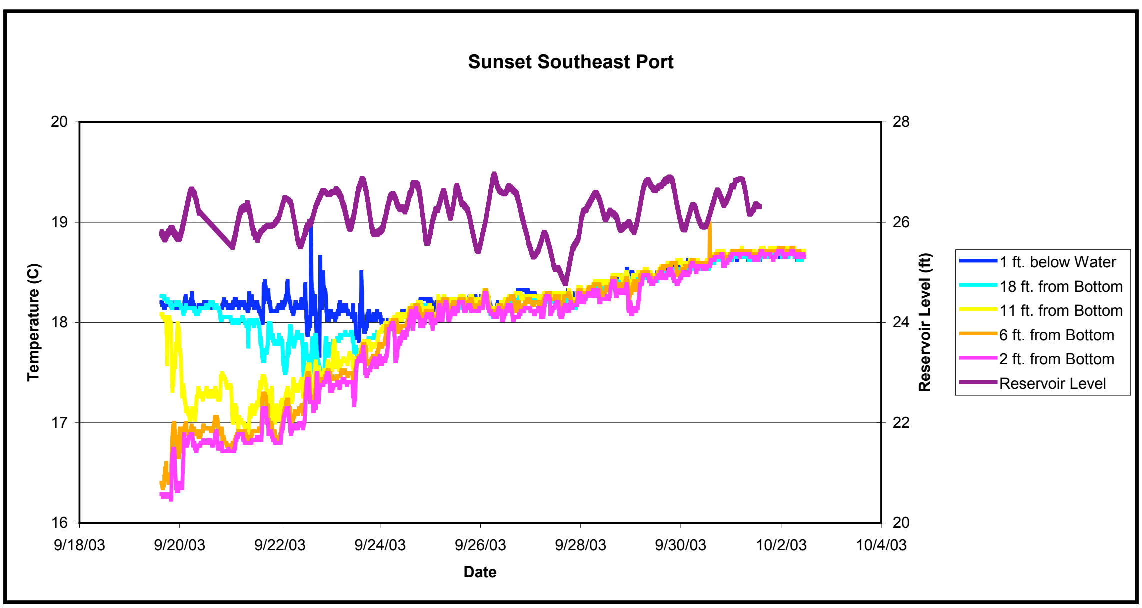

Figure 4: Example of In-Service Stratified Conditions Returning to Mixed Conditions between Summer and Fall—No Mixers.

[11] Spatial Sampling Report (Charlotte Smith & Associates, 2003)

For this study, stratification was considered present when a temperature difference (ΔT) >0.2°C existed between overlying temperatures and underlying temperatures (Charlotte Smith, personal communications, 2002), or when water temperatures were seen layered directionally through the water column like a layer cake (temp. vs. time graph shows parallel lines that do not intersect). Stratification was considered not present if overlying and underlying temperatures were roughly the same (<0.2°C), and when temperatures at different levels 'flip-flopped' and 'criss-crossed' or did not consistently increase or decrease directionally through the water column (temp. vs. time graph shows intersecting lines).

Thermistors collected temperature data from up to seven vertical locations at each sample port. The thermistor sets consisted of two static probes and one floater probe for Tests 1 and 2, and five static probes and two floater probes for Tests 3 and 4 (see example in Figure 5; actual thermistor placement for each test is located in Appendix C). The floater probes were able to fluctuate with reservoir levels so that water temperatures at 1-ft and 2-ft below the surface were continuously measured. The thermistors recorded temperature data before, during, and after each test, to measure any temperature changes during each test.

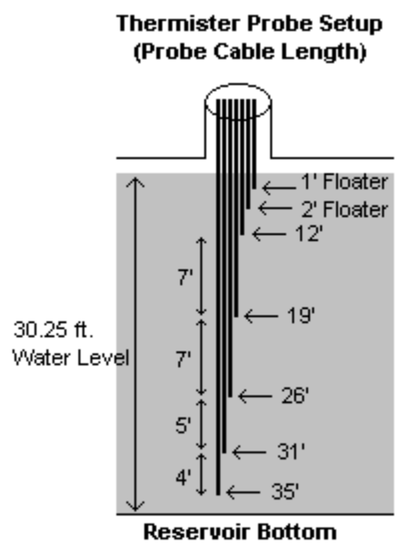

Figure 5: Example of Thermistor Setup

3.1.7 Hydraulic Conditions

Meetings were held with operations staff prior to each Solarbee test to define the hydraulic conditions for each study plan. As of November 2002, the California Department of Safety of Dams (DSOD) imposed a requirement that the water level at Sunset Reservoir stay below 3 ft of spill (spill is 30.25 ft above floor). Therefore, normal operating levels fluctuated between 3 ft and 6 ft below spill during the study.

For Tests 1 and 2, the plan was to draw down the reservoir to approximately 6-ft below spill, isolate the outlet, and rapidly fill the reservoir to approximately 3-ft below spill, simultaneously injecting chlorine into the inlet, and powering two Solarbee units (located in the center of two identical halves, if the reservoir were divided equally; See Figure 2 and Appendix B) during and after the injection and fill. For Tests 3 and 4, the plan was to completely isolate the reservoir, wait for inflow energies to dissipate, inject chlorine at the MID sample port (slug-inject for Test 3 and meter-inject for Test 4), and then power one mixer (also located at the MID sample port; See Figure 2 and Appendix B) to disperse the chlorine.

The actual hydraulic conditions for each test were similar to what was planned, but some differences occurred. The actual hydraulic conditions for each test are summarized in Table 3 of the Results and Discussion section (see Appendix E for more complete comparisons).

3.2 Evaluation Criteria and Terms

Several terms were defined by the project team to quantify the mixing rates in the reservoir as measured by the spread of chlorine. These terms are not commonly used, standardized terms and were defined specifically for this study by the project team.

3.2.1 Arrival Time

Arrival time is used as a measure of how quickly a tracer travels to a specific location in the reservoir and is defined as the time from when the chlorine is first added to when the chlorine measurements are greater than 0.2 ppm (on top of background concentrations) at a particular sampling location. The longest of all 'arrival times' determines the 'observed complete dispersion time' but is not to be confused with the 'uniform mixing time' (terms defined in next section).

3.2.2 Dispersion[12] Rates and Velocities

Three dispersion rate terms were compared and contrasted in order to evaluate the Solarbee's mixing effectiveness:

- Theoretical Dispersion Rate – The manufacturer claimed rate at which water (and tracer) is circulated or dispersed by the Solarbee mixer. This rate is equal to the manufacturer specified theoretical flow rate of the mixer (14.4 mgd or 10,000 gpm). This rate is used to calculate the 'theoretical complete dispersion time' (presented in

[12] The term 'dispersion' is used generically throughout this report to mean the spatial property of being scattered about over an area or volume. The study assumes that molecular and thermal diffusion, though present, is negligible compared to the dispersion caused by Solarbee mixing energy and/or by inlet momentum.

the next section) and is a measure of how fast chlorine is expected to move throughout the reservoir based on manufacturer claims.

- Observed Dispersion Rate – A rate based on the observed last arrival time, or 'observed complete dispersion time' (explained in the next section). It is assumed that the last arrival time is also the time when tracer is completely dispersed, or when all areas have a consistent chlorine concentration greater than or equal to 0.2 mg/L. This rate is calculated by dividing the reservoir volume by the last arrival time and is a general indication of how fast chlorine was dispersed throughout the reservoir.

- Surface Dispersion Rate – The average rate at which tracer >0.2 mg/L arrives at all surface samples, calculated by dividing each distance by its corresponding time of arrival.

The terms dispersion rate and flow rate are both used in this report. Dispersion rate is a measure of how fast water with tracer is volumetrically distributed throughout the reservoir, whereas the manufacturer specified flow rate (14.4 mgd; 10,000 gpm) is the rate at which water is expected to actually move through the Solarbee mixer. The dispersion rate can be less than or equal to a mixer's flow rate. If the dispersion rate is less than the specified flow rate, water with tracer is recirculating through the mixer, or the mixer is flowing at a lower rate than specified. If the dispersion rate is equal to the specified flow rate, then the mixer is performing as specified.

Dispersion rates related to Solarbee mixing energies could not be calculated for Tests 1 and 2 because the inlet momentum during Test 1 confounded the dispersion by the mixers, and the mixers were not employed during Test 2.

3.2.3 Complete Dispersion Times

Two terms for complete dispersion times were used to evaluate the mixing effectiveness of the Solarbee mixers (these terms are related to the terms presented in the previous section):

- Theoretical Complete Dispersion Time – The theoretical time for the entire reservoir to be completely mixed (or tracer completely dispersed), calculated by dividing the reservoir volume by the 'theoretical dispersion rate' specified by Solarbee (14.4 mgd or 10,000 gpm). This term represents the time for tracer to be completely dispersed if the dispersion rate equals the mixer's theoretical flow rate.

- Observed Complete Dispersion Time – The actual time of complete tracer dispersion, as witnessed during each study. The observed complete dispersion time is equal to the last arrival time, and when chlorine is consistently greater than or equal to 0.2 mg/L throughout the entire reservoir. This term **is not** a measure of tracer uniformity. For this study, tracer can be completely dispersed and still not be uniform.

The ‘theoretical complete dispersion time’ and the ‘observed complete dispersion time’ for each test are often compared in this report as a measure of the Solarbee’s overall performance. If the observed complete dispersion time is greater than the theoretical complete dispersion time, then it is concluded that the mixer(s) performed better than anticipated, or other factors such as inlet momentum or molecular diffusion are occurring. If the observed time is less than the theoretical time, then the mixer(s) performed worse than expected. If the observed time equals the theoretical time, then the mixer(s) performed as specified by the manufacturer. Theoretical and observed complete dispersion times are compared for all tests in the study.

3.2.4 Uniform Mixing Time

Uniform mixing time is the time it takes for the maximum and minimum chlorine concentration difference, or ΔC, of a particular monitoring set to consistently fall within a specific tolerance. Originally, a tolerance of 0.2 ppm was chosen, but this fell within the error range of the Dulcometer instrument used. Therefore, a tolerance of 0.4 ppm was chosen by the project team to be a more accurate measure of uniform mixing time, and a more realistic goal for future breakpoint chlorination.

This measurement was helpful in quantifying the mixer’s ability to uniformly distribute chlorine throughout the reservoir, which would be necessary for breakpoint chlorination. The ‘uniform mixing time’ is not equivalent to the ‘observed complete dispersion time’. Tracer can be completely dispersed and not be uniform. The uniform mixing time is equal to or greater than the observed complete dispersion time.

4 Results and Discussion

The results of Tests 1 and 2 are presented and discussed in a separate section than the results for Tests 3 and 4. Results criteria for each test include arrival time, uniform mixing time, and temperature monitoring. These criteria are discussed in each section as well as several other comparative observations of each test. A summary of all test conditions, including hydraulic conditions, is presented below in Table 3.

4.1 Test Proceedings – Tests 1 and 2

Initially two tests were planned to quantify the mixing effectiveness of the Solarbee mixers—*Baseline* (no mixers) and *Mixer On* (with mixers). Both tests would incorporate a continuous feed of chlorine into the inlet during a typical fill. The *Mixer On* test (Test 1) was conducted first in September 2002, and the *Baseline* test (Test 2) was conducted second in December 2002. Both tests were designed to run under identical conditions, though slight differences were present. These differences were minimal and the results of both tests are directly comparable. The differences between the two tests are outlined in the below sections followed by the test results.

4.1.1 Hydraulic Differences

Operations for the two tests were controlled to provide similar hydraulic test conditions. The beginning and ending reservoir levels differed slightly between the two tests (~7 inches), and the water volume pumped into the reservoir during both tests was roughly the same (~2.8% difference).

The inflow rates differed significantly between the two tests, both fluctuating sporadically though achieving the same fill goal: supplying ~10 MG in roughly 16 hours (see Figure 6). These rates were difficult to control and were largely dependent upon pump station operations, treatment plant flows, and system demands. The fluctuating rates may have caused some minor hydraulic and mixing differences between the two tests. Both tests showed similar average inflow rates of approximately 15 mgd (See Figure 6 and Appendix E).

Table 3: Conditions Summary of All Tests

	Test 1	Test 2	Test 3	Test 4
Description	Continuous Feed at Inlet 2 Mixers On	Continuous Feed at Inlet Mixers Off (Baseline)	Slug Test using One Mixer	Continuous Feed at One Mixer
Level Start	6.2-ft below spill (24.1-ft above floor)	6.9-ft below spill (23.4-ft above floor)	4.8-ft below spill (25.5-ft above floor)	5.2-ft below spill (25.1-ft above floor)
Level End	3.4-ft below spill (26.9-ft above floor)	3.9-ft below spill (26.4-ft above floor)	Same as start 4.8-ft below spill (25.5-ft above floor)	Same as start 5.2-ft below spill (25.1-ft above floor)
Fill Volume	9.8 mg	10.1 mg	No Fill	No Fill
Fill Duration	16.3 hours	16.6 hours	No Fill	No Fill
Fill Rate	15.0 mgd	15.4 mgd	No Fill	No Fill
Test Volume	75.2 mg	73.1 mg	70.1 mg	68.7 mg
Theoretical Complete Dispersion Time[1]	2.6 days	2.5 days[2]	4.9 days	4.8 days
Test Start[3]	11-19-02, 10:40	12-16-02, 10:00	05-08-03, 13:30	07-21-03, 09:00
Test End	11-23-02, 12:20	12-20-02, 15:10	05-14-03, 10:05	07-29-03, 09:20
Test Duration[4]	98 hours	101 hours	141 hours	192 hours
Injection Duration	15.4 hours	15.8 hours	1.3 hours[5]	7.0 hours
Isolation Duration	81 hours	85 hours	504 hours[6]	433 hours[6]
Mixing Duration[7]	2 @ 96 hours	No Mixers	1 @ 282 intermittent hours during test[8]	1 @ 192 continuous hours during test
Degree of Stratification at Start	$\Delta C = 0.0$ °C	$\Delta C = 0.0$ °C	$\Delta C = 1.3$ °C	$\Delta C = 3.9$ °C

[1] At Solarbee specified 14.4 mgd or 10,000 gpm per mixer unit
[2] Mixers were off for Test 2, represents theoretical complete dispersion time if mixers were on for comparison purposes.
[3] Tests 1 and 2 began right after isolation with simultaneous fill, injection, and mixers turned on. Tests 3 and 4 began when chlorine was injected or lifted, many days after isolation.
[4] Refers to duration between chlorine injection, or chlorine lift, and reservoir isolation at the test end.
[5] Refers to slug injection time at MID sample port, not chlorine lift time at reservoir outlet.
[6] Isolation occurred prior to test start.
[7] The number of Solarbee mixers running and duration.
[8] This number refers to the total time the Solarbees were employed. The mixers were periodically turned on and off throughout Test 3. This is detailed in Section 4.3.1.

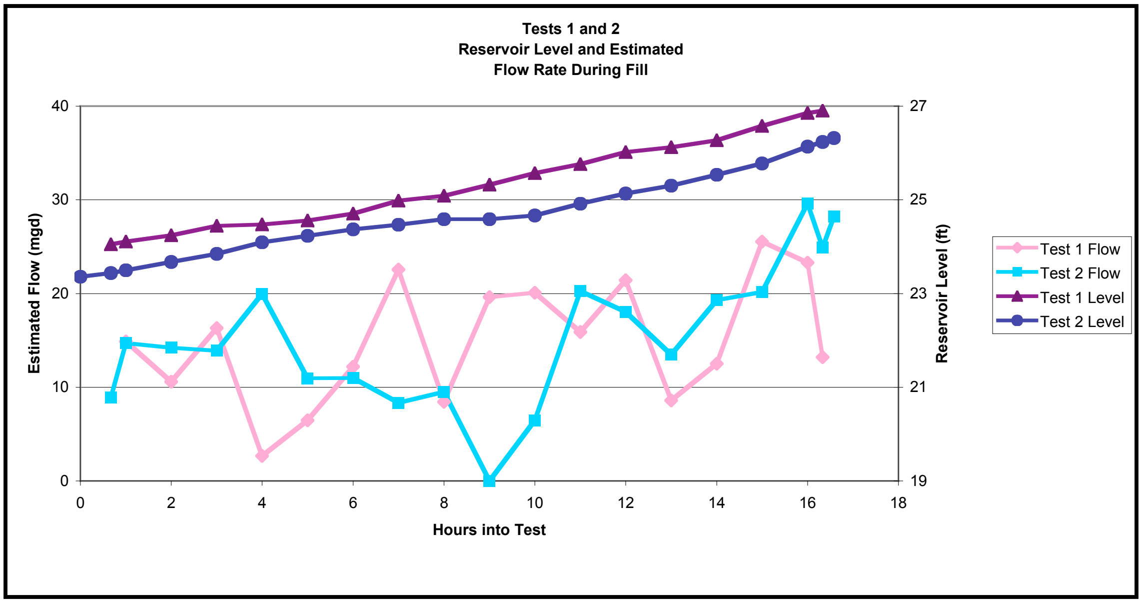

Figure 6: Graph of Reservoir Levels and Estimated Flow Rates for Tests 1 and 2[13]

4.1.2 Chlorine Injection Differences

The chlorine injection rates were controlled to provide similar conditions for both tests. This was accomplished by adjusting injection rates, depending on the inflow rate, to achieve 9-10 ppm dosage at all times in the inlet stream. About 810 gallons[14] of chlorine was injected into the reservoir, over a 15 to 16 hour period, to provide a total theoretical chlorine concentration[15] (equal to the total mass of chlorine injected divided by the reservoir volume) of 1.7 mg/L if the reservoir was completely mixed. When the chlorine injection volumes were graphed they were remarkably similar (see Figure 7).

4.1.3 Chlorine Concentration Differences

The chlorine injection rates and volumes for both tests were controlled purposely to provide roughly the same chlorine concentration once the reservoir was completely mixed. Though the theoretical chlorine concentrations for Tests 1 and 2 were the same (1.7 mg/L), the overall average observed concentrations within the reservoir were quite

[13] Flows estimated from reservoir levels and dimensions—includes both Sunset Supply and San Andreas flows.
[14] Originally planned to inject 1,000 gallons. Injections were halted after 1,000 gallons were displaced in the chlorine tanks. However, it was later determined that roughly 190 gallons was metered to the Sunset System from Sunset North Reservoir.
[15] The theoretical chlorine concentration is calculated by dividing the mass of injected chlorine by the reservoir volume.

different: 0.9 and 1.4 mg/L, respectively[16]. This may have been due to an initial reservoir chlorine demand (sediment, sidewalls, etc.) being satisfied during Test 1, and the same demand not being present during Test 2. Also, Test 1 had a lower background concentration (0.04 mg/L, below detection level) than what was provided for Test 2 a month later (0.20 mg/L). Background concentrations were taken into account when determining arrival times and uniform mixing times.

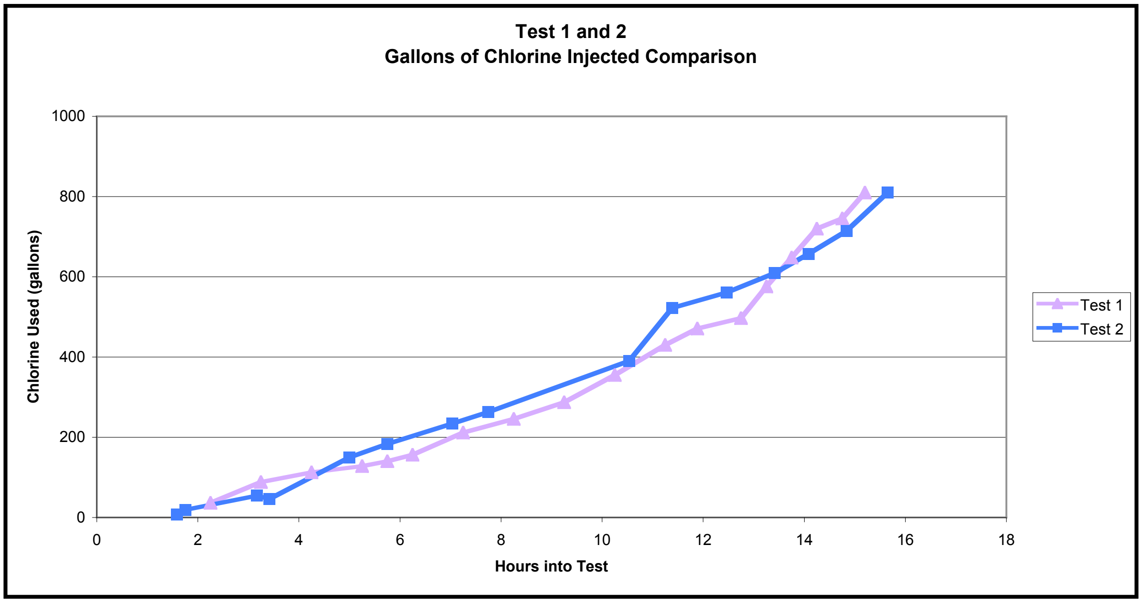

Figure 7: Comparison of Chlorine Gallons Injected – Tests 1 and 2

4.1.4 Mixing Mechanisms: Inlet Velocity vs. Solarbee Mixers

Test 1 received both inlet momentum energy and Solarbee mechanical energy. The results showed that the reservoir continued to mix and approach uniformity after it was filled and isolated by closing the inlet valve. Test 2 received only inlet momentum energy. The results for Test 2 showed the reservoir continued to mix after fill and isolation in an almost identical fashion to Test 1 (See Appendix F). The inlet for Sunset South is 42 inches in diameter. With an average inflow rate of 15 mgd for both Tests 1 and 2, the average inflow velocity for both tests was roughly 2.5 ft/s.

[16] Number represents the average of all concentration readings taken between chlorine injection (or lift) and the end of the test when the reservoir was placed back into service. Background concentrations were removed prior to averaging.

4.2 Tests 1 and 2 Results

4.2.1 Temperature Measurements

The results of temperature monitoring for Tests 1 and 2 are summarized in Table 4. Appendix F contains all temperature graphs for these tests. The degree of stratification is expressed as the temperature difference (ΔT) between water at the top and at the bottom.

Table 4: Results of Temperature Monitoring for Tests 1 and 2

	Test 1	Test 2
Condition before injection and fill	ΔT = 0.0 to 0.1 °C ***Mixers Off*** Uniform Bottom water fluctuating colder at NW (near inlet) during fill.	ΔT = 0.0 to 0.3 °C ***Mixers Off*** Uniform to mild stratification Bottom water fluctuating colder at NW (near inlet) during fill.
Condition during chlorine injection and fill	ΔT = 0.0 to 0.2 °C ***Mixers On*** Uniform to minor stratification Bottom water fluctuating colder at NW during fill.	ΔT = 0.0 to 0.3 °C ***Mixers Off*** Uniform to mild stratification Bottom water fluctuating colder at NW during fill.
Condition during reservoir isolation	ΔT = -0.1 to 0.0 °C ***Mixers On*** Uniform Minor warmth of bottom water.	ΔT = 0.0 °C ***Mixers Off*** Uniform
Condition after isolation and just before reservoir placed back into service	ΔT = 0.0 °C ***Mixers On*** Uniform	ΔT = 0.0 °C ***Mixers Off*** Uniform
Condition after reservoir placed back into service	ΔT = 0.0 to 0.4 °C ***Mixers On*** Uniform to mild stratification Bottom water fluctuating colder at NW due to consecutive fills.	ΔT = 0.0 to 0.5 °C ***Mixers Off*** Mild stratification Bottom water fluctuating colder at NW due to consecutive fills.
Total Improvement	No significant improvement observed; water temperatures remained uniform throughout test.	No significant improvement observed; water temperatures remained uniform throughout test.
Conclusions	Thermistor data indicates mostly uniform temperature before, during, and after test, with mild stratification only seen during reservoir fills. Bulk water, air, and inflow temperatures all similar ~15.0˚C. Reservoir bulk water remained constant as the test progressed.	Thermistor data indicates mostly uniform temperature before, during, and after test, with mild stratification only seen during reservoir fills. Bulk water and inflow temperature ~13.3˚C and air temperature ~10.6˚C. Reservoir bulk water slowly became colder as the test progressed.

The temperature conditions of both Tests 1 and 2 were very similar and showed mostly uniform temperature conditions before, during, and after each test. Both tests showed mild stratification existed at NW-bottom due to colder inflow water during fill conditions. A notable temperature difference existed between Tests 1 and 2. Test 1 bulk water (majority water within reservoir), air, and inflow temperatures were all similar (~15.0°C), whereas Test 2 ran colder with bulk water and inflow water equaling ~13.3°C and air temperature averaging ~10.6°C. Test 2 bulk water slowly became colder as the test progressed (possibly a result of colder air temperature) whereas Test 1 bulk water remained constant (see Appendix F).

It is clear from the temperature results of both Tests 1 and 2 that stratification was not significant during the time period covered by these tests (winter months: November and December 2002). This is likely due to the temperature uniformity seen between ambient air temperatures and inflow water temperatures. The uniform temperature conditions seen during Tests 1 and 2 represent best-case conditions for inlet momentum and/or mechanical mixing, since stratification is not present.

4.2.2 Arrival Time

Table 5 outlines the arrival time at each sampling port for Tests 1 and 2. The arrival time was measured when the chlorine concentration arriving at a particular location became consistently greater than or equal to 0.2 mg/L of background concentrations.

Table 5: Test 1 and 2 Estimated Time to Arrival Records in Hours and Distance[1] from Chlorine Injection

Sample Port / Depth[2]		Test 1 (hrs)	Test 2 (hrs)	Distance[1] (ft)
NW	Top	14[3]	6	42
	Middle	7	7	38
	Bottom	2	0	37
NE	Top	7	7	543
	Middle	6	3	
	Bottom	2	3	
MID	Top	6	5	268
	Middle	5	3	
	Bottom	1	3	
SW	Top	13	15	242
	Middle	9	10	
	Bottom	5	5	
SE	Top	9	7	577
	Middle	4	5	
	Bottom	4	3	
Average	Top	10	8	333
	Middle	6	6	
	Bottom	3	3	
Observed Complete Dispersion Time[4]		**14**	**15**	

[1]Single distances represent the distance for top, middle, and bottom sample locations, since the depth is insignificant compared to the horizontal distance.
[2]Top = 22-ft above floor; Middle = 12-ft above floor; Bottom = 2-ft above floor; reservoir level ~26.6 ft deep (See Figure 3)
[3]NW-T chlorine levels fluctuated sporadically and did not become constant until 14 hours after test start.
[4]Equaivalent to the longest 'arrival time'.

Minimal differences in dispersion between Test 1 and 2 were discernable based on arrival times (see Table 5). The only major difference seen was at the NW port, top sample. Data from Test 1 showed sporadic fluctuations at this location whereas Test 2 showed constant chlorine measurements >0.2 mg/L almost instantaneously. During Test 1, chlorine actually first appeared at the NW-Top location after 6 hours, but unlike other locations, was not consistently above 0.2 mg/L for another 8 hours. The cause of this phenomenon is unclear, but one hypothesis is this was caused by the Solarbee's proximity to the NW sample port and the reservoir inlet.

The westernmost mixer is closest to the NW sample port (~105 feet), but is actually in the peripheral of the reservoir inlet and is bypassed by new water entering the reservoir (See Figure 2). The NW sample port, however, is located directly in front of the reservoir inlet, and is likely first to come into contact with new water entering the reservoir. The NW sample location likely received chlorine at all depths quickly as expected. But the west mixer, initially being bypassed by the inlet chlorine plume, pulled older nonchlorinated water from the bottom and pushed it towards the NW-Top sample location until chlorinated water reached the intake of the west mixer.

The results indicate that the overall mixing between the two tests was exceptionally similar, and provided strong evidence that inlet momentum was the dominant mixing mechanism for Sunset South. Inlet momentum masked any mixing caused by the Solarbee mixers during Test 1.

The elevated chlorine concentrations in Tests 1 and 2 revealed mixing patterns that were less discernable during earlier spatial sampling studies[17]. The arrival times for Tests 1 and 2 indicated a flow pattern caused by inflow momentum rather than as a result of the mixer. This flow pattern appeared to be similar to the flow pattern seen in earlier PSM studies with the inlet water shooting eastward across the basin and slowly dispersing back towards the outlet in a mushroom pattern (see Figure 8 and Appendix F). Test 2 validated inlet momentum as the dominant mixing agent.

4.2.3 Theoretical Dispersion vs. Observed Dispersion

Solarbee specified a theoretical dispersion rate of 10,000 gpm (14.4 mgd) per mixer unit. At Test 1 and 2 reservoir volumes (~75.5 MG), this rate equates to a theoretical complete dispersion time of 2.5 days (60 hours). Both Tests 1 and 2 showed observed complete dispersion times of 0.6 days (14 hours), 77% less than the theoretical complete dispersion time. This finding further supports the conclusion that inlet momentum was the dominant mixing agent for Tests 1 and 2.

[17] Spatial Sampling Report (Charlotte Smith & Associates, 2003)

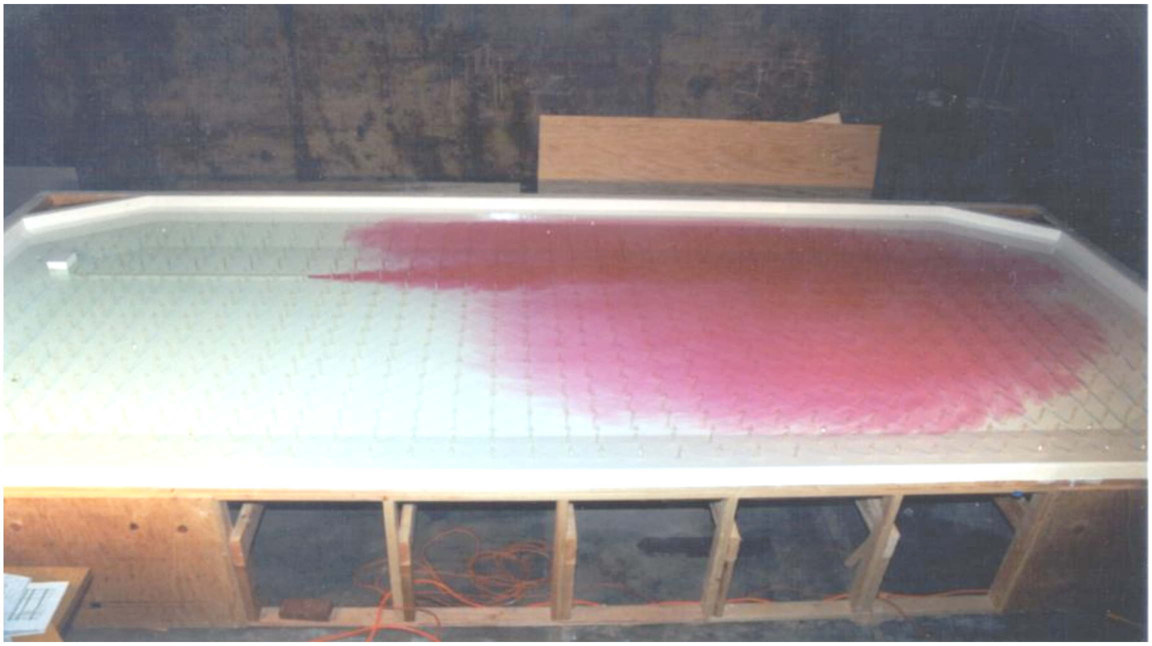

Figure 8: Example of Test 1 and 2 Flow Pattern – Taken from "Physical Modeling Studies of Sunset South" (Hydroconsult Engineers, 2001)

4.2.4 Uniform Mixing Time

Table 6 presents Test 1 and 2 uniform mixing times for the horizontal sections (top, middle, bottom), vertical sections (NW, SW, MID, NE, SE), and the entire reservoir. Uniform mixing time is the time it takes for the maximum and minimum chlorine concentration difference, or ΔC, of a particular set of monitoring data to consistently fall within 0.4 mg/L of one another.

The initial threshold criterion for measuring uniform mixing time was selected as ΔC = 0.2 mg/L, but was later changed to 0.4 mg/L. This change was because 0.2 mg/L was not quickly achieved and was within the error of the Dulcometer instruments used. This caused the values to inflate significantly and did not provide comparative results. It was decided by the project team to switch the uniform mixing time criterion to ΔC = 0.4 mg/L, which was more realistic of future breakpoint chlorination goals and produced more comparable results.

Test 1 and 2 'entire reservoir' uniform mixing times (Table 6) are difficult to compare since Test 2 did not proceed after 98 hours. Vertical uniform mixing results were virtually identical, with Test 2 (mixers off) becoming uniform minutely faster than Test 1 (mixers on). However, Test 1 showed horizontal uniformity occurring faster than Test 2.

Table 6: Test 1 and 2 Uniform Mixing Times in Hours

	Test 1 (Mixer On)	Test 2[1] (Baseline)
Horizontal Sections:	Hours[2]	Hours[2]
Top	48	77
Middle	36	77
Bottom	49	52
Avg / Median	44 / 48	69 / 77
Vertical Sections:		
NW	34	19
SW	31	25
MID	17	37
NE	35	30
SE	18	16
Avg / Median	27 / 31	25 / 25
Entire Reservoir:	***147***	***>98[3]***

[1] Mixers were off for Test 2, represents baseline test with inlet momentum as sole mixing energy.
[2] Sampling was switched from hourly to once or twice daily after 36 hours from start of test. Uniform mixing times after 36 hours may be inflated.
[3] No data available after this time.

The vertical uniformity results presented above (Table 6) may be counterintuitive, since it is expected that vertical uniformity would be reached faster with the mixers on than with the mixers off. The results are very close overall, as the average and median statistics indicate, but the following may have caused errors or noise in the results data:

- Sampling interval changes – For both Tests 1 and 2 sampling intervals were changed after 36 hours from hourly samples to once or twice a day. The longer sampling intervals may have inflated values (e.g. the uniform mixing time recorded at a particular sampling location could have unknowingly occurred earlier).

- Minor hydraulic differences (see *Hydraulic Differences* Section, 4.1.1) – There were slight differences in filling rates, starting water levels, and ending volumes. Filling rates were dependent upon pump station operations, etc. but averaged 15 mgd for both tests. Test 2 began filling with a water level 7 inches lower than for Test 1. Test 2 had a lower ending reservoir volume than Test 1 (73.1 mg vs. 75.2 mg).

- Temperature differences (see *Temperature Measurements* Section, 4.2.1) – There were small differences in bulk water and ambient air temperatures. Test 1 bulk water, air, and inflow temperatures were all similar (~15.0°C), whereas Test 2 ran colder with bulk water and inflow water equaling ~13.3°C and air temperature averaging ~10.6°C. Test 2 bulk water slowly became colder as the test progressed whereas Test 1 bulk water remained constant.

- Chlorine demand differences (see *Chlorine Concentration* Section, 4.1.3) – Test 1 showed a much larger chlorine demand than seen in Test 2, causing Test 1 to have a lower overall average chlorine residual than Test 2 (0.9 mg/L vs. 1.4 mg/L).

These results only indicate the degree of mixing "uniformity" (up to 0.4 mg/L difference) and do not reflect the overall effectiveness of chlorine dispersion. This is to say that a ΔC somewhat greater than 0.4 mg/L may still be sufficient to satisfy uniformity goals (i.e. for breakpoint chlorination).

4.2.5 PSM and CFD Model Comparison

The results of the Solarbee tests were similar to the mixing behavior predicted by SFPUC's Physical Scale Modeling (PSM) study, "Physical Modeling Studies of Sunset Reservoir South" (Hydroconsult Engineers, 2001; see Figure 8). The complete dispersion time predicted by PSM was 15 hours and the complete dispersion time measured in Tests 1 and 2 were 14 and 15 hours, respectively.

The hydraulic/flow conditions were different between the two studies. The PSM study was conducted with unsteady flows and diurnal level fluctuations for a 24-hr period, whereas the reservoir during Tests 1 and 2 was filled and isolated. The PSM study did not address vertical mixing or effects of stratification. See Appendix G for a more detailed summary and for hydraulic conditions of the PSM study.

The Computational Fluid Dynamic (CFD) modeling by Flow Science predicted a complete dispersion time occurring at Sunset South after about 36 hours, significantly higher than the 15 hours seen during Test 1 and 2. The CFD modeling was conducted under steady-state inflow and outflow conditions, with different initial conditions, boundary conditions, inlet size (36 inch versus existing 42 inch), and flow rate (7.3 mgd versus 15 mgd). See Appendix G for a more detailed explanation of these findings.

4.3 Test Proceedings – Tests 3 and 4

The results of Tests 1 and 2 provided information on the relative contributions of inflow momentum and mechanical mixing on the mixing characteristics of Sunset South. Testing was suspended in December 2002 pending the onset of stratified conditions at the reservoir, determined by further temperature monitoring. Stratified conditions were detected in spring, and Tests 3 and 4 were conducted April/May 2003 and July 2003, respectively. Tests 3 and 4 goals included:

1. Evaluate the Solarbee during stratified conditions
2. Establish dispersion rates when one mixer is on
3. Document the mixer's ability to facilitate break-point chlorination
4. Test the mixers with no inlet momentum energies present

4.3.1 Test 3

The reservoir was completely isolated from the distribution system (at 4.8-ft below spill) 2 days prior to chlorine injection, so inflow energies could completely dissipate prior to beginning the test. One mixer was placed at the middle of the reservoir and a 1,000-gallon chlorine slug was injected directly below the mixer (which remained off) near the draft tube intake. This was accomplished by anchoring 1-inch flexible tubing to just below the mixer's impeller and pumping chlorine from a storage vehicle through the tubing. This was completed as fast as possible and took about 1.3 hours. The mixer was not powered for 4 days to check for any tracer movement due to convection, or diffusion[18]. The sampling indicated no convection or diffusion was present, but indicated that the slug had migrated from its original location.

The mixer was powered for 6 days in an attempt to lift the missing slug while boat sampling was conducted to locate the slug. The sampling showed the entire chlorine slug moved horizontally across the reservoir floor, from the injection location to the lowest reservoir floor elevation located near the reservoir drain and outlet structure, some 420 feet away (See Figure 9). This occurred despite only 2 feet of floor elevation difference between the two locations. The slug proved to be too dense (Specific Gravity = 1.2) and too far away horizontally for the mixer to lift it up.

By this time the priority was to distribute the slug by any means possible (so the reservoir could be returned to service) and the original priorities of Test 3 became secondary. The mixer was moved to and placed against the outlet structure (2 days to complete), directly over the slug[19] (See Figure 9). The mixer was powered for 1 hour at the outlet and was still unable to pick up the dense material because the strainer plate (located at the bottom of the draft tube intake and purposely elevated to minimize entrainment of floor sediment) was higher than the slug (~6 inches higher). CDD Divers cut the PVC draft tube legs (1 day to complete) and placed the intake directly into the slug. The mixer was powered for another 5 days in which time the chlorine was picked up and distributed throughout the entire reservoir. Monitoring was insufficient to thoroughly characterize mixing because the test deviated significantly from the original test plan, and samples were taken sporadically (1 sample / 1-3 days). However, the limited data still provided some valuable findings.

[18] Diffusion is the movement of tracer on the molecular level from an area of high concentration to an area of low concentration, and convection is the movement of tracer due to temperature gradients in the water.
[19] The mixer was off during this move which took approximately 2 days to complete.

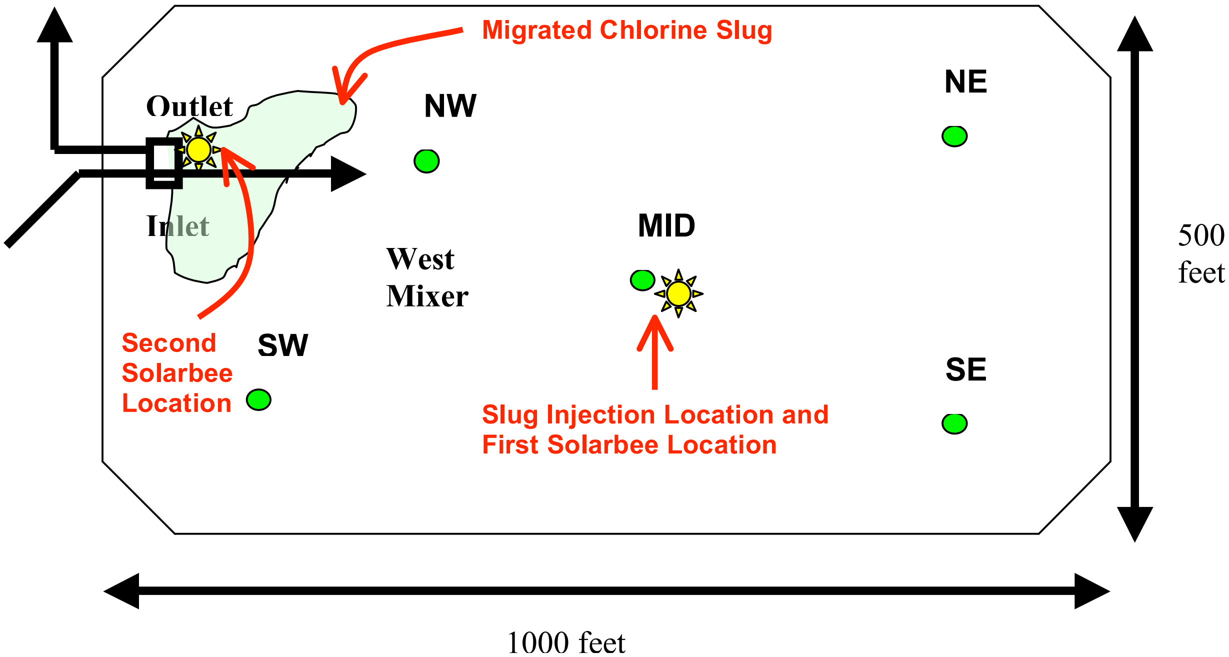

Figure 9: Schematic of Test 3 Proceedings

4.3.2 Test 4

Test 4 was planned as the follow up, or repeat, of Test 3, but utilized continuous chlorine injection into the impeller rather than slug injection. Also, Test 3 employed the mixer intermittently prior to the chlorine slug being picked up and distributed, whereas the mixer was off prior to chlorine injection in Test 4. The mixer remained at the middle of the reservoir (MID port, see Figure 9) during the entire test, unlike Test 3. Both tests provided valuable results, but the tests are not directly comparable.

4.3.3 Hydraulic Differences

Sunset South was isolated before both Tests 3 and 4 began to allow all inlet momentum energies to dissipate prior to the beginning of each test. The volume of water in the reservoir was slightly greater in Test 3 than in Test 4 (70.1 MG vs. 68.7 MG). The other hydraulic difference was that the mixer was located at the outlet (against the valve tower) for Test 3 and under the MID port for Test 4. The placement of the mixer against the valve tower wall during Test 3 may have inhibited the mixers full potential (the wall was a barrier that may have dissipated some of the mixer's energy).

4.3.4 Chlorine Injection Differences

The mixer and chlorine injection locations were different between Tests 3 and 4. Though the initial plan for Test 3 was to pull a chlorine slug off the bottom using one mixer located under the MID port, the slug quickly traveled down the slope of the floor to the lowest floor elevation near the outlet; the mixer had to be relocated to above the outlet in order to complete the test. A slug was not used for Test 4 but rather chlorine was continuously injected onto the mixer impeller for about 6 hours at the MID port. Both tests utilized 1000 gallons of 12.5% sodium hypochlorite.

4.3.5 Chlorine Concentration Differences

The volume of chlorine injected for Tests 3 and 4 was identical (1000 gallons). This volume was expected to produce the theoretical chlorine concentration of 2.1 mg/L. The overall average observed concentration for Tests 3 and 4 were 1.0 and 2.1 mg/L, respectively[20]. The lower average seen for Test 3 may have been a result of chlorine decay and demand on the reservoir floor. The chlorine slug sat on the reservoir bottom, in contact with high-demand silt and sediment accumulated near the outlet, for 13 days[21]. A loss of 1.1 mg/L (2.1 theoretical – 1.0 observed) equates to 530 gallons of chlorine lost in 13 days, or a decay rate of 0.1 mg/L/day. This decay rate is somewhat less, but still comparable, with previous free chlorine decay rate estimates for SFPUC[22]. The overall average observed concentration from Test 4 exactly matched the theoretical chlorine concentration, indicating little to no chlorine demand during Test 4.

4.4 Tests 3 and 4 Results

4.4.1 Temperature Measurements

The results of temperature monitoring for Tests 3 and 4 are summarized in Table 7. Figures 10 and 11 show examples of thermistor data obtained during Tests 3 and 4. Appendix H contains all temperature graphs for both tests. The degree of stratification is expressed as the temperature difference between water at the top and water at the bottom, or ΔT[23]. For Test 3, three sets of seven temperature probes (five static and 2 floaters) were placed at the NW, SE, and SW sample ports, and for Test 4, two identical sets of seven probes were placed at the SW and MID sample ports.

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[20]The theoretical chlorine concentration is calculated by dividing the mass of injected chlorine by the reservoir volume. Overall average observed concentrations represent the average of all concentration readings taken between chlorine injection (or lift) and the end of the test when the reservoir was placed back into service. Background concentrations were removed prior to averaging, but were less than the 0.1 mg/L.

[21] Represents the duration between the slug injection on 4/25/03 and when the slug was picked up and distributed on 5/8/03.

[22] Charlotte Smith & Associates (CS&A) estimated bulk water decay to be 0.17 to 0.18 mg/L/day for Sunset South in the May 2003 "Spatial Sampling Study."

[23] ΔT represents the largest top/bottom temperature difference measured at any of the probe locations.

Table 7: Results of Temperature Monitoring for Tests 3 and 4

	Test 3	Test 4
Condition before reservoir isolation	ΔT = 1.7 to 3.6 °C ***Mixer Off.*** Stratified but fluctuating.	ΔT = 0.5 to 1.2 °C ***Mixer Off.*** Stratified but fluctuating.
Condition after isolation and before chlorine injection (or chlorine lift)	ΔT = 1.0 to 2.9 °C ***Mixer On 6 days; Mixer Off 3 days[1].*** Stratified. ΔT dropped from 2.9 °C to 1.0 °C in about 6 days.	ΔT = 1.1 to 3.9 °C ***Mixer off.*** Stratified. Stratification increased from 1.1 °C to 3.9 °C in about 10 days of isolation, before start of test.
Condition during chlorine injection	ΔT = 1.3 °C ***Mixer on at new location-outlet.*** Stratified. After the mixer was turned off, ΔT rose slightly to 1.3 °C after 3 days[2].	ΔT = 3.9 °C ***Mixer first on*** Stratified.
Condition after injection (or lift) and just before reservoir placed back in service	ΔT = 0.8 to 1.3 °C ***Mixer on.*** Stratified. Dropped from 1.3 °C to 0.8 °C in about 6 days.	ΔT = 1.0 to 3.9 °C ***Mixer on.*** Stratified. Dropped from 3.9 °C to 1.0 °C in about 8 days[3].
Condition after reservoir placed back into service.	ΔT = 0.7 to 1.4 °C ***Mixer on.*** Stratified but fluctuating.	ΔT = 0.2 to 1.0 °C ***Mixer on.*** Mostly stratified but fluctuating.
Total Improvement	ΔT dropped from 2.9 °C to 0.8 °C for a total top to bottom decrease of 2.1 °C in 12 intermittent days of mixer run time[2].	ΔT dropped from 3.9 °C to 1.0 °C for a total top to bottom decrease of 2.9 °C in 8 days of continuous mixer run time[3].
Conclusions	The mixer demonstrated its ability to decrease ΔT significantly, though this was mostly achieved prior to chlorine lift and the start of the test. The mixer destratified a depth of 17 ft in 6 days prior to injection. Destratification was slower after injection (~5 ft in 4 days). Complete destratification was never reached. A smaller ΔT (1.3 °C) at time of injection aided chlorine dispersion.	Stratification worsened prior to injection and start of test because the mixer was off during this time, unlike Test 3. The mixer still demonstrated its ability to significantly decrease stratification. The mixer destratified a depth of 7 ft the 1st day[4], though this slowed significantly and complete destratification was never reached. A larger ΔT (3.9 °C) at time of injection inhibited chlorine dispersion.

[1] Mixer was on for 6 of 9 days in attempt to mix the slug prior to moving the mixer to the outlet.
[2] Mixer was turned off for a period of 3 days on 5/5/03 and then powered on 5/8/03. This was conducted in order to move and modify the mixer for picking up the slug at the outlet.
[3] This occurred at the MID sample port only, the same location as the mixer. Destratification at the mixer location was likely faster than other locations in the reservoir.
[4] Considered an initial destratification rate; insufficient data to predict an overall destratification rate for Test 4.

Test 3

For Test 3, chlorine injection occurred for 1.3 hours down the Solarbee's draft tube, with the mixer off. Complications arose and the slug was not located and dispersed until 13 days later, during which time the mixer was powered intermittently in an attempt to mix the slug, located approximately 370 feet away. This attempt proved unsuccessful, but resulted in stratification being significantly lessened immediately after power was applied to the mixer (see Figure 10).

By the time the slug was located and the mixer placed directly above it, the temperature difference (ΔT) between top and bottom sections decreased considerably: 2.9°C to 1.0°C from 6 days of intermittent mixing (see Table 7 and Figure 10). This decrease in stratification appeared to provide more favorable initial conditions for chlorine dispersion by Solarbee (compared to Test 4), allowing chlorine concentrations to show up throughout the entire reservoir in <118 hours (5 days).

The largest decrease in stratification occurred from the mixers being employed prior to the chlorine slug being located and lifted. A destratification rate[24] of approximately 2.8 feet per day (17 feet in 6 days) was observed during this time. After the chlorine slug was lifted, destratification appeared to be slower and occurred at approximately 1.25 feet per day (5 feet in 4 days). This resulted in an overall destratification rate of 2.2 feet per day of intermittent mixing.

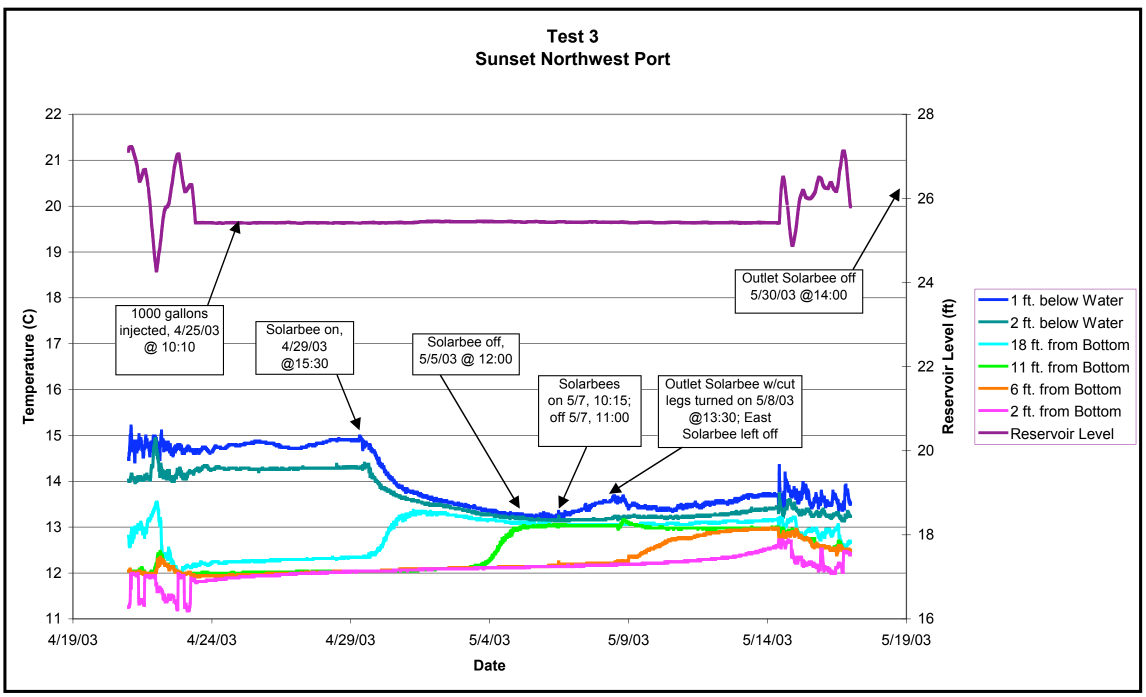

Figure 10: Example of Test 3 Thermistor Data – Decrease of Stratification by Solarbee

[24] This term is the approximate rate at which various layers at specific depths changed sharply and became more uniform with upper layers (See Appendix XX for sample calculation). These rates are specific to Sunset Reservoir dimensions and should not be used for other reservoirs.

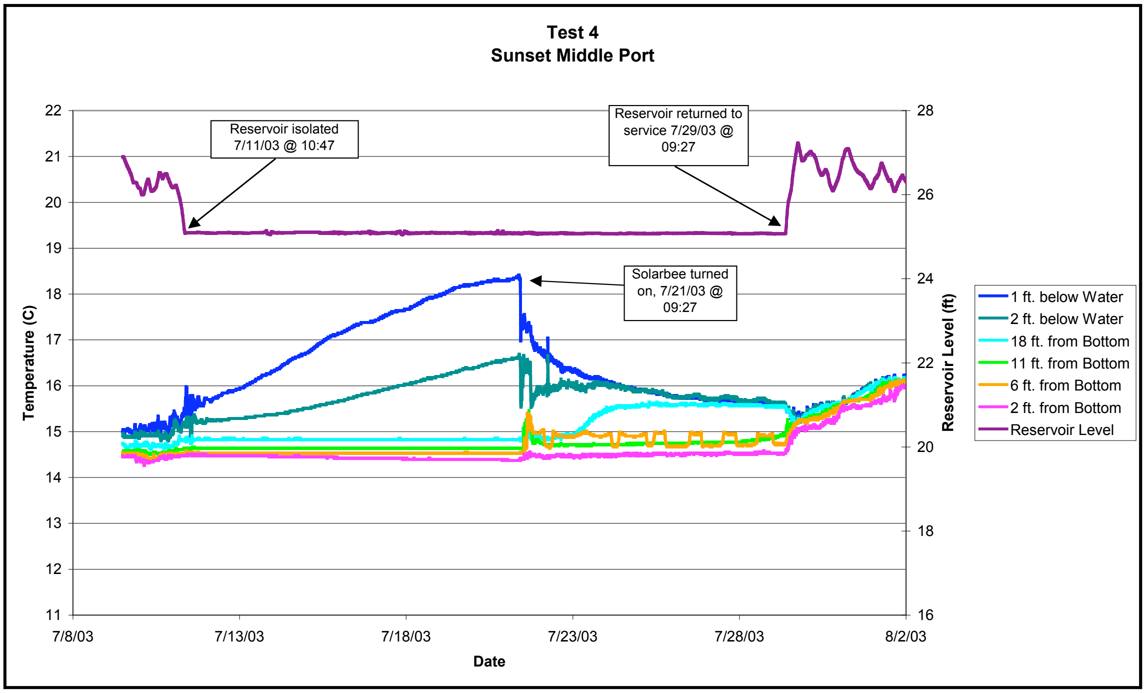

Figure 11: Example of Test 4 Thermistor Data – Decrease of Stratification by Solarbee

Test 4

For Test 4, the test was delayed and the reservoir remained isolated with the mixer off for 10 days prior to chlorine injection. Chlorine was then injected continuously for 7 hours, with the mixer on. During the 10 days of isolation, stratified conditions worsened: ΔT went from 1.1°C to 3.9°C. When the Solarbee was powered, stratification improved greatly: ΔT went from 3.9°C to 1.0°C in about 8 days[25] (see Figure 11). Both thermistor locations (MID and SW) showed destratification occurring to 7 feet below the surface in the first day. There was insufficient data to estimate an overall destratification rate.

Since ΔT was so large at injection (3.9°C compared to 1.3°C for Test 3), the mixer had trouble dispersing the chlorine vertically. This resulted in high chlorine concentrations at top samples, measurable but lower chlorine concentrations at middle samples, and extremely low or zero chlorine concentrations at bottom samples (See Appendix H).

Solarbee staff hypothesized that this phenomenon was a result of the high degree of stratification existing at the start of the test, and that a thermocline[26] existed between newer colder water on the

[25] This drop in temperature was only documented at the mixer location (MID port) because problems occurred at the other temperature monitoring station (SW port; top probe out of water).
[26] The term "thermocline" is traditionally associated with raw water reservoirs and lakes, the predominant application of Solarbee mixers. The term is used here and throughout the report to mean the horizontal temperature interface between the newer cold-water layer (transported from the bottom to the top of the reservoir by Solarbee) and the older warm water layer (water that presided on the surface prior to employing Solarbee).

surface (recently displaced from the bottom by Solarbee) and warmer water below the surface (previously located on the surface before Solarbee was employed). Solarbee staff explained that the specified theoretical dispersion rate of 10,000 gpm (14.4 mgd) perhaps could not be reached, or that much of this flow was recirculating, because the large amount of initial stratification caused the 7,000 gpm of induced flow to be compartmentalized at the surface above the thermocline (See Figure 12). This limited the mixers flow rate to 3,000 gpm of direct flow[27], with the flow rate slowly increasing as the stratified layers were systematically broken. The Solarbee appeared to steadily lower the thermocline, slowly decreasing higher elevation temperatures, and slowly increasing lower elevation chlorine concentrations, over time.

If this hypothesis is correct, the Solarbee's ability to destratify a reservoir is largely dependent on initial temperature conditions and the degree of stratification. It suggests there is a threshold of destratification that must be reached before chlorine can be uniformly dispersed. Test 3 appeared to have passed this threshold, whereas Test 4 appeared to stop short of this threshold. Further tests need to be conducted to validate this hypothesis.

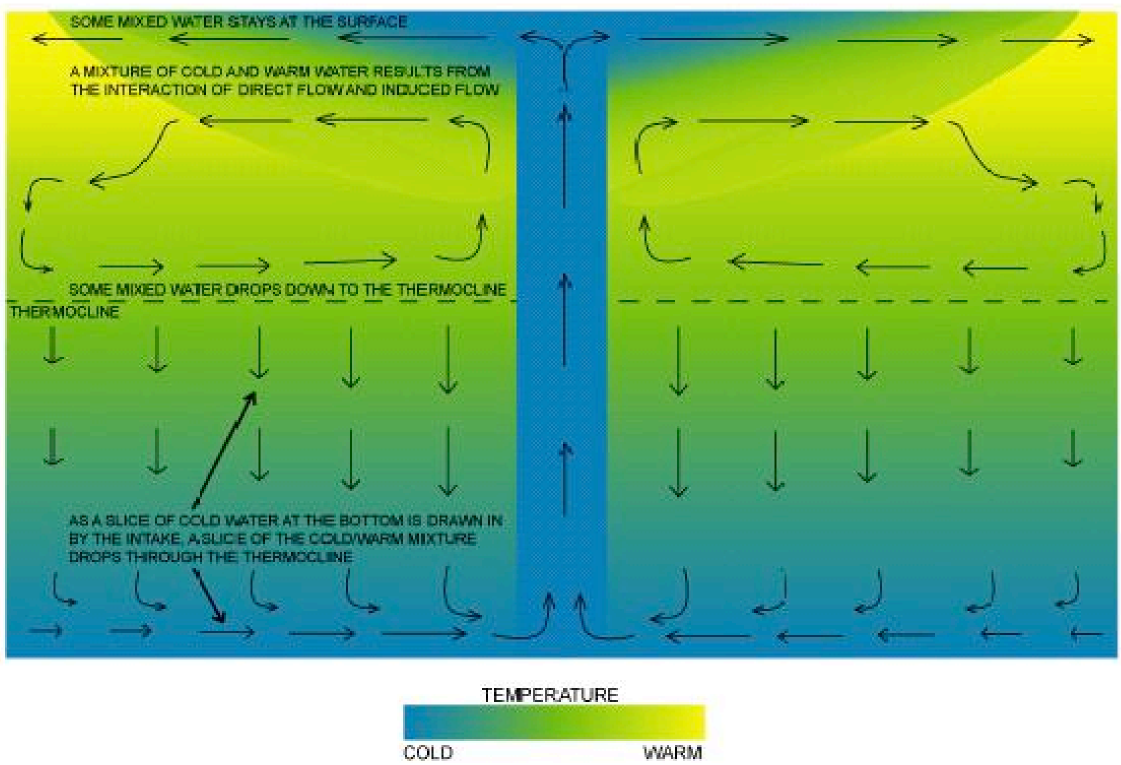

Figure 12: Diagram of Solarbee Flow Pattern During Stratified Conditions (Solarbee, 2003)

Tests 3 and 4 showed that Solarbee is effective for destratifying a reservoir and dispersing chlorine, but that limitations exist. Initial temperature conditions and the degree of stratification appear to be key factors to the mixer's performance. The mixer initially requires time to break

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[27] Solarbee specifies 10,000 gpm (14.4 mgd) of total flow from the mixer, of which 3,000 is 'direct' flow of bottom water traveling up through the draft tube, and 7,000 is 'induced' flow which is entrained around the exterior of the draft tube and surrounding water column. See Section 2.1 for more description.

stratification, during which the full mixing capability of the mixer may not be achieved (as seen in Test 4—see Figure 12). Once destratification reaches a particular threshold, mixing occurs rapidly (as seen in Test 3). Employing more mixer units would likely offset these limitations[28].

The success seen during Test 3 showed the benefit of running the Solarbee prior to chlorine injection rather than at the same time as injection, as was done in Test 4. Also, Test 4 showed that the mixers should be employed immediately after the reservoir is isolated to avoid increasing stratification. Both tests suggest that a destratification threshold exists that controls Solarbee's ability to effectively disperse chlorine and completely mix the reservoir.

4.4.2 Arrival Time

Table 8 outlines the arrival time at each sampling port for Tests 3 and 4.

Table 8: Tests 3 and 4 Estimated Time to Arrival Records in Hours and Distance from Chlorine Injection

Sample Port / Depth[2]		Test 3 Distance[1] (ft)	Test 3 Arrival Time (hrs)	Test 4 Distance[1] (ft)	Test 4 Arrival Time (hrs)
NW	**Top**	212	14	236	5
	Middle		<22		22
	Bottom		<23		>172
NE	**Top**	701	<95	318	13
	Middle		<95		15
	Bottom		<95		16
MID	**Top**	420	42	0	1
	Middle		<42	10	2
	Bottom		<23	20	2
SW	**Top**	199	4	399	17
	Middle		<22		67
	Bottom		<23		>172
SE	**Top**	726	<95	310	15
	Middle		<118		>111
	Bottom		<95		>111
Average	**Top**	452	<50	253	10
	Middle		<56		>43
	Bottom		<66		>95
Observed Complete Dispersion Time			**<118**		**>172**

[1] Single distances represent the distance for top, middle, and bottom sample locations, since the depth is insignificant compared to the horizontal distance.
[2] Top = 22-ft above floor; Middle = 12-ft above floor; Bottom = 2-ft above floor; reservoir level ~25.3 ft deep (See Figure 3)
[3] Equaivalent to the longest 'arrival time'

The arrival time is the time required for chlorine arriving at a particular location to have a concentration consistently greater than or equal to 0.2 mg/L of background concentrations. The arrival times for Tests 3 and 4 are presented together, but should not be directly

[28] Only one mixer was used at Sunset South for Tests 3 and 4, despite the large water volume of 70 MG and 720 roof columns. Solarbee recommended a minimum of 2 mixers be used at Sunset South.

compared. This is because the injection/mixer locations differed for both tests, resulting in different sampling distances. It is important to note that arrival times are not a measure of chlorine uniformity.

Test 3

Test 3 results show that chlorine concentrations greater than 0.2 mg/L arrived at all sampling locations and depths in less than 118 hours. Test 3 deviated considerably from the original plan due to complications encountered during the test. Sampling intervals were limited to 1 sample every 1 to 3 days. This may have resulted in inflated values (this is why most Test 3 values in Table 8 have a "<" symbol in front of the value). The arrival times for Test 3 showed little difference between top, middle, and bottom values. This indicated that more favorable initial conditions allowed the chlorine to be dispersed throughout the entire reservoir more effectively (than Test 4).

Test 4

Test 4 results show that chlorine was dispersed rather quickly on the surface of the reservoir, but middle and bottom areas of the reservoir received chlorine late or not at all. The test ended before most of the bottom samples registered any chlorine consistently greater than 0.2 mg/L. Chlorine was unable to reach middle and bottom areas farthest away from the mixer, but was able to reach (or reach more quickly) the middle and bottom areas located closer to the mixer.

This phenomenon appears to be related to the initial stratification conditions present during the test. Test 4 showed significantly more stratification at the start of the test than there was for Test 3. The arrival time data for Test 4 supports the hypothesis by Solarbee that a thermocline existed during the test (this was discussed earlier in Section 4.4.1 and is illustrated in Figure 12), which prevented the mixer from achieving its full potential.

Tests 3 and 4 serve as an example of how initial temperature conditions, or the existence of a thermocline, can effect the mixing and/or chemical dispersion in a reservoir. If planning to breakpoint chlorinate a reservoir during known stratified conditions, the mixers should be turned on ahead of time so that stratification is reduced prior to injecting chlorine. They should also be employed just after a reservoir is isolated to prevent stratification from worsening prior to injection.

4.4.3 Dispersion Rates and Complete Dispersion Times

Chlorine arrival times were used to estimate the surface dispersion rate. The theoretical complete dispersion time was calculated using the manufacturer's specified theoretical dispersion rate of 14.4 mgd. The observed dispersion rates were calculated based on the last arrival time seen (or observed complete dispersion time when all sample locations showed a chlorine residual greater than or equal to 0.2 mg/L above baseline concentrations). For Test 4 this time never occurred. Sample calculations are located in Appendix I. Section 3.2 defines each of the terms used in Table 9.

Table 9: Tests 3 and 4 Estimated Dispersion Rates and Complete Dispersion Times

Parameter	Test 3	Test 4
Surface Dispersion Rate	>12.3 ft/hr[1]	23.3 ft/hr
Theoretical Dispersion Rate	14.4 mgd	14.4 mgd
Theoretical Complete Dispersion Time[2]	4.8 days	4.8 days
Observed Dispersion Rate	>14.3 mgd[1]	<9.5 mgd
Observed Complete Dispersion Time[3]	<4.9 days	>7.2 days[4]

[1] May be a deflated value because of large sampling intervals
[2] Based off Solarbee claims of 14.4 mgd (10,000 gpm) per mixer unit and reservoir volume
[3] Equivalent to the Last Arrival Time: taken from 'Arrival Time' results, Table 8
[4] For Test 4, the test ended before complete dispersion was observed.

Test 3
The surface dispersion rate for Test 3, estimated using arrival times at top sample locations only, was estimated to be >12.3 ft/hr (limited sampling during Test 3 may have deflated this value). The theoretical complete dispersion time, based on the manufacturer's specified theoretical dispersion rate of 14.4 mgd, was calculated to be 4.8 days. The observed complete dispersion time based on the last arrival time, or the time at which all sample stations showed a chlorine concentration greater than or equal to 0.2 mg/L above baseline concentrations, was observed to be 4.9 days. This time equated to an observed dispersion rate of 14.3 mgd, which matched the manufacturer's theoretical rate almost exactly.

Test 4
The Test 4 surface dispersion rate of 23.3 ft/hr was estimated to be higher than Test 3 (12.3 ft/hr). This was likely due to the amount of stratification, or the existence of a thermocline, which isolated Solarbee's direct and induced flow to the reservoir surface rather than throughout the entire reservoir volume. This isolation caused increased recirculation and higher velocities to occur at the reservoir surface.

For Test 4, chlorine never reached the NW-Bottom, SW-Bottom, SE-Middle, and SE-Bottom sample locations during the duration of the study. Since these locations never showed chlorine arrival, the observed complete dispersion time was estimated to be >7.2 days, the duration of the test. This time equated to an estimated observed dispersion rate of less than 9.5 mgd, quite lower than the manufacturer's theoretical dispersion rate of 14.4 mgd. This low dispersion rate was likely a result of initially elevated stratification, and the possible existence of a thermocline and surface recirculation, as described in Section 4.4.1. It is possible that the mixer was actually flowing at 14.4 mgd during Test 4, but much of the water with tracer was recirculating near the surface such that the overall reservoir dispersion rate measured by chlorine arrival was observed to be less, around 9.5 mgd.

The results from Tests 3 and 4 indicate that Solarbee is very effective at dispersing chlorine across the reservoir surface, regardless of temperature conditions. Test 3 showed that Solarbee can perform as specified by the manufacturer. Test 4 demonstrated that limitations exist that are likely related to initial stratification conditions. Depending on the degree of initial stratification and the number of mixers employed, Solarbee may require time to break stratification, or pass a certain destratification threshold, before the reservoir can become completely mixed. Test 3 illustrates the benefit of running Solarbee and thus improving stratified conditions prior to injecting chlorine.

4.4.4 Uniform Mixing Time

Table 10 presents Test 3 and 4 uniform mixing times for the horizontal sections (top, middle, bottom), vertical sections (NW, SW, MID, NE, SE), and the entire reservoir. Uniform mixing time is the time it takes for the max and min chlorine concentration difference, or ΔC, of a particular monitoring set (vertical or horizontal) to consistently fall within 0.4 mg/L of one another. If this never occurs, Table 10 indicates a "greater than" symbol (>) before the time and the last available ΔC in parentheses.

Table 10: Test 3 and 4 Uniform Mixing Times in Hours and ΔCs (mg/L) if Uniform Mixing Time is Unknown

	Test 3[1]	**Test 4[1]**
Horizontal Sections:	Hours (ΔC-mg/L)	Hours (ΔC-mg/L)
Top	>118[2] (0.8)	153
Middle	>118[2] (1.1)	>206[2] (1.0)
Bottom	>118[2] (1.1)	93[3]
Vertical Sections:		
NW	<117[3]	>172[2] (1.9)
SW	>117[2] (0.5)	>172[2] (1.9)
MID	>117[2] (0.8)	>172[2] (1.5)
NE	>118[2] (1.2)	>206[2] (1.7)
SE	<118[3]	>111[2] (2.4)
Entire Reservoir:	***>118[2]***	***>206[2]***

[1] Mixer and chlorine were located at outlet for Test 3 and at the MID port for Test 4. Only one mixer was used for both tests.
[2] No data available after this time.
[3] Represents uniformly low chlorine residuals at the bottom, ~0 mg/L at several locations.
[3] Limited sampling intervals may have inflated this value.

Test 3

Due to time constraints, Test 3 ended before many uniform mixing times were identified. Therefore, most uniform mixing times were estimated to be greater than 118 hours, the duration of the test. Table 10 tabulates the last available ΔC value in parentheses.

The results show there was trouble reaching uniformity at all of the horizontal sections during Test 3, indicating a significant difference in concentrations existed between one side of the reservoir and the other. This difference is illustrated in the graphs located in Appendix H.

The NW and SE vertical sections just reached uniform conditions before the test ended (limited sampling may have inflated this value). The SW vertical section almost reached uniformity (ΔC=0.5 mg/L), while both the MID and NE vertical sections significantly lacked uniformity. Overall the test showed more pronounced uniformity in the vertical sections than in the horizontal sections, and showed that successful chlorine dispersion is not necessarily equivalent to successful chlorine uniformity.

Test 4

Test 4 also ended before most uniform mixing times could be identified. The bottom horizontal uniform mixing time of 93 hours appeared to be faster than that seen during Test 3 (>118 hours). However, this time is misleading because the data shows chlorine never arrived at most of the bottom sample locations. Bottom sample locations closest to the mixer initially showed chlorine concentrations greater than 0.4 mg/L (outlying bottom sample locations consistently reported ~0 mg/L) that actually decreased to below 0.4 mg/L (the uniformity criterion used for the analysis) before the bottom section was considered uniform in 93 hours. Therefore the bottom section technically became uniform in 93 hours but was uniformly low in chlorine concentration (0 mg/L to 0.4 mg/L).

The top horizontal section reached uniform conditions in 153 hours, indicating good surface dispersion. The middle section, with a ΔC of 1.0 mg/L, still had not reached uniformity after 206 hours. The data indicates this large ΔC was a result of higher chlorine concentrations existing at middle sample locations closest to the mixer, and lower chlorine concentrations existing at middle sample locations farthest away from the mixer. This phenomenon is consistent with the stratification / thermocline hypothesis explained in Section 4.4.1. Significantly more stratification, and perhaps a thermocline, existed during Test 4 that caused recirculation and chlorine dispersion to occur only in the areas closest to the mixer and near the surface. This prevented mixing and dispersion from occurring in areas farthest away from the mixer, such as bottom corners.

The ΔC values for all of the vertical sections showed a significant difference existed between top and bottom chlorine concentrations. This is because chlorine concentrations were elevated at the surface and close to or equal to zero on the bottom. This phenomenon is consistent with the stratification / thermocline hypothesis explained in Section 4.4.1.

The uniformity results from Tests 3 and 4 reiterates the conclusion that depending on the degree of initial stratification and the number of mixers employed, Solarbee may require time to break stratification, or pass a certain destratification threshold, before the reservoir can be completely mixed. The results also reiterate the benefit of running Solarbee and thus improving stratified conditions prior to injecting chlorine.

4.5 Functionality Findings

4.5.1 Reliability

Both Solarbee mixers required little to no maintenance during the tests. There were no problems encountered when powering them up even after they had been sitting idle for several months. Corrosion was not seen on any of the units. There were slight problems encountered with the draft tube when the units were moved to different locations. This is explored further in the *Transferability* Section (4.5.4) below.

4.5.2 Power Use

Solarbee states that the SB10000F uses 220 Watts at 2 amps. CDD Electricians validated the claimed power use in the field. Assuming that electricity costs 13.3¢ per kilowatt-hour, continuous operation of one unit would cost approximately 70¢ per day and $256 per year.

CDD electricians conducted an independent evaluation of the Solarbee electrical system and noted that the environment (moisture) and installation arrangement would be prone to future electrical problems. It was recommended that a more permanent setup (corrosion resistant security enclosure with on/off switch and diagnostic mechanisms) be designed if Solarbees are to be operated in the City in the future.

It was difficult to verify if the mixers were running once they were powered, and they had to be physically inspected each time.

4.5.3 Installation

Sunset South was equipped with a 15' x 11' rolling hatch that allowed the Solarbee units to be installed completely assembled. Only Sunset South, Sutro, University Mound South, and Stanford Heights have been outfitted with hatch openings. Summit is expected to have a smaller hatch and Merced Manor and Sunset North will receive the standard 15' x 11' hatch. If a mixer were to be placed in a reservoir without a hatch (or smaller hatch—Summit) the unit would require assembly inside the reservoir. Solarbee can be collapsed to 24-inch x 24-inch.

4.5.4 Transferability

The Solarbee units were moved in-situ several times utilizing a boat. The difficulty in moving a mixer stems from the draft tube that drapes down from the mixer to the bottom.

CDD divers encountered problems with the crank arm used to mechanically lift the draft tube. The bottom of the draft tube must be supported so that it will not drag when the unit is being moved. CDD divers used a makeshift hook to support the bottom of the draft tube.

SFPUC staff noted that the draft tube could only be retracted a certain distance. It seemed the adjustment range was below the depth of the water. This distance was also longer than the depth of many of the other mid-sized reservoirs. The draft tube would most likely need to be individually sized for each reservoir, which limits the transferability between deeper and shallower reservoirs[29].

Solarbee mixer units could be transferred from reservoir to reservoir utilizing a crane-truck, 2 boats, and approximately 4 people for assembly. If rolling hatches exist at both reservoirs, this could be conducted in a day. If no hatches exist at the receiving reservoir, the units would need to be disassembled and then reassembled inside the reservoir requiring approximately double the manpower and time. However, Solarbee now has models that can be collapsed to 24-inch x 24-inch.

4.5.5 Chemical Injection Kit

CDD divers were able to install chlorine injection piping into the mixer's impeller during Test 4 using flexible tubing and zip-ties. Solarbee offers a chemical injection kit to be used with the mixer. The injection kit consists of a 100 gpd LMI C-series injection pump (Model C72-75S; see Appendix J), a suction hose assembly and check-valve, and 200 feet of polyethylene tubing. A chlorine injection assembly of this nature would facilitate break-point chlorination utilizing Solarbee.

4.5.6 Maintenance

Solarbee recommends the motor brushes be replaced every 4 months if the mixers are setup for 24-hour operation using supplemental shore power[30]. The brushes are $10/set. Every 2 to 4 years a new $500 gear motor may be required due to the armature being worn down by the brushes[31]. Otherwise, the unit itself should be periodically checked to make sure it is operational and should be periodically cleaned to ensure optimal performance.

[29] Solarbee has since redesigned the retraction system for the new SB10000PW model, a model designed for potable water applications.
[30] Brushes should be replaced every year if solar option is used.
[31] Solarbee currently offers a brushless high-torque large diameter motor option. The motor is low RPM, low wattage, and has no gearbox. It is designed to have a 20+ year life and is offered at a higher cost.

4.5.7 Expected Life

Solarbee provides the following expected life estimates:

- Floats – 20 years
- Structure / Distribution Dish – 20 years
- Gear Motor – 5 years
- Solar Panels – 30 years
- Wiring and Electrical Components – 20 years
- Brushes – 4 months
- Gear motor – 2 to 4 years

4.5.8 Warranty

Solarbee has a limited replacement warranty for each unit to "be free of defective parts, materials, and workmanship for a period of two years from the date of sale (see Appendix A for full copy of manual with warranty).

4.5.9 Solarbee Customer References

Solarbee provided five customer references that were contacted and interviewed by WQB staff. All of the customers contacted had very positive comments about Solarbee and experienced significant improvement in their water quality goals. Since potable water applications of the Solarbee are relatively new, none of the references contacted utilized Solarbee for potable water storage. The uses consisted of wastewater sewage ponds, a recreational lake, and a raw water reservoir. It is reassuring that all of the references gave positive feedback, with many utilizing the mixers under harsher conditions and for larger volumes than SFPUC will ever experience. The interview results are available in Appendix K.

5 Summary and Conclusions

5.1 Test 1 and 2

Tests 1 and 2 showed that Sunset South was well mixed during the observed winter conditions (November and December 2002), with no to minimal stratification, and is likely well mixed whenever air temperature and inflow temperatures are similar. Therefore nitrification should be less of a problem during winter months under similar hydraulic and temperature conditions, and supplemental mixing should not be necessary. If nitrification were to occur under such conditions, break-point chlorination would likely not require any supplemental or artificial mixing, since the inlet velocity could be used successfully to mix injected chlorine. This finding was a result of the large amount of mixing due to inlet momentum existing at Sunset South during Tests 1 and 2. The results do not imply that well-mixed conditions exist at all SFPUC tanks and reservoirs under similar ambient conditions. Individual studies should be completed (or previous studies consulted) to evaluate each individual tank/reservoir.

Tests 1 and 2 showed complete dispersion of chlorine (concentration consistently greater than 0.2 mg/L everywhere) in 14 to 15 hours after a fill and subsequent isolation, whereas the theoretical complete dispersion time (if the Solarbees acted alone) was 2.6 days (62.4 hours). This indicates Solarbee would likely not significantly improve mixing, under the observed winter conditions, since the theoretical complete dispersion time was so much longer than the observed complete dispersion time. Complete reservoir uniformity (ΔC greater than or equal to 0.4 mg/L throughout entire reservoir) for Tests 1 and 2 occurred at Sunset South in roughly 6 days (147 hours).

These tests were conducted with Sunset South water levels between 6-ft and 3-ft below spill because of Division of Safety of Dams regulations for Sunset Reservoir at that time. It is unknown if the same degree of mixing would occur at the normal higher operating range of 3-ft to 0.5-ft below spill. CDD should incorporate these lower operating levels into normal operations to ensure this level of mixing is repeated.

5.2 Tests 3 and 4

Tests 3 and 4 demonstrated that stratification does exist at times during the summer months when air temperatures become warmer than inflow temperatures. Therefore, compartmentalization and high water age can occur resulting in a higher potential for nitrification. It is evident from previous and concurrent thermistor studies that similar or worse degrees of stratification do exist in other SFPUC tanks and reservoirs under similar conditions, especially if no CIP improvements have been implemented[32]. Both

[32] "Hydraulic Analysis for City and County of San Francisco Water Storage Reservoirs," Flowscience, 2000. "Spatial Sampling Study for Stanford Heights, Summit, Sunset North, Sunset South, and University Mound Reservoirs," Charlotte Smith and Associates, 2003.

supplemental mixing and breakpoint chlorinating under such conditions could greatly benefit from the use of Solarbee mixers.

Test 3 showed complete dispersion occurring in less than 5 days (118 hours), which equated to 14.4 mgd—the same theoretical dispersion rate specified by Solarbee. This indicates that with one mixer and minimal stratification, breakpoint chlorination could be achieved at Sunset South in 5 days (possibly ~2.5 days if two mixers were employed). Test 4 never reached complete dispersion, and performed much slower (< 9.5 mgd) than the specified theoretical rate. Both tests were concluded before they reached complete uniformity.

Tests 3 and 4 showed that Solarbee can be effective for reducing stratification and dispersing chlorine, but that limitations exist. The initial degree of stratification appears to be a key factor to the mixer's performance. The mixer initially requires time to break stratification, during which the full mixing capability of the mixer may not be achieved (as seen in Test 4—see Figure 12). Once destratification reaches a particular threshold, mixing occurs rapidly (as seen in Test 3).

The successful dispersion seen during Test 3 showed the benefit of running the Solarbee and reducing stratification prior to chlorine injection, rather than at the same time as injection, as was done in Test 4. Additionally, Test 4 showed the importance of employing the mixers immediately after the reservoir is isolated to avoid intensifying stratification before injection. Both tests suggest that a destratification threshold exists that limits Solarbee's ability to effectively disperse chlorine and completely mix the reservoir.

Only one mixer was used for Tests 3 and 4, and the mixing goal was optimistic (to mix a 70 MG, 11.5 acre reservoir with 720 roof columns). Solarbee recommended a minimum of two units be used at Sunset South. Employing more mixer units would likely offset the limitations associated with initial stratification conditions.

5.3 Significance of T_{max} vs T_{avg}

CDM's 2002 report entitled "Operational and Mixing Strategies to Maintain Water Quality in CDD Reservoirs" estimated a T_{max} and T_{avg} of 16 and 12 days, respectively, based on CFD modeling using the new inlet configuration. Both the Solarbee test and the PSM studies were unable to predict T_{max} or T_{avg}, only estimates of complete dispersion (stated as mixing time in the PSM report). Detention time and dispersion time are two different measurements, with detention time requiring much more time and effort to validate in the field. WQB believes the Solarbee mixers can help T_{max} approach T_{avg} as $Q_{Solarbee}$ approaches Q_{avg}, but this remains to be validated.

5.4 Strategy for Nitrification Response

Nitrification response in a reservoir may require breakpoint chlorination. Breakpoint chlorination requires the addition of chlorine into the reservoir, and the reservoir to be isolated from the system. Breakpoint chlorination should be employed at SFPUC in one of two ways:

- **Continuous Injection, Inlet Momentum –** Considered a good option if a reservoir is known to have excellent mixing capability from inlet momentum and can be significantly drawn down. The reservoir is drawn down to its minimum level, the outlet valve closed, and chlorine injected into the inlet simultaneously with a rapid fill. This option requires some sort of injection capability at the inlet.

- **Continuous Injection, Mechanical Mixer –** Considered a good option if a reservoir cannot be significantly drawn down and/or does not have good mixing from inlet momentum. The reservoir is isolated and chlorine injected and distributed using a mechanical mixer. This option requires chlorine to be transported and stored onsite, with temporary or permanent chlorine injection and conveyance capabilities installed at the mixer.

Solarbee's ability to reduce stratification and disperse chlorine indicated it would be useful for assisting breakpoint chlorination. Both breakpoint methods could benefit from the use of Solarbee mixers, especially during stratified conditions. As Test 3 showed, slug injection should be avoided when breakpoint chlorinating a reservoir. Continuous injection is the preferred method for injecting chlorine for breakpoint chlorination.

Another less desirable method of breakpoint chlorination is to distribute dry or liquid chlorine over the reservoir surface using a boat. Mechanical and/or inlet momentum could then be employed to attempt to mix the chlorine. This option is not preferred because of the large volume of chlorine that is required for breakpointing SFPUC reservoirs, but mostly because of the inherent danger of a boat operator being exposed to highly concentrated chlorine.

Test 3 indicated that with one mixer and minimal stratification, breakpoint chlorination could be achieved at Sunset South in 5 days. Adding a second mixer, as recommended by Solarbee, would likely result in breakpoint chlorination being achieved in less time (~2.5 days).

5.5 Solarbee Use

Tests 3 and 4 showed that Solarbee is effective in reducing stratification and improving vertical and horizontal mixing. However, depending on the number of mixers used for a particular volume of water, and the degree of initial stratification, the mixer(s) may require time to break stratification and to achieve its full mixing potential. Based on the results of Tests 3 and 4 using one mixer, WQB believes that two Solarbee units, as specified by Solarbee, would be more adequate in the summer, at Sunset South, to break stratification enough to allow the inlet momentum to mix the reservoir as designed. In this sense, Solarbee is expected to compliment mixing at reservoirs when mixing by CIP modifications is deficient (i.e. summer stratified conditions with no vertical inlet component). Little to no benefit is expected when CIP modifications are performing optimally (as was seen in Test 1 and 2).

In addition to Solarbee being effective as a supplemental mixer, the mixer would also be useful for breakpoint chlorinating a reservoir if nitrification is unavoidable. Test 3 indicated that with one mixer and minimal stratification, breakpoint chlorination could be achieved at Sunset South in 5 days. Adding a second mixer, as recommended by Solarbee, would likely result in breakpoint chlorination being achieved in less time (~2.5 days).

WQB believes that the positive results seen at Sunset South (SFPUC's largest reservoir) are an indication that Solarbee would be effective for comparable or smaller sized reservoirs with similar aspect ratios (relative dimensions). Such reservoirs may only require one mixer.

5.6 In-service Conditions

All of the results obtained in this study were formulated from tests completed while the reservoir was completely isolated (termed isolated conditions). The results showed that Solarbee can perform as specified by the manufacturer (Test 3) but can be significantly limited by initial stratification conditions (Test 4). The results also indicated that Solarbee can be effectively used for breakpoint chlorinating a reservoir, during isolated conditions, if necessary in the future. But the tests did not indicate Solarbee's ability to mix water while the reservoir was in service (termed in-service conditions), especially when a reservoir is extremely stratified and has a continual influx of cold, fresh water near the bottom. In-service conditions were not tested due to resource limitations and the difficulty associated with controlling a tracer under such conditions.

Based on the results of the study, WQB has confidence that Solarbee can perform as specified by the manufacturer (14.4 mgd), after an initial destratification threshold is reached and stratified conditions are sufficiently minimized. WQB believes this rate will likely exist regardless of whether a reservoir is isolated or in-service, but may require additional mixer units. If this assumption is correct, the supplemental mixing effectiveness of Solarbee during in-service conditions should be optimal when the Solarbee flow rate ($Q_{Solarbee}$) is equal to or greater than the average flow rate of a reservoir (Q_{ave}). The optimal number of Solarbee units needed for a candidate reservoir would then to be equal to $Q_{ave}/Q_{Solarbee}$, or $Q_{ave}/14.4$ (See Figure 13)[33].

[33] These claims are speculation, and are meant to provide preliminary estimates. They are not supported by the results of this study. Further testing is required to evaluate the true effectiveness of Solarbee mixers during in-service conditions.

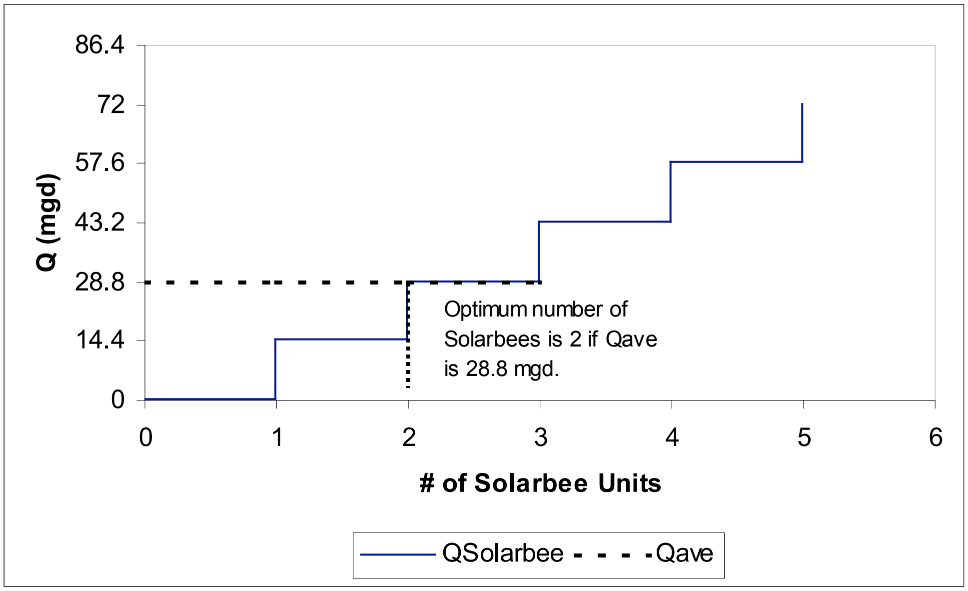

Figure 13: Estimated Number of Solarbee Units Required for In-Service Conditions

5.7 Solarbee Mixer Summary

The following tables outline the conclusions of the Solarbee study relating to the Solarbee mixer:

Solarbee Conclusions:

- If stratification exists, Solarbee mixes at a slower pace until stratification is sufficiently minimized.
- Mixing effectiveness and destratification depends on the number of mixing units used for a particular reservoir volume; the performance and number of mixers is expected to be optimum when $Q_{Solarbee} \langle Q_{ave}$ of a reservoir.
- The performance of Solarbee during in-service conditions may be limited by successive fill cycles.
- Solarbee provides effective surface dispersion.
- Employing Solarbee prior to chlorine injection reduces stratification and subsequently promotes faster and more efficient mixing.
- Solarbee is expected to compliment mixing at reservoirs when mixing by CIP modifications is deficient (i.e. summer conditions with no vertical inlet component).
- Solarbee appears reliable, cost-effective and low maintenance.
- Setup and installation can be completed in < 1 day, while a reservoir is in service, but may require more time if hatch is not available.
- The draft tube makes moving unit within a reservoir somewhat difficult.
- Solarbee has a good record (other utilities were contacted).

Breakpoint Conclusions:

- Breakpoint chlorination of Sunset South in winter can be achieved by inlet momentum and chlorine injection at the inlet; mechanical mixers are not necessary.
- During summer conditions at Sunset South, supplemental mixing would be beneficial.
- Breakpoint chlorination should be conducted with metered injection, either by rapid fill or by mechanical mixing.
- Slug injection should not be conducted when breakpoint chlorinating a reservoir.
- Breakpoint chlorination with Solarbee is optimal with metered injection occurring at the impeller.
- When breakpointing a reservoir, mixers should be employed prior to chlorine injection, and just after reservoir isolation, to maximize destratification and subsequent dispersion.
- Tests 1 and 2 indicated that breakpoint chlorination in winter could be achieved at Sunset South without supplemental mixing in roughly 15 hours.
- Test 3 indicated that with one mixer during the summer with minimal stratification, breakpoint chlorination could be achieved at Sunset South in 5 days. Adding a second mixer, as recommended by Solarbee, would likely result in breakpoint chlorination being achieved in less time (~2.5 days).

General Mixing and CIP Conclusions:

- Inlet momentum was the dominant mixing force at Sunset South during Tests 1 and 2.
- Sunset South is naturally well mixed during winter months. CIP inlet modifications were credited for good mixing seen.
- Stratification not seen at Sunset South in winter months.
- Sunset South should not require supplemental mixing in winter.
- Stratification exists at Sunset South in summer months, despite the new CIP inlet modifications.
- Stratification similar to what was seen at Sunset South occurs at other oversized SFPUC reservoirs.
- Earlier free chlorine decay estimates of 0.17 to 0.18 mg/L/day were similar to the decay seen during Test 3.
- A vertical inlet component should be incorporated into reservoir upgrades (CIP or In-house) where possible, to combat stratification.
- Previous Physical Scale Modeling (PSM) results were similar to Test 1 and 2 results.

6 Recommendations

WQB recommends Solarbee mixers be used at SFPUC based on the positive results seen in the study, on findings of previous San Francisco Water Team chloramine planning documents, and on a concurrent study evaluating alternative mixing technologies[34]. Further spatial sampling studies (chlorine and temperature) should be completed at reservoirs with new CIP modifications to verify the need for supplemental mixing at these locations.

WQB believes that the Solarbee mixers provide cost effective supplemental mixing and destratification for oversized SFPUC terminal drinking water reservoirs with poor mixing and/or chronic stratification. They also provide the mixing conditions to assist breakpoint chlorination if nitrification occurs.

Given chloramine conversion was completed in February 2004, WQB should work with CDD to decide which reservoirs would benefit most by Solarbee. The number of Solarbees prescribed for a particular sized reservoir should be carefully evaluated. Under sizing the number of units for a severely stratified reservoir will likely cause the mixer to run less efficiently and at less than its specified rate.

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[34] Evaluation of Mixing Alternatives for Distribution Reservoirs and Tanks (Charlotte Smith & Associates and Walter M. Grayman, Consulting Engineer; 2004)

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APPENDICES