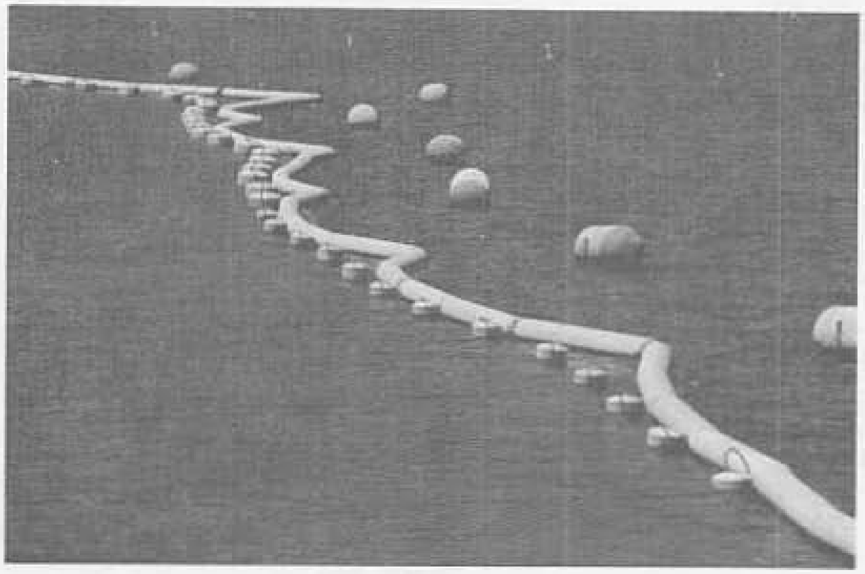
R-97-09

USE OF TEMPERATURE CONTROL CURTAINS TO CONTROL RESERVOIR RELEASE WATER TEMPERATURES



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Reclamation (Bureau of Reclamation) has constructed four temperature control curtains to reduce release water temperature at structures in the Sacramento and Trinity River drainages in northern California. Curtains can provide selective withdrawal at intake structures, control topography induced mixing, and control interfacial shear mixing associated with plunging density currents entering reservoirs. Comprehensive field monitoring has been conducted to measure curtain performance characteristics. Monitoring included extensive temperature profiling and velocity profiling using an ADCP (acoustic Doppler current profiler). This report presents and summarizes curtain performance data collected in Lewiston and Whiskeytown Reservoirs for the years 1992 through 1994.

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USE OF TEMPERATURE CONTROL CURTAINS TO CONTROL RESERVOIR RELEASE WATER TEMPERATURES

by

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Water Resources Research Laboratory
Water Resources Services
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Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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INTRODUCTION

Water delivery and hydroelectric operators are committed to meeting Federal and State water quality standards and reservoir release objectives. Water quality parameters (temperature, dissolved oxygen, taste and odor, etc.) vary with depth in reservoirs. To release water of desired quality, reservoir outlets must be located at appropriate elevations. However, many dams have limited options for withdrawal elevations. Historically, improved release control (selective withdrawal) has been achieved with expensive, rigid, gated structures. Reclamation (Bureau of Reclamation) recognized a need for lower cost alternatives that can be included in new designs or retrofitted to existing structures. This research project, which was a cooperative effort between Reclamation's Water Resources Research Laboratory, Mid-Pacific Regional Office, and Northern California Area Office, had the objective of developing lightweight flexible fabric (curtain) barriers that could be used to control reservoir release water temperatures.

Temperature control curtains are positioned around intake structures where they control withdrawal elevation. Curtains may also be positioned at other locations within a reservoir to control hydrodynamics that might adversely affect reservoir release water quality. Curtains offer substantial cost savings over traditional selective withdrawal structures. However, uncertainties with hydraulic performance, deployment, operation, maintenance, and reliability prompted this applied research project with closely monitored prototype installations.

CONCLUSIONS

- Temperature control curtains have been successfully employed to reduce release temperatures at Lewiston and Whiskeytown Reservoirs, California. Density stratified physical models were used to develop an effective temperature control curtain design.

- The largest flow through temperature gains in Lewiston and Whiskeytown Reservoirs occur at plunging flow zones where cold water flows as a density current into a thermally stratified reservoir.

- Temperature control curtains have been successfully used to reduce mixing of cold water inflows and warm surface waters in Lewiston and Whiskeytown Reservoirs, California.

- Temperature control curtains allow CVP (Central Valley Project) operators to manage hydropower generation while controlling reservoir release water temperatures.

- When the Lewiston Reservoir curtain was installed in 1992, it rapidly modified reservoir stratification, and Lewiston Reservoir release temperatures were reduced by 2.5 °F.

- 1994 data showed similar temperature gains through Lewiston and Whiskeytown Reservoirs for base load power operation and partial peaking power operations.

- 1994 data showed that peaking power operations resulted in a 3°F temperature gain in water routed through Lewiston Reservoir. Smaller temperature gains were measured at the Carr (Judge Francis Carr) Powerplant tailrace curtain. Consequently, peaking power operations should be avoided for Trinity and Carr Powerplants during periods when release temperature restrictions are in effect. Peaking operations did not negatively impact the Spring Creek Tunnel intake curtain performance.

- For similar reservoir operations, average temperature gain of water routed through Whiskeytown Reservoir in August 1988 (pre-curtain) was 3.7 °F higher than the curtain-controlled temperature gains measured in August 1994.

- ADCP (acoustic Doppler current profiler) data were useful in determining how a variety of powerplant operations affect temperature control curtain performance. Acoustic Doppler current profiler data were used to quantify the hydraulics associated with warm surface water retention at Lewiston Reservoir and the underflow jet hydraulics downstream from the Carr tailrace curtain.

- ADCP data showed underflow velocities were normally at or below the design value of 0.3 ft/s.

- Monitoring of the curtain performance resulted in an understanding of the hydraulic characteristics but also revealed that these curtains are very dynamic structures, and their performance depends on many factors, such as flow rate, powerplant operations, inflow temperatures, reservoir stratification, etc.

BACKGROUND

During the late 1980s and early 1990s, extended drought in northern California resulted in the potential for summer and early fall Sacramento and Trinity River temperatures to exceed critical levels for sustaining salmon populations. Reservoir storage had been low, and volumes of stored cold water were limited. In the critical low water year of 1992, the potential existed for reservoir release temperatures coupled with in-river warming to generate lethal water temperatures for salmon egg incubation and juvenile fish. Furthermore, anadromous fish populations in both rivers are in decline. The steelhead and salmon runs on the Trinity River are of major concern to the Hoopa Indian Tribe and are being addressed by a multi-agency task force. The "winter run" of Chinook salmon on the Sacramento River has been listed as endangered (threatened) with extinction under the Federal Endangered Species Act. Consequently, Reclamation initiated an aggressive program to modify operations and add structural features that would optimize cold water releases into the upper Trinity and Sacramento Rivers. Additional details concerning temperature control curtains and other temperature control features associated with the Sacramento Basin Fish Habitat Improvement Study can be found in the Final Environmental Assessment Report (Bureau of Reclamation, 1994).

The Shasta and Trinity River Divisions (fig. 1) of Reclamation's CVP (Central Valley Project) include Trinity and Lewiston Dams on the Trinity River and Shasta and Keswick Dams on the Sacramento River. Water from the Trinity River Basin is diverted to the Sacramento River Basin through two tunnels and two reservoirs. Trinity River water is diverted from Lewiston Reservoir through Clear Creek Tunnel to the Carr Powerplant and into Whiskeytown Reservoir. From there, water flows through the reservoir and into the Spring Creek Tunnel and through Spring Creek Powerplant. Spring Creek Powerplant releases water into Keswick Reservoir, where it combines with water released from Shasta Dam. Water released from Keswick Dam enters the upper Sacramento River. Over the course of this diversion and prior to curtain installation, the temperature of diverted Trinity River water commonly rose 10 to 13 °F (Bureau of Reclamation, 1990).

Reservoir and river system numerical models have been used to develop CVP operating guidelines. The models defined release rates that would yield an extended supply of cold water. The models were used to estimate atmospheric warming and tributary influences for predicting the reaches of river over which adequate temperatures could be maintained. In fact, in Orders WR 90-5 and WR 91-01, the California SWRCB (State Water Resources Control Board) requires Reclamation to maintain Sacramento River temperatures at or below 56 °F at the Bend Bridge temperature monitoring station (see fig. 1).

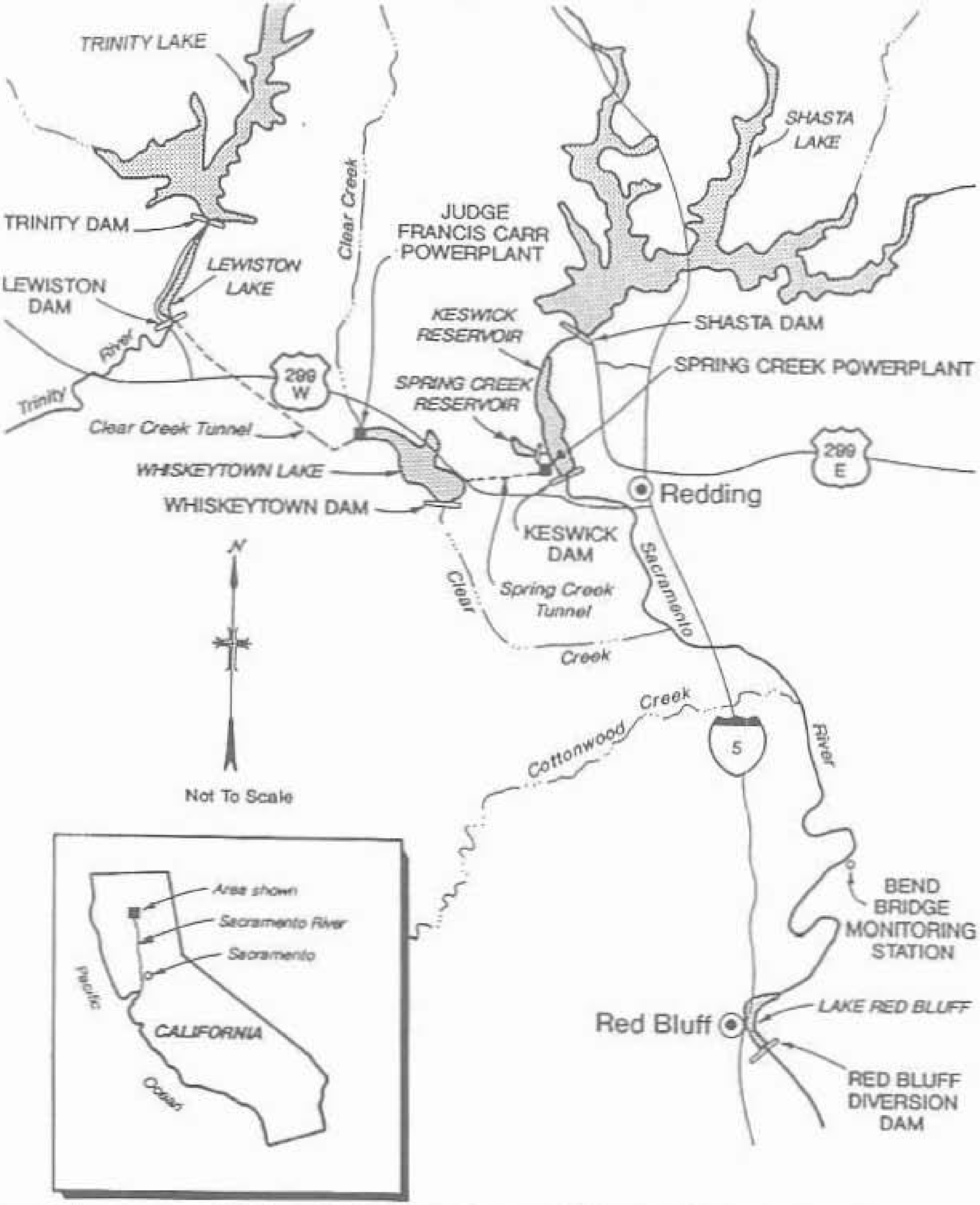


Figure 1. - Location map of the Central Valley Project—Shasta and Trinity River Divisions (not to scale).

Drought conditions in 1992 caused reduced water deliveries to agricultural and urban projects. Project operators coordinated with Federal and State agencies to develop plans to maximize temperature control in the Trinity and Sacramento River basins. As the summer progressed, it became apparent that colder releases could only be supplied from both Trinity Dam and Shasta Dam by curtailing power operations and by making all releases through low-level outlet works. At both dams, the power intakes are positioned higher than the low level outlets. Power releases were bypassed at Shasta and Trinity Dams for 170 days and 110 days, respectively, in water year 1992. About $10,000,000 in power revenues were lost that year. To provide operational flexibility and to meet SWRCB temperature requirements, Reclamation constructed three temperature control curtains and completed a selective withdrawal retrofit for the penstock intakes at Shasta Dam. This report summarizes the design, construction, and performance of the temperature control curtains in Lewiston and Whiskeytown Reservoirs.

LITERATURE REVIEW

When a reservoir is thermally or density stratified, water can be withdrawn from distinct horizontal layers or elevations. The vertical position and thickness of the withdrawal layer depends on the vertical position of the intake, intake size and orientation, withdrawal discharge, density stratification profile, topography, and boundary interference (reservoir water surface and bottom). Numerous studies have been conducted to define the upper and lower bounds of the withdrawal layer as a function of critical parameters (Bohan and Grace, 1969 and 1973; Hino, 1980; Smith, et al., 1987). Typically, these studies were conducted in laboratory facilities with simplified intake and reservoir geometry. The laboratory findings have been generally confirmed by field observations.

Structures, such as suspended curtains, can be placed in a stratified reservoir to control the vertical position, size, and orientation of the withdrawal outlet. Thus, these structures can be used to control the withdrawal from the reservoir and influence the release water quality. However, general selective withdrawal theory does not address site specific influences such as topography, approach channel shape, and intake location. Thus, variations from the withdrawal layer bounds predicted by theory can be expected. If reservoir topography is restrictive or if intake geometry is unusual, stratified physical models should be used to evaluate selective withdrawal performance and to refine structure design. Physical models were used to develop the curtain designs described in this report. Physical model results were coupled with reservoir and river mathematical models to determine reservoir and river responses to the installation of temperature control curtains.

An ASCE (American Society of Civil Engineers) Task Committee on Density Currents and Their Applications in Hydraulic Engineering has published a concise paper that summarizes the state of the art for analysis of plunging flows and flows with interfacial shear (Alavian et al., 1992). The authors note that a plunging inflow enters a reservoir as a plug flow of uniform density. At Lewiston and Whiskeytown Reservoirs, diversion inflows are colder and thus more dense than much of the reservoir water. Density differences can be caused by temperature, total dissolved solids (salinity), and suspended sediment concentrations. However, for Lewiston and Whiskeytown, density differences are predominantly caused by temperature. Depending on the density differential between the inflow and reservoir, density currents can enter the epilimnion, metalimnion, or hypolimnion. When the inflow density is less than the surface water density, the inflow will flow on top of the reservoir surface (epilimnion); this occurrence is called an overflow. This condition occurs in the spring when Clear Creek inflow, near Judge Francis Carr Powerplant, is warmer than Whiskeytown's water surface. If the inflow density is greater than the surface water density, inflows will plunge beneath the surface water. The plunge point is often marked by floating debris or a change in water clarity. The location of the plunge point is determined by a balance of the inflow momentum, the pressure gradient across the density interface separating the inflow and the surface water, and the shear forces at the bed and surface (caused by the wind). The plunge point location will vary depending on the flow rate and density, but flow rate is the dominant factor. Significant mixing occurs in the plunge zone, but the extent of mixing is difficult to determine. Estimates vary from 10 to over 100 percent, and no consistent theory is currently available to quantify the mixing (Ford and Johnson, 1983).

Interflows occur when density current leaves the reservoir bottom and flows horizontally into a stratified reservoir. Interflows are common in the summer when inflow temperatures fall between epilimnetic and hypolimnetic temperatures. Interflows need continuous inflow and/or outflow to propagate through the reservoir. If inflows or outflows stop, the interflow stalls and collapses into a thin layer. Mixing into an interflow is usually minimal because the large density gradient in the metalimnion suppresses interfacial entrainment (Ford and Johnson, 1986).

At Lewiston and Whiskeytown Reservoirs, interfacial mixing between underflow and warmer reservoir water yields inflow warming. The strength of the interfacial mixing is a function of the interfacial density gradient and interfacial shear as described by the Richardson number. Experimental work shows that mixing depends on these parameters (Ford and Johnson, 1983 and 1986). However, theory does not adequately address the influence of site specific factors such as reservoir density gradient, unsteady flow (peaking power operation), channel morphology, inflow turbulence intensities, and non-uniform velocity profiles. It was speculated that curtains might be developed to control mixing that is generated by plunging inflows (Reclamation, 1990). For example, to minimize warming of inflows, a curtain could be designed to control the mixing between the cold inflow and the warm surface water layer (epilimnion) by limiting the supply of surface water to the plunge zone. It was concluded that to achieve such a design, the under curtain velocities should be small (0.3 ft/s) to limit kinetic energy available for mixing, and a significant vertical distance should be established between the curtain bottom and the thermocline to isolate the underflows from the epilimnion.

PREVIOUS TEMPERATURE CONTROL CURTAIN APPLICATIONS

Lewiston Reservoir

The California Department of Water Resources conducted a study in 1983 and 1984 (Boles, 1985) in Lewiston Reservoir to evaluate the effectiveness of a temperature control curtain encompassing the Clear Creek Tunnel intake structure. The goal was to provide warmer water to a fish hatchery intake structure which skims water from the reservoir surface. This goal could be achieved if the Clear Creek Tunnel intake structure could be modified to selectively withdraw water from well below the water surface, thus preserving the warmer surface water for the fish hatchery intake. A 13-ft-deep, 1,100-ft-long vinyl curtain was installed in September 1983 to block surface withdrawal at the Clear Creek Tunnel intake. Monitoring of curtain performance showed that the curtain produced surface water temperature increases of 5.3 °F in 1983 and 3.4 °F in 1984. This promising study ended prematurely when the curtain fabric was damaged beyond repair during the 1984 tests.

Shasta Dam

Reclamation first considered using a temperature control curtain (fig. 2) as a selective withdrawal option for Shasta Dam (Bureau of Reclamation, 1987). Shasta Dam creates the largest reservoir in the CVP (4,000,000 acre-ft of active storage). The dam, which is 602 ft high, has a maximum hydropower release of 17,600 ft^3/s. The power intakes are located on the right abutment at elevation 815, about 240 ft above the reservoir bottom. In recent drought years, late summer and early fall water temperatures at the penstock intakes exceeded acceptable levels. Numerical models of Shasta Lake show that to achieve optimum cold water management, releases should be made from high in the reservoir in the spring and early summer, conserving cold water for the late summer and fall. Thus, a vertically adjustable curtain was required which would allow control of both under- and over-curtain withdrawals.

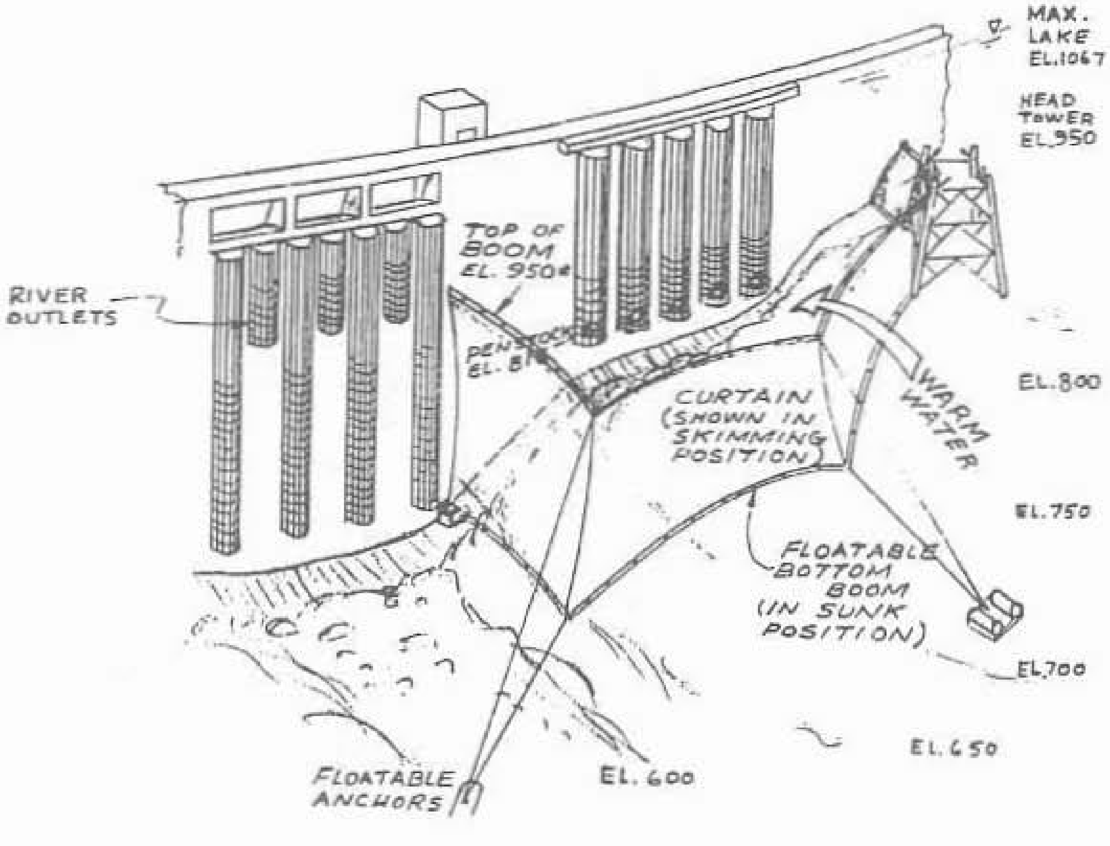


Figure 2. - Conceptual sketch of the Shasta temperature control curtain (Bureau of Reclamation, 1987).

A density stratified physical model was used to study the Shasta curtain performance (Johnson, 1991). The model defined the withdrawal characteristics, determined dynamic and density generated differentials (loading), established operations guidelines, and was used to optimize curtain design. Depending on operation, the curtain created a modified stratification between the curtain and the dam. For example, drawing release water over the top of the curtain (overdraw) resulted in a thickened warm water surface layer between the curtain and the dam. Overdraw flow often would drop as a density current from the top of the curtain to an intermediate level inside the curtain. This plunging density current resulted in substantial vertical mixing and increased release water temperatures. If the curtain extended to the surface (creating a positive barrier to overdraw), drawing water under the curtain would generate cooler temperatures in the lower regions inside the curtain. However, warm water would be entrained into the power release from above. Even with reduced discharges and thus, low velocities, mixing inside the curtain would entrain at least 10 percent of the total release from the surface layer. Because the surface water could be 18 to 27 °F warmer than the underdraw water, surface water entrainment significantly reduced curtain effectiveness.

Although the estimated curtain construction cost for Shasta Dam was one-quarter to one-third the cost of a traditional selective withdrawal retrofit, a gated steel structure that would be attached to the dam face was selected for installation (Johnson et al., 1991). Concerns about the very large curtain size, need for extensive operational flexibility, lack of experience with curtain structures, and large fluctuations in reservoir level prompted the choice of a traditional selective withdrawal design concept.

Because of the potential cost benefits, the Lewiston and Whiskeytown curtain project was initiated with the objective of installing and studying a field prototype curtain. The study goal was to develop temperature control curtain structures as a proven, generally accepted, release water quality control option.

LEWISTON RESERVOIR TEMPERATURE CONTROL CURTAINS

The 91-ft-high Lewiston Dam re-regulates releases from Trinity Dam and creates a diversion pool for Clear Creek Tunnel. Lewiston Reservoir has an active volume of 14,700 acre-ft and a maximum depth of 65 ft. During summer, the hydraulic residence time varies from 2 to 10 days. Maximum combined summer releases from Lewiston Reservoir are about 3,700 ft^3/s. In the summer of 1992 under a tight schedule, two curtains were installed (O'Haver, 1992): a reservoir curtain to cool all summer releases and an adjustable curtain surrounding a fish hatchery intake, which was designed to control hatchery inflow temperatures.

The Lewiston reservoir curtain design was developed using a physical model (Vermeyen and Johnson, 1993). The 830-ft-long, 35-ft-deep curtain was suspended from surface floats and retained by a cable and anchor system. The curtain was used to prevent epilimnetic withdrawal; thus, cooler water from the hypolimnion was released into the Sacramento and Trinity River basins.

Hydraulic Model Study

A 1:120 scale, density stratified physical model was used to examine the effectiveness of temperature control curtain structures in reducing water temperatures released through Clear Creek Tunnel and the Judge Francis Carr Powerplant (fig. 3). The scale was chosen to include, in a limited laboratory space, potential curtain locations along with reservoir topography that exerts a critical influence on the withdrawal characteristics. Although scaling effects in the physical model limit representation of turbulent mixing, the Lewiston model was used to generate qualitative results. Elements of the study included evaluating withdrawal layer thicknesses, velocity profiles at several reservoir cross sections, and resulting modifications to density stratification for a range of Clear Creek Tunnel intake flow rates. Two curtain sites were studied, one surrounding the Clear Creek Tunnel intake and the other located in the body of the reservoir, about one-half mile upstream from the intake (fig. 3).

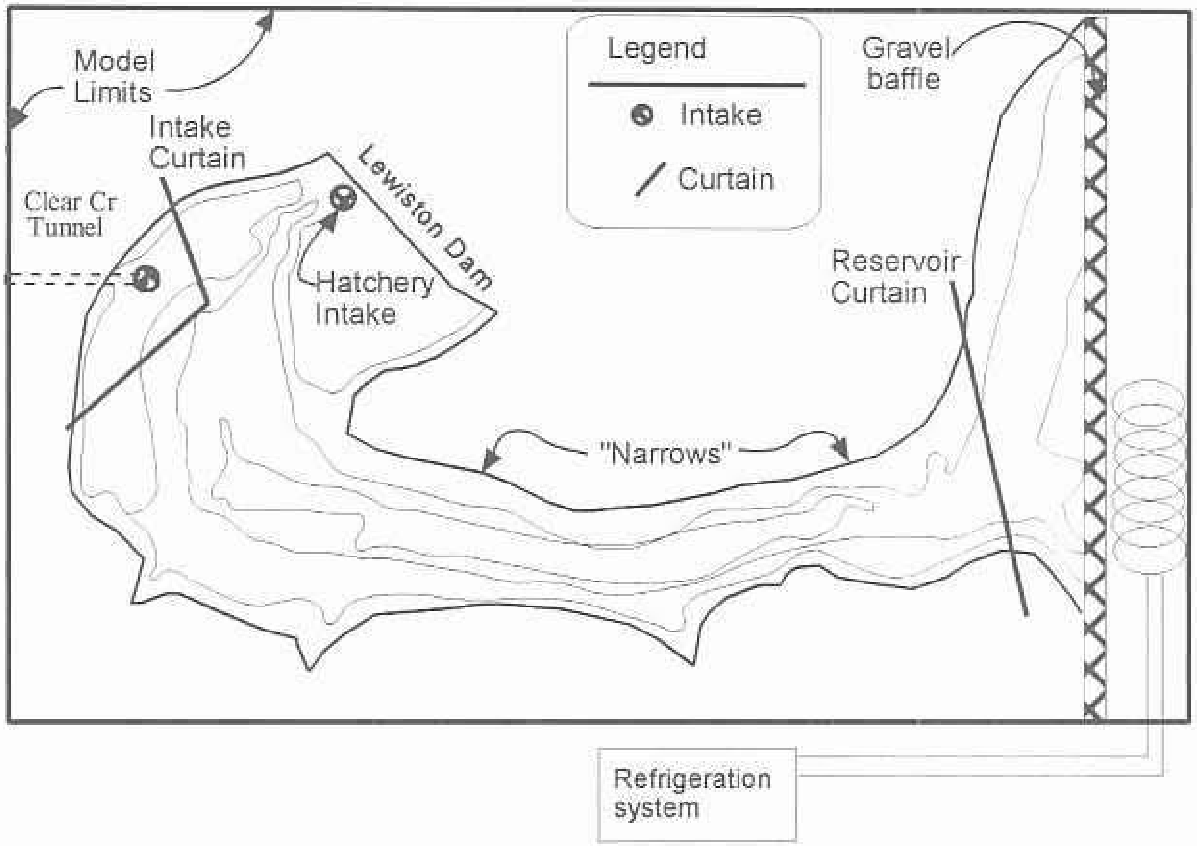


Figure 3. - Plan view of Lewiston Reservoir hydraulic model (not to scale).

Model Study Results

In general, model data indicated that both the intake and reservoir curtains were effective in cooling release temperatures when compared to the no-curtain condition. Curtain effectiveness depended on design, location, discharge, and topographic effects. At discharges in the 2,500- to 3,700-ft^3/s range, stratified flow through the "narrows," a restricted portion of the reservoir, caused mixing with substantial release warming. Locating the reservoir curtain upstream from the "narrows" controlled release warming by preventing epilimnetic water from feeding the mixing zone. For the reservoir and discharge conditions observed in the physical model, the reservoir curtain reduced water temperatures released to the Clear Creek Tunnel by about 2.5°F.

The physical model showed that two curtains provided the highest release temperature control for a range of operational discharges of 1,000 to 3,700 ft^3/s. The intake curtain supplied release temperature control at low discharges, and the reservoir curtain provided release temperature control at higher discharges. Because reservoir operations are normally in the high flow range, only the reservoir curtain was recommended for installation.

Lewiston Reservoir Prototype Curtains

Reclamation constructed and installed an 830-ft-long, 35-ft-deep temperature control curtain in Lewiston reservoir in August 1992. The curtain was installed at the reservoir curtain location (upstream from the narrows) identified during the physical model study.

In addition to the reservoir curtain, a second curtain funded by the California Department of Fish and Game was installed surrounding the Lewiston Fish Hatchery intake structure. The hatchery desired both warmer and cooler water depending on the season and fish rearing requirements. Therefore, a 300-ft-long, 45-ft-wide curtain was designed which could skim warmer water and/or underdraw cooler water depending on whether the curtain was in a submerged or floating position. By allowing the surface flotation tanks to be partially filled with water, the entire curtain can be submerged, creating an underwater dam which blocks cooler water while permitting the warmer water to be drawn over the top. Raising this curtain to a floating position is accomplished by de-watering the tanks using compressed air.

Curtain Design Concepts and Criteria

Curtain siting was an important component of the successful implementation of temperature control curtains in Lewiston and Whiskeytown Reservoirs. Initial site selection was made using the simple energy balance shown by equation 1:

$$\frac{V_o^2}{2g} \leq Y\frac{\Delta\rho}{\rho_o} \tag{1}$$

where:

V_a = mean flow velocity under the barrier, ft/sec
Y = vertical distance from bottom of the barrier to the bottom of the epilimnion, ft
$\Delta\rho$ = $\rho_o - \rho_a$, slugs/ft^3
ρ_o = mean density between the bottom of the epilimnion and the bottom of the curtain, slugs/ft^3
ρ_a = representative epilimnion density, slugs/ft^3
g = gravitational constant, ft/sec^2

Application of this energy balance resulted in an initial proposal to locate the curtain at a section where the underflow velocity head was equal to or less than the potential energy required to displace buoyant epilimnetic water downward to the bottom of the curtain. As previously discussed, final curtain locations were determined using hydraulic model studies.

Lewiston and Whiskeytown temperature control curtains were designed by engineers from Reclamation's Northern California Area Office. The design concepts and criteria are summarized as follows:

1) Maximum under curtain velocities are limited to 0.3 ft/s.

2) Curtains are fully floatable for ease of installation and maintenance; all components are surface accessible.

3) Curtains are adjustable to accommodate fluctuating reservoir levels and large construction tolerances.

4) Curtain vertical positions can be changed and components retrieved using compressed air flotation.

5) No structural loads are transferred to the Hypalon curtain fabric.

6) All pressure-bearing components of the curtain fabric and main load carrying chains are sagged (70 to 75 degrees of arc) to limit member loading.

7) The Lewiston Reservoir curtain can be easily opened to allow warmer surface water passage for fish hatchery withdrawal during colder months.

8) All anchor connections are attached to the top of the curtains to permit rapid curtain removal.

9) The maximum curtain deflection (under full simultaneous density and dynamic loading) is limited to 40 percent of the working curtain depth. The average design load is 0.6 lb/ft^2.

10) Mechanical connections are designed with a factor of safety of 15 to accommodate wear and fatigue caused by wave loading. The main support chain has redundancy at wear points.

11) Hypalon curtain fabric was used because it is resistant to water, sunlight, bacteria, organic growth, and corrosion, and is designed with a loading factor of safety of 10 to accommodate unusual forces during assembly and installation.

12) All steel surfaces are coated with a zinc-based paint to prevent corrosion.

13) Use of divers should be minimized for curtain installation and maintenance.

Description of Curtain and its Components

Figure 4 shows the basic components of a curtain and their relationship to each other. The following is a description of each component and its function:

Top Boom Floating Tanks.—These tanks support each curtain section from the water surface. They are fabricated from steel pipe and are partially filled with polyethylene foam. Drain valves may be mounted to the bottom flanges as desired to convert a floating section of a curtain to a section which also sinks. The amount of foam in the tank is sufficient to provide buoyancy to the top of the curtain but not adequate to float the whole curtain; the top tanks must be full of air to float the whole curtain.

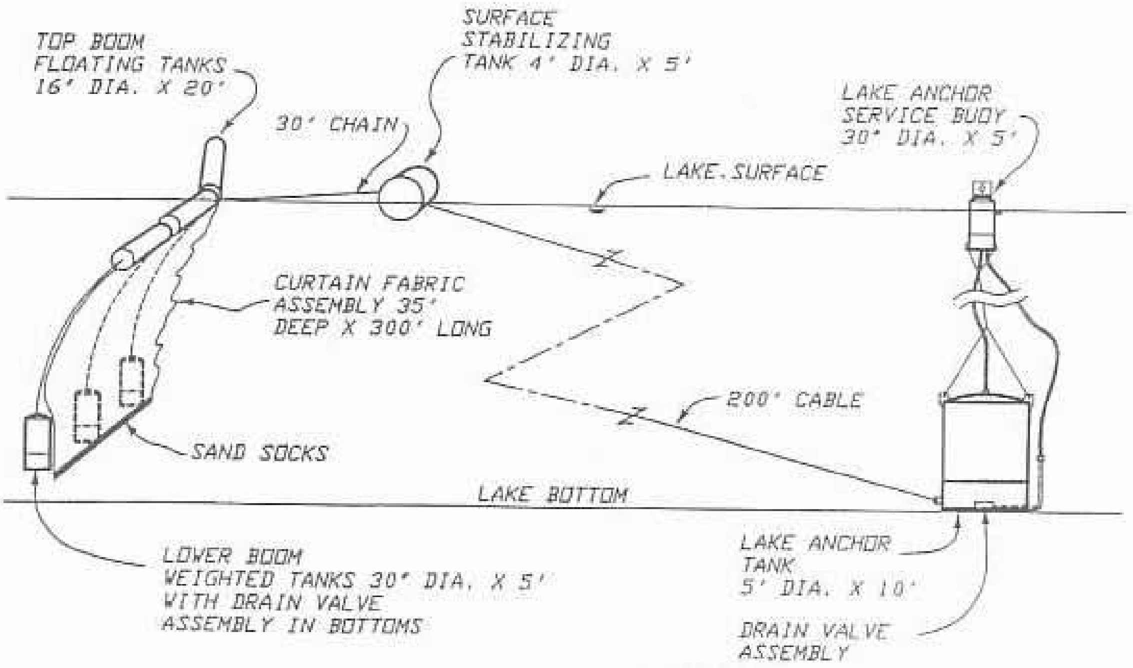


Figure 4. - Elevation view of a typical temperature control curtain and its structural components.

Lower Boom Weighted Tanks.—These tanks are weighted with concrete and hold the bottom of the curtain down against the pressure forces. Drain valves installed in the bottom of each tank permit the tanks to be raised to the water surface using compressed air. The tanks are fabricated from rolled steel. A 3/8-inch chain connects these tanks to each other and to the top boom tanks.

Lake Anchor Tanks.—These tanks are floatable, 10,000-pound concrete weights with spikes on the bottom. They are used in conjunction with the surface stabilizing tanks to anchor the curtain. A drain valve in the bottom of each tank allows them to be raised to the surface with compressed air. One anchor tank is used for every 100 ft of curtain.

Surface Stabilizing Tanks.—These tanks yield a horizontal load into the top of the curtain, which prevents anchorage forces from pulling the curtain under water. They are fabricated from rolled steel sheet and connected to other curtain components with 1/2-inch, 30,000-pound, tensile strength chain.

Lake Anchor Service Buoy.—This buoy retains the lake anchor tank flotation hoses. The buoy also includes warning signs for boat navigation.

Curtain Fabric Assembly.—The curtain fabric is 60-mil, nylon reinforced, Hypalon rubber. The curtain is heat welded into continuous pieces 300 ft long. Overlaps of 14 ft occur between pieces when joined together in the field. All seams and grommets are factory installed. Sand socks, made from 120-mil Hypalon filled with sand, were connected at the grommets to the bottom of the curtain on final field assembly. The sand socks hold the bottom of the curtain down between the lower boom tanks.

Drain Valve Assembly.—This valve was designed to allow raising and lowering any tank by adding or removing compressed air from the tank through a single hose connected to the top of the tank. The valve has a polyurethane, 4-inch-diameter, foam-filled ball which floats to open the valve when water is present. This design permits the valve to pass water in both directions but prevents the discharge of air. With this valve installed in tanks connected in series, all tanks can be controlled from one hose.

Construction Details

Total time for engineering, procurement, and construction was 5 months. A fast-track design and construction process was used in which engineering was completed after the contractor began construction. GSE Construction of Livermore, California, began subcontract work in June 1992 under a negotiable price agreement with Reclamation. By August 26, 1992, the 830-ft-long reservoir curtain was operational. The 300-ft-long hatchery curtain was operational 2 weeks later. The hatchery curtain was completely assembled and installed in 7 working days. The costs for the reservoir curtain and the hatchery curtain were $650,000 and $150,000, respectively.

WHISKEYTOWN RESERVOIR TEMPERATURE CONTROL CURTAINS

Whiskeytown Reservoir receives diverted Trinity River water through Carr Powerplant. The diverted flow is passed through the Whiskeytown Reservoir, the Spring Creek Tunnel, Spring Creek Powerplant, and released into Keswick Reservoir and then the Sacramento River. The 214,000-acre-ft, 250-ft-maximum-depth reservoir is located on Clear Creek, an intermittent tributary of the Sacramento River. Throughout the summer, diverted inflows are dominant; typical maximum discharges are about 3,800 ft^3/s. The diverted inflows are cold, and Spring Creek Powerplant withdrawals are made from deep in the reservoir. So ideally, inflows would be routed through the hypolimnion or the cold water zone of the reservoir and into the Spring Creek Tunnel intake structure.

Carr Powerplant Tailrace Curtain

Cold water from the Carr Powerplant enters Whiskeytown Reservoir and pushes warm surface water ahead of it. As the reservoir cross-sectional area increases, the inflowing cold water velocities decrease and a point is reached where the cold water plunges below the warm surface water. From this plunge point, an interface exists where the top of the cold water inflow mixes with the bottom of the warm water layer above. The extent of this interfacial mixing zone is exaggerated by the long, narrow inflow channel. The net effect is considerable warming of the inflowing cold water. As a result, the Carr Tailrace curtain was designed to hold back the warm surface water and introduce the cold inflow into the Whiskeytown Reservoir hypolimnion with reduced mixing.

Hydraulic Model Study

A 1:72 scale, density stratified physical model was used to optimize curtain placement and size to assure that cold inflow was introduced at sufficient depth and at velocities low enough to minimize mixing. The energy balance previously described was initially used for site selection. Three curtain locations were evaluated. Initially, warm water depletion rates without the curtain were determined to establish the baseline conditions. Then, depletion rates for three curtain sites were determined. Depletion rates of epilimnetic water downstream from the curtains were used to indicate the degree of mixing and overall curtain effectiveness. Because of scaling inaccuracies (fully turbulent flows could not be generated at a 1:72 model scale), the resulting depletion rates were qualitative representations of the curtain performance.

Model Study Results

The model indicated that a 600-ft-long, 40-ft-deep curtain should be installed downstream from Carr Powerplant at a cross section that is about 90 ft deep (fig. 5). As with previous modeling efforts, model study results were qualitative, indicating relative reductions in mixing achieved with various curtain designs and locations. The optimum curtain location was about 1.5 miles downstream from Carr Powerplant and just upstream from the Oak Bottom Campground and Marina. The curtain had to be located upstream from the campground, otherwise, a popular swimming beach would be located on the cold water side of the curtain.

Construction Details

The Carr Powerplant tailrace curtain was completed on June 6, 1993. The curtain was fabricated and installed over a 1-month period at a cost of $500,000. The curtain was of similar design to the Lewiston Reservoir curtain. The curtain was designed for removal in the winter to avoid storm runoff with heavy debris loads, which could damage the curtain. Because of the heavy recreational use of the reservoir, this curtain was designed to allow boat passage. A 16-ft-wide, 6-ft-deep boat passage was constructed into the top boom of the curtain as is shown in figure 6. The boat passage was positioned in a slack water area about 100 ft from the underflow zone. The boat passage has an adverse effect on curtain performance because warm water passes through the opening and feeds the mixing zone. The differential loading across the curtain, influenced by both density and dynamic effects, and the resulting leakage rates through the boat passage, are not well defined. However, if leakage is found to significantly reduce curtain efficiencies, a boat lock design may be pursued.

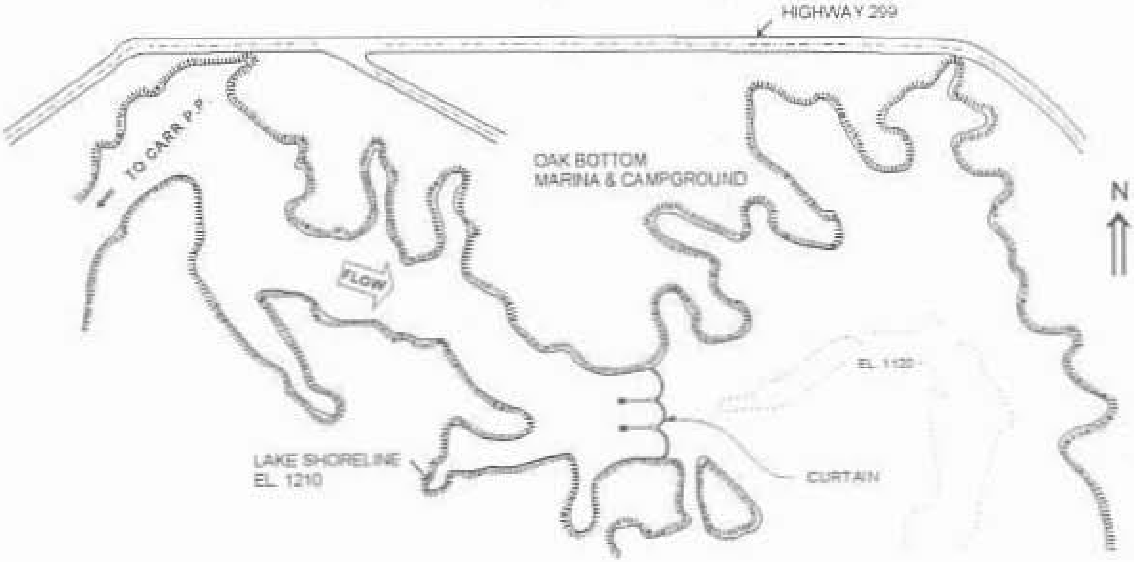


Figure 5. - Location map of the Carr tailrace curtain site, Whiskeytown Reservoir, California (not to scale).

Figure 6. - Photograph of the 16-ft-wide, 6-ft deep boat passage in the Carr Powerplant tailrace curtain.

Spring Creek Powerplant Intake Curtain

The Spring Creek Powerplant intake sits in an excavated basin located off of the deepest portion of Whiskeytown Reservoir (fig. 7). A physical model study was not conducted because the withdrawal is from a large, unrestricted impoundment. Pre-curtain temperature profiles collected over the intake structure indicated that during diversions, the intake basin geometry generated a deepened warm water layer, possibly caused by a submerged, vortex-like effect. Consequently, considerable warming of releases occurs with higher flows even though the intake is located nearly 100 ft below the reservoir surface. For example, in July 1992, temperatures measured at the Spring Creek Tunnel intake (El. 1085) were 4 °F warmer than at the same elevation in the main body of the reservoir. The curtain configuration was selected to eliminate the influence of the intake basin, thus preventing the withdrawal of epilimnetic water. Like the Lewiston Reservoir curtain, the Spring Creek Tunnel intake curtain was designed to exclude the warm surface water and allow cold water withdrawals.

Figure 8 is an interesting photograph taken by a technician servicing the temperature monitoring equipment. This photograph shows a circulation which developed inside the curtain. The circulation is highlighted by debris on the water surface. This circulation developed in the spring when temperature stratification was weak. This photograph verifies that a circulation still develops inside the curtain. However, the curtain limits the supply of epilimnetic water, which minimizes the warming of water diverted into the Spring Creek Tunnel.

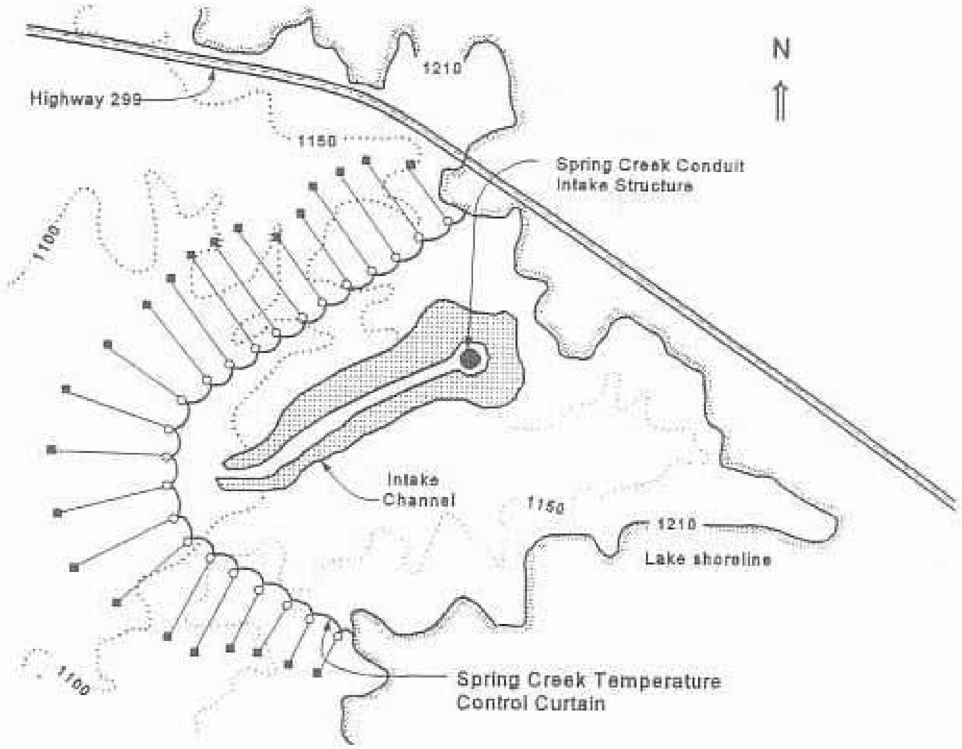


Figure 7. - Location map of the Spring Creek Tunnel intake curtain, Whiskeytown Reservoir, California (not to scale).

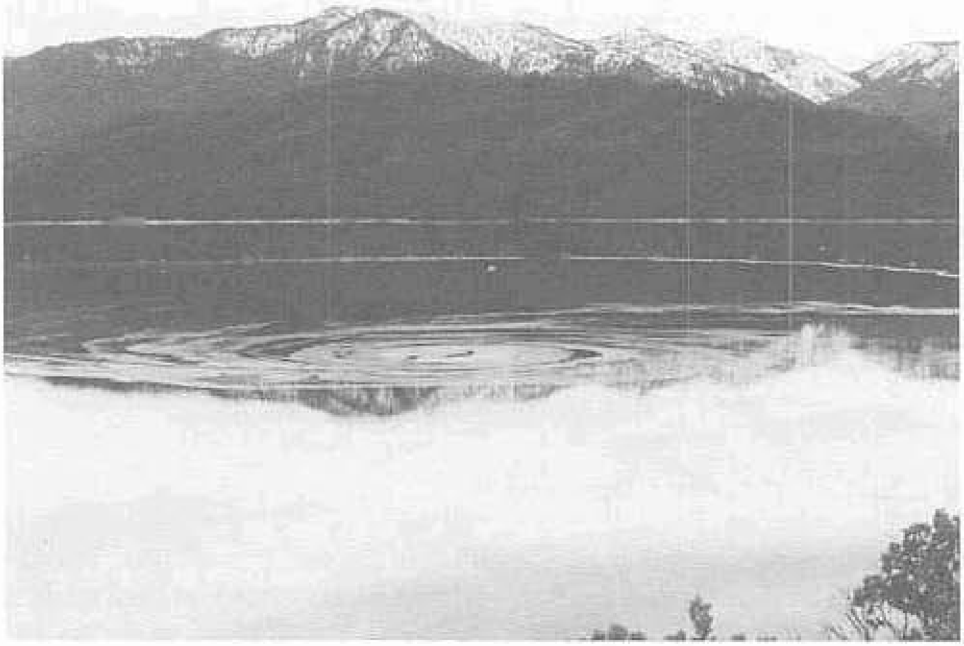


Figure 8. - Photograph of a large-scale circulation which formed over the Spring Creek Tunnel intake structure in the spring of 1995. The temperature control curtain is visible in the background. Photograph by John Martin.

Construction Details

A 100-ft-deep, 2,400-ft-long, surface suspended curtain which enclosed the Spring Creek Tunnel intake basin was completed on July 1, 1993. The Spring Creek curtain was fabricated and installed over a 4-month period at a cost of $1,800,000.

FIELD EVALUATIONS

Reservoir Operations

Reservoir operations are an important component in the analysis of temperature control curtain performance. A summary of the average monthly operations of Whiskeytown Reservoir is presented in table 1. Also included in table 1 are the release water temperatures, when available, for Carr and Spring Creek Powerplants. Operations for Lewiston Reservoir are not included because they are almost identical to the Whiskeytown Reservoir operations. The reason for the similarity is that during the summer months, both reservoirs are kept at a nearly constant water surface elevation. Consequently, flows from Lewiston passing through Carr Powerplant must be passed immediately through Spring Creek Powerplant. Similarly, Carr Powerplant flows are almost always the same as outflows from Trinity Dam. When possible, Carr and Spring Creek powerplants are operated to produce power during periods of peak power demand.

Historical data indicate that large volumes (on average 1.3 million acre-ft) of Trinity River water are diverted to the Sacramento River basin in the months of July through September. Ideally, Trinity River diversions are cold enough to help cool warmer water passing through the Shasta Powerplant to help meet the 56 °F temperature requirement in the Sacramento River below Keswick Reservoir. Diversions are stopped if the diverted water gets too warm. This situation occurred in 1992 when northern California was experiencing a drought and again in 1993, when a wet year limited transbasin diversions. Consequently, the only month with similar operations for pre- and post-curtain conditions was August for years 1988 and 1994, respectively. As a result, the majority of the performance evaluations will be based on data collected from these comparable months.

1992 Curtain Installations and Operations

The Lewiston Reservoir curtain was installed in late August 1992, which allowed a short time period to collect performance data during the 1992 stratified season. A summary of the average monthly releases through Carr Powerplant (outflows) is contained in table 1. Peaking power operations were typical during the 1992 evaluation period.

1993 Curtain Installations and Operations

Two Whiskeytown Reservoir curtains were installed in the summer of 1993. The Carr Tailrace curtain was installed on June 8, and the Spring Creek curtain was installed on June 30, 1993. Although an extensive monitoring system was installed, very limited performance data were collected in 1993. During the wet year of 1993, only intermittent diversions were made through Carr Powerplant and into Whiskeytown Reservoir during the spring and early summer. As a result, the Oak Bottom curtain could not deliver cold water inflows as designed.

This operational scenario resulted in August water temperatures that were too warm (above 56 °F) to be diverted into the Sacramento River. Consequently, continuous, high volume diversions did not occur in 1993. As a result, meaningful curtain evaluations were not possible in 1993.

Table 1. - Summary of Whiskeytown Reservoir operations for July through September 1988-1994.

Year	Water Surface Elevation (ft)	Carr Powerplant Flow (ft^3/s)	Carr Powerplant Release Temperature (°F)	Spring Creek Powerplant Flow (ft^3/s)	Spring Creek Powerplant Release Temperature(°F)
July Mean Monthly Values					
1988	1209.01	2391.3	53.4	2304.4	59.7
1989	1209.01	2524.1	51.5	2635.9	N/A
1990	1208.91	2471.7	49.2	2458.4	N/A
1991	1208.96	1533.7	N/A	1514.4	N/A
1992	1209.08	1124.1	N/A	1076.3	57.2
1993	1209.09	1187.7	55.9	1255.3	53.7
1994	1209.01	2991.5	49.3	2956.0	52.3
August Mean Monthly Values					
1988	1209.09	3272.3	49.6	3280.7	56.8
1989	1208.92	2257.3	50.5	2227.8	N/A
1990	1209.00	1646.9	50.2	1617.8	N/A
1991	1208.85	2504.3	N/A	2463.6	N/A
1992	1209.06	523.7	55.1	451.2	57.0
1993	1209.18	690.4	53.2	654.0	56.3
1994	1209.00	2823.0	49.4	2809.0	52.9
September Mean Monthly Values					
1988	1209.05	3503.7	49.0	3529.3	54.7
1989	1208.74	2914.0	49.0	2978.2	N/A
1990	1208.94	2757.8	48.9	2742.2	N/A
1991	1202.14	2981.9	N/A	3446.2	N/A
1992	1208.98	493.6	53.1	415.4	58.5
1993	1209.12	751.0	51.9	734.0	57.9
1994	1208.90	992.0	51.1	962.0	54.1

1994 Operations

In 1994, water was diverted through the system continuously beginning in mid-May, which provided optimum conditions for curtain evaluation. For about a 2-month period, full capacity base load power operations were maintained at both the Carr and Spring Creek Powerplants. As of late July, reservoir operations were modified to a partial peaking power generation mode. Full peaking power operations were started in September. Extensive monitoring using thermistor chains and an ADCP (acoustic Doppler current profiler) was conducted to document curtain performance.

SYSTEM-WIDE PERFORMANCE EVALUATION

In 1990, a value engineering team was formed to investigate and develop methods to control release water temperatures through the Spring Creek Powerplant (Reclamation, 1990). Observations of temperature gains as water flows from Trinity Lake (formerly known as Clair Engle Reservoir) through Lewiston and Whiskeytown reservoirs and the Spring Creek Powerplant, using limited data collected in 1987, 1988, and 1989, are summarized as follows:

- A 2 °F increase in water temperature occurs between hypolimnetic water in Lewiston Reservoir and water released into the Carr Powerplant tailrace. The temperature increase results because the Clear Creek Tunnel intake is positioned near the surface of Lewiston Reservoir. As a result, the withdrawal zone includes a combination of epilimnetic and hypolimnetic water. Warming was also identified in the 10.8-mile-long Clear Creek Tunnel, but the temperature gain was not quantified.
- A 3 to 5 °F increase in water temperature occurs as water released into the Carr Powerplant tailrace flows as a density current into the hypolimnion of Whiskeytown Reservoir. The temperature gain likely results from interfacial mixing, which occurs as cold water released from Carr Powerplant plunges below the warm surface water in the reservoir.
- A 3 to 4 °F increase in water temperature occurs between hypolimnetic water in Whiskeytown Reservoir and water released into the Spring Creek Powerplant tailrace. The temperature increase likely results from the withdrawal zone extending into the epilimnetic water above the Spring Creek Tunnel intake structure. Warming was also identified in the 3.1-mile-long Spring Creek Tunnel, but the temperature gain was not quantified.

Because of limited pre-curtain temperature data, August 1988 was the only month during which reservoir operations resembled post-curtain operations during August 1994. As a result, performance evaluations were based on data collected from these comparable months.

A comparison of August data for 1988 and 1994 indicated that for similar reservoir operations, the Lewiston and Whiskeytown Reservoir curtains reduced the Spring Creek Powerplant release temperatures by 3 to 5 °F from the pre-curtain condition. This comparison was conservative because estimates of Trinity Dam release temperatures were probably 1 °F cooler because the water surface elevation at Trinity Lake was 30 ft higher in 1988. In addition, average daily flows in August 1988 and 1994 were 3,300 and 2,800 ft^3/s, respectively. Higher flows in 1988 would have reduced net temperature gain through the system because greater warm water dilution would occur. For example, 1988 data showed a decrease in Spring Creek Powerplant release temperatures from 59.7 °F in July to 56.8 °F in August when flows were increased from 2,300 to 3,300 ft^3/s. Another possible reason for the decrease in release temperatures was a change in power operations (e.g., changing from peaking to base load power operations). However, this relationship could not be confirmed because the discharge data available for 1988 were average daily values.

An analysis of the August 1988 temperatures measured at Carr and Spring Creek Powerplant tailraces showed that an average 7.2 °F temperature gain occurred between Carr and Spring

Creek Powerplants. A similar analysis of the August 1994 data showed an average 3.5 °F temperature gain between Carr and Spring Creek powerplants. A comparison of similar data for Carr Powerplant releases showed that August 1994 release temperatures were 0.2 °F cooler than in 1988. The apparent poor performance of the Lewiston Reservoir curtain was probably a result of the differences in the Trinity Lake pool elevation and diversion flow rates.

In summary, for August 1988 operations (pre-curtain), a 3.5 °F temperature gain occurred in Lewiston Reservoir, and a 7.2 °F gain occurred in Whiskeytown Reservoir. For August 1994 operations, a 3.3 °F temperature gain occurred in Lewiston Reservoir, and a 3.5 °F gain occurred in Whiskeytown Reservoir. This analysis demonstrates that most of the curtain benefit occurs in Whiskeytown Reservoir. This analysis contains some uncertainties, which include unknown meteorological conditions (wind, air temperatures, relative humidity, etc.), unknown hourly reservoir operations for 1988 data, and travel time effects on water routed through the Lewiston and Whiskeytown reservoirs.

LEWISTON RESERVOIR AND FISH HATCHERY CURTAIN EVALUATIONS

Reclamation, U.S. Fish and Wildlife Service, and California Department of Fish and Game implemented a monitoring program to evaluate the Lewiston Reservoir temperature control curtains. Temperature profiles were measured upstream and downstream from the reservoir curtain site for pre- and post-curtain conditions. Measurements were also collected in the Clear Creek Tunnel and Lewiston Fish Hatchery intake structures. Two criteria were used to determine the performance of the two curtains deployed in Lewiston Reservoir. The first criteria was to determine if the curtain was effective in modifying the reservoir stratification. The second criteria was to determine if the temperature gain of water being conveyed through the reservoir was reduced.

Figure 9 presents a set of pre- and post-curtain temperature profiles collected from August 15 through September 4, 1992, which illustrate the modification to the reservoir stratification. The reservoir curtain installation began on August 21 (day 234) and was fully operational on August 26, 1992 (day 239). The 35-ft-deep curtain is represented on figure 9 by a vertical bar. Pre-curtain profiles collected upstream and downstream from the curtain site are essentially identical, but post-curtain profiles show a substantial modification to the reservoir stratification. The profiles collected upstream from the curtain indicated a slight thickening of the epilimnion. Profiles collected downstream from the curtain indicated an upward displacement of the thermocline and a very shallow epilimnion. Minor fluctuations in the stratification, especially surface temperatures, were attributed to variable reservoir operations and meteorological conditions.

A thicker epilimnion forms upstream from the curtain because warm water accumulates and increased energy is available at depth to draw warm water downward. These profiles were collected during peaking power operations rather than base load operations at Carr Powerplant. For base load operations, the temperatures inside the curtain should be even more homogenous because warm water would not be able to accumulate as it does during periods with no power generation.

Figure 10 shows 1992 Lewiston Reservoir operations, air temperatures, hourly temperatures collected in Clear Creek Tunnel, and the Lewiston Fish Hatchery intake temperatures. Figure 10a shows the reservoir operations for the period of evaluation and hourly air temperatures measured at Lewiston Dam. These data help explain the short-term variations in Clear Creek Tunnel and Lewiston Fish Hatchery intake temperatures. However, the long-term variation in withdrawal temperatures was a direct result of the temperature control curtains. Figures 10b and 10c show the effectiveness of the reservoir and hatchery curtains in reducing water temperatures entering the intakes for several days after curtain installation. For similar operational conditions (flow, duration, time of day), temperatures released through Carr Powerplant were decreased by 1.5 to 2.5 °F (fig. 10b). This result corresponded well to the reservoir and discharge conditions observed in the physical model, where the reservoir curtain reduced water temperature released through Clear Creek Tunnel by about 2.5 °F. The limited cooling achieved was in part caused by weak temperature stratification in Lewiston Reservoir. During high diversions, the relatively shallow reservoir can be fully flushed in less than 3 days and experiences significant mixing. Figures 10b and 10c both show reduced diurnal fluctuations in withdrawal temperatures because base flow surface withdrawals (200 ft^3/sec) to the hatchery, in combination with Clear Creek Tunnel withdrawals, evacuated warm surface water while the curtain blocked epilimnetic replacement water. In other words, warm water was withdrawn faster from inside the curtain than it could accumulate.

Figure 10c shows the versatility of the Lewiston fish hatchery curtain. Initially, curtain installation was completed and set in an underdraw position (day 248) and was tested in raised and lowered positions on day 252 and finally set in a skimming position on day 254. Underdraw operation reduced withdrawal temperatures an additional 1.5 °F for a total reduction of 4.0 °F with respect to pre-curtain temperatures. After 6 days of operation, the hatchery curtain was submerged to withdraw warmer water from the surface of Lewiston Reservoir. Skimming operations increased hatchery withdrawal temperatures by about 1.5 °F, which was similar to the withdrawal temperatures measured prior to installation of the hatchery curtain. This performance was indicative of a weak stratification which existed downstream from the reservoir curtain. However, hatchery withdrawal temperatures might be further increased in the fall and winter by breaching the reservoir curtain to allow all available warm surface water upstream from the reservoir curtain to replenish surface withdrawals.

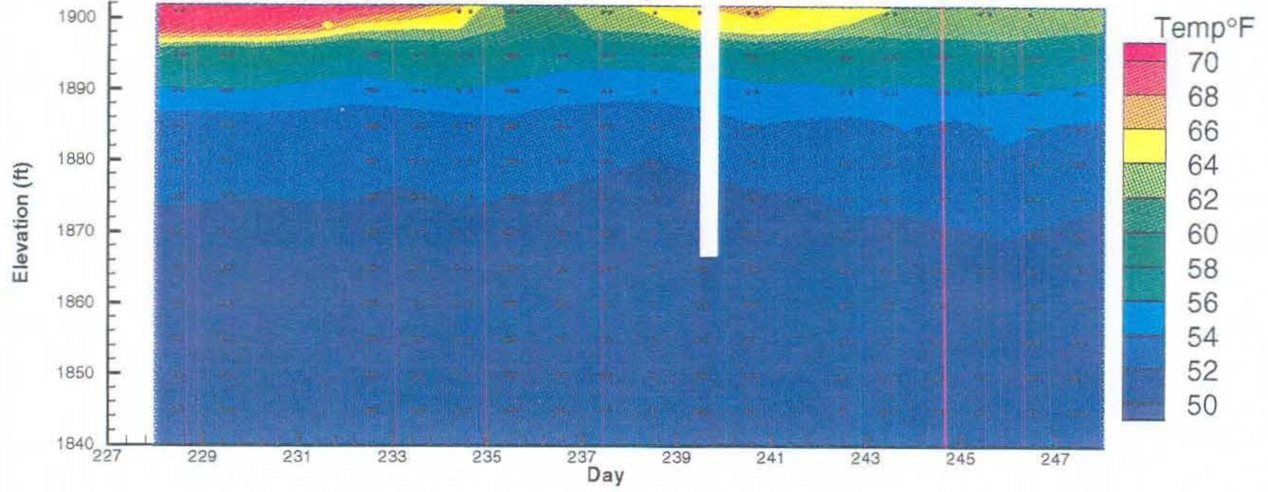
Figure 11 presents 1994 data that illustrate the curtain's performance for three types of power operations at Trinity and Carr Powerplants:

1. During calendar days 220 through 228, the flows through the reservoir were base load power operations, and the average daily discharge was about 3,200 ft^3/s.

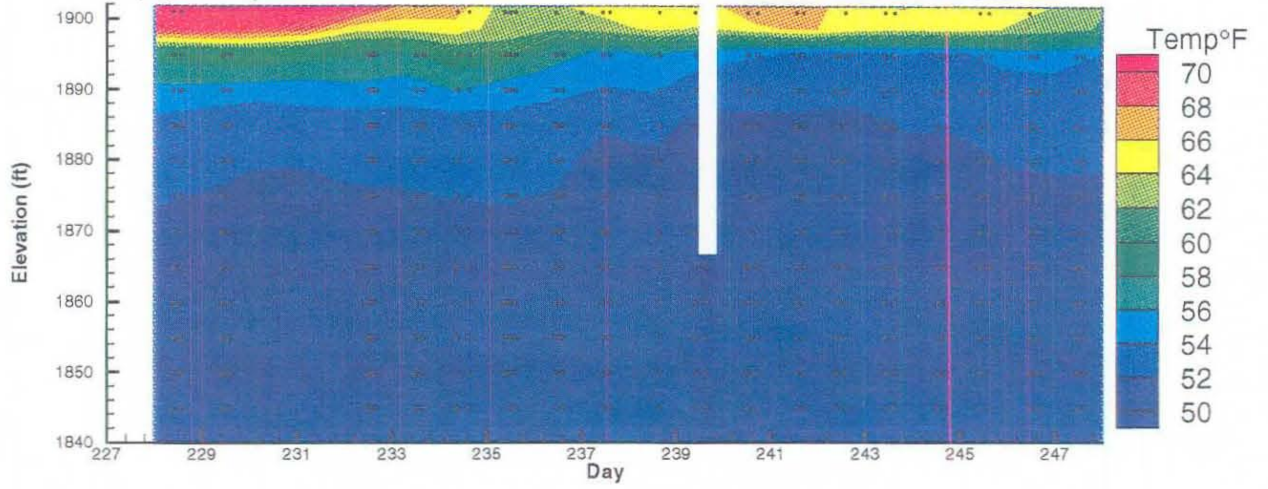
2. During days 229 through 241, partial peaking power operations were in effect with 1 turbine on continuously at 1,800 ft^3/s, and peaking was performed with the second turbine operating for 12 to 15 hours a day for a total flow of 3,500 ft^3/s. For this period, the average daily discharge was about 2,900 ft^3/sec.

3. During days 243 through 260, peaking operations were used with 1 and occasionally 2 turbines operating for 6 to 12 hours. For this period, the average daily discharge was about 500 ft^3/sec.

(A) Temperature Profiles Collected Upstream of Reservoir Curtain



(B) Temperature Profiles Collected Downstream of Reservoir Curtain



(C) Temperature Profiles Collected near Clear Creek Tunnel Intake

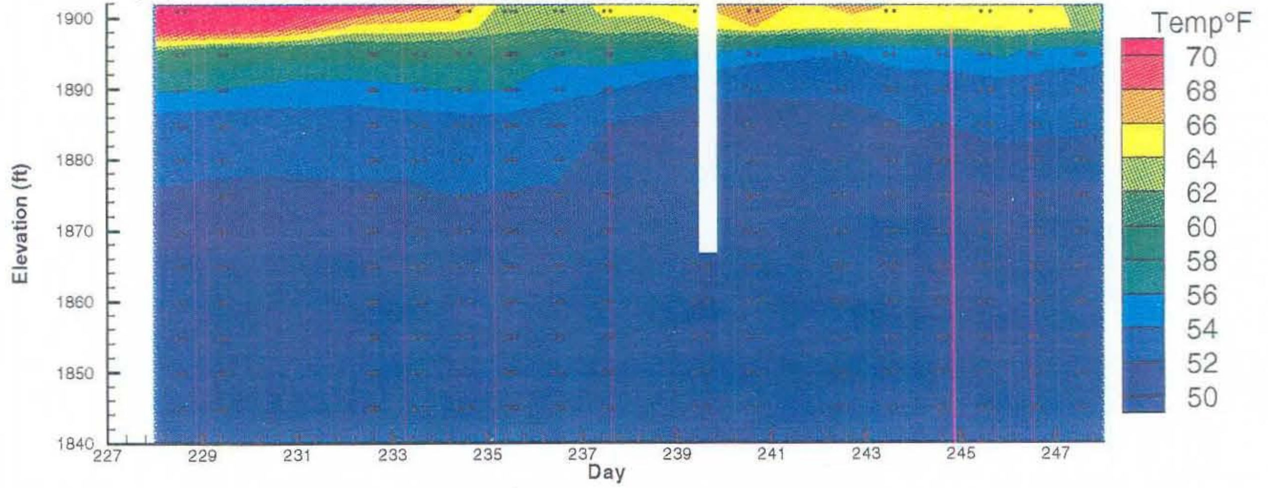
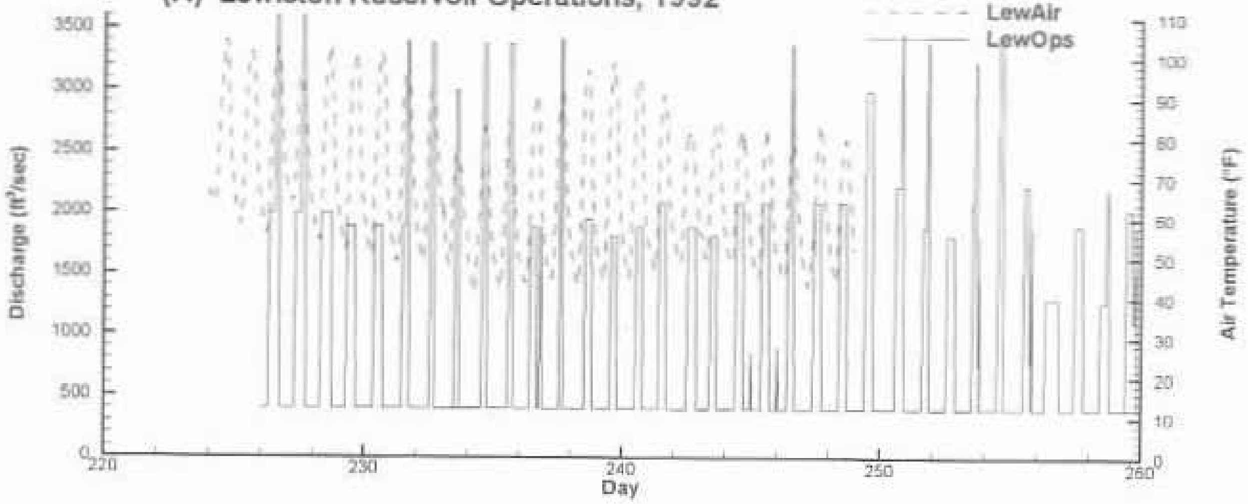
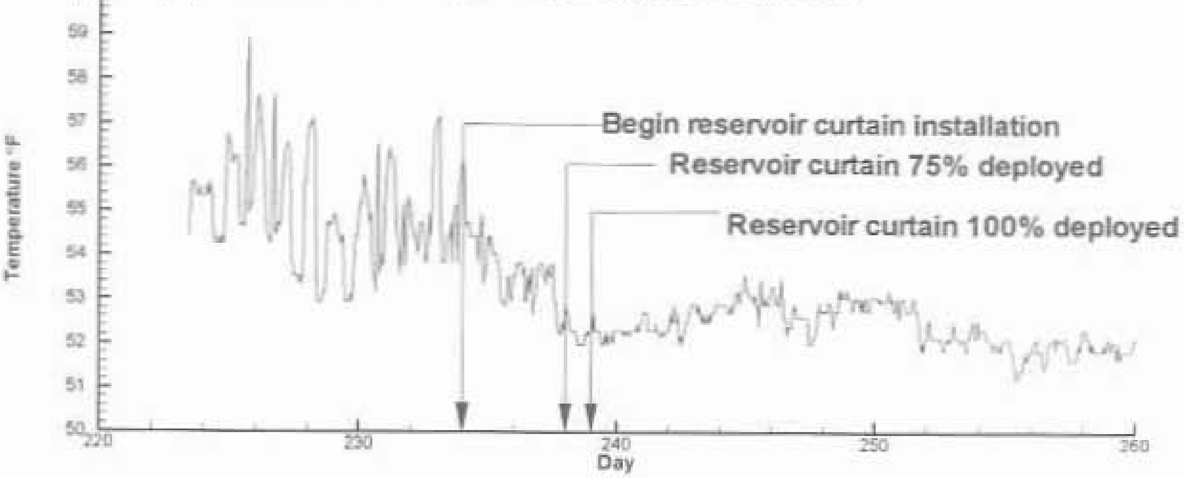


Figure 9. - Temperature profiles collected (a) upstream and (b) downstream from the Lewiston Reservoir curtain site, and (c) near the Clear Creek Tunnel intake structure from August 15 through September 4, 1992. A comparison for pre- and post-curtain temperature profiles indicates that the curtain modified the reservoir stratification, especially downstream from the curtain. Note: Black dots indicate temperature data points.

(A) Lewiston Reservoir Operations, 1992



(B) Clear Creek Tunnel Intake Temperatures, 1992

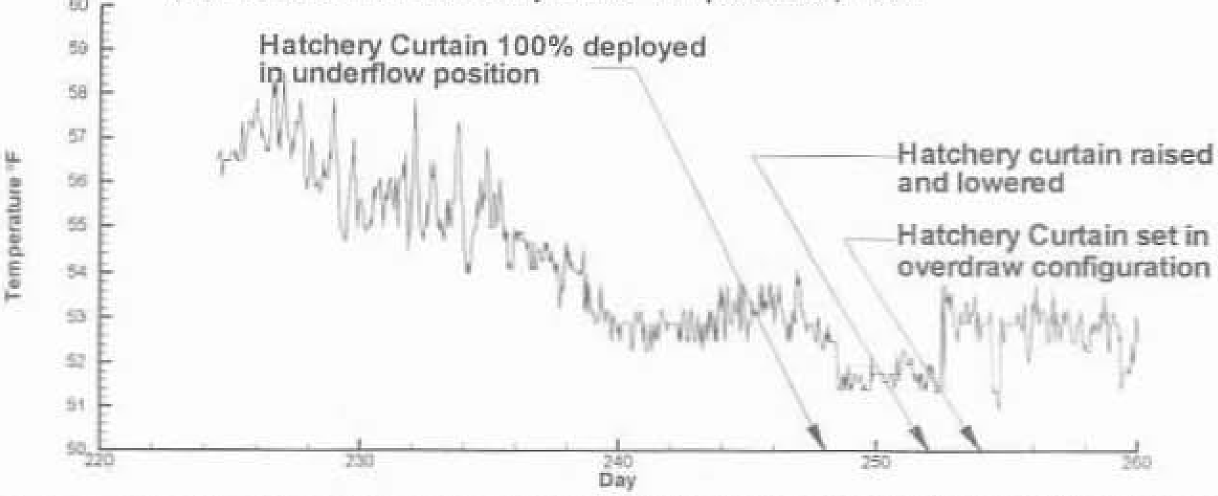


Begin reservoir curtain installation

Reservoir curtain 75% deployed

Reservoir curtain 100% deployed

(C) Lewiston Fish Hatchery Intake Temperatures, 1992

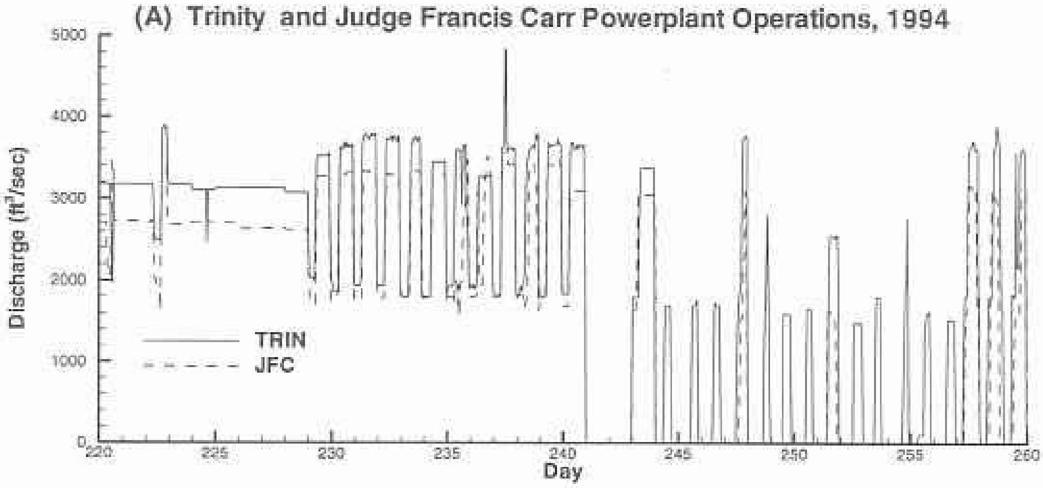


Hatchery Curtain 100% deployed in underflow position

Hatchery curtain raised and lowered

Hatchery Curtain set in overdraw configuration

Figure 10. - (a) Lewiston Reservoir operations and air temperatures, (b) Clear Creek Tunnel intake temperatures, and (c) Lewiston Fish Hatchery intake temperatures from August 11 to September 16, 1992. Curtain construction milestones are included on plots b and c.


(A) Trinity and Judge Francis Carr Powerplant Operations, 1994

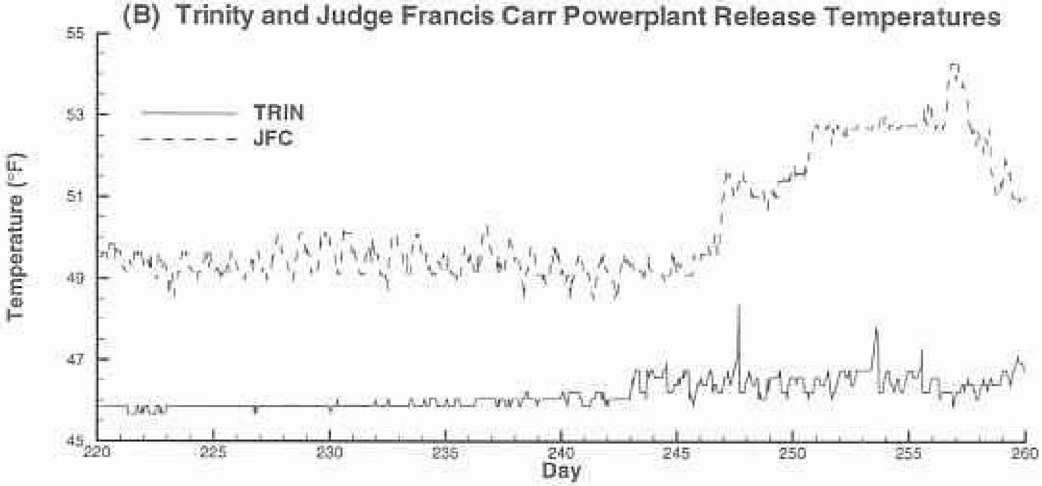

(B) Trinity and Judge Francis Carr Powerplant Release Temperatures

Figure 11. - (a) Lewiston Reservoir inflows and outflows and (b) inflow and outflow temperatures illustrate the temperature gains for various reservoir operations during August and September 1994.

A comparison of average reservoir inflow and outflow temperatures (fig. 11b) shows a consistent 3.5 °F temperature gain through the reservoir for days 220 through 242 regardless of the two types of operations. About 1.9 °F of warming occurs upstream from the reservoir curtain and 1.6 °F downstream. However, when peaking operations went into effect on day 242, a steady increase in outflow temperature was observed. After day 252, the temperature gain through Lewiston Reservoir had stabilized to 6.4 °F; about 4 °F of warming occurred upstream from the curtain and 2.4 °F downstream. The additional 2.9 °F temperature gain occurred because warm water accumulated throughout the reservoir during no flow periods. Then, during full peaking operations, this warm water was mixed into Trinity Dam releases and was withdrawn. Another way of describing this temperature gain is that because of the lower average daily discharge, the accumulated warm water undergoes less dilution. It should be noted that about a 0.5 °F temperature gain can be attributed to increasing inflow temperatures from Trinity Powerplant. As a result of this significant temperature gain, it was concluded that full peaking operation (both turbines either on or off) should be avoided during periods when release temperature restrictions are in effect.

Continuous temperature profile data collected at hourly intervals on both sides of the Lewiston Reservoir curtain for August 12 through 23, 1994 (calendar days 225 to 236), are shown on figures 12b and 12c. These plots of temperature contours (isotherms) illustrate the modification to the temperature stratification generated by the temperature control curtain for two types of power generation schemes as described earlier (Fig. 10a). For both these operational scenarios, the temperature profiles collected downstream from the curtain are very uniform in the 50 to 54 °F range. The temperature profiles collected upstream from the curtain show periods of variable thermal stratification caused by diurnal fluctuations in the amount of insolation (solar heating). Figures 12b and c illustrate that the curtain was effective at isolating the Clear Creek Tunnel intake structure from the thermally stratified reservoir. When operations were switched to partial peaking, greater fluctuations in temperatures occurred upstream from the curtain because flow fluctuations caused periods of increased and reduced mixing. Intense mixing occurred during peaking that would begin to break down the stratification in the upstream pool. Conversely, peaking had little effect downstream from the curtain. This operational change had little or no impact because the intake would continuously withdraw surface water, so warm water was unable to accumulate. Unfortunately, no temperature profile data were available for full peaking operations, which went into effect on calendar day 243.

CARR POWERPLANT TAILRACE CURTAIN PERFORMANCE EVALUATION

The Carr tailrace curtain was reinstalled in Whiskeytown Reservoir for stratified season operation on May 10, 1994 (day 130). Continuous temperature profile data collected upstream from the curtain site show significant warming of the inflow temperatures in the 10 days prior to installation and a significant reduction in inflow temperatures in the 20 days after curtain installation was complete (fig. 13). The reduction in temperature was attributed to a reduction in warm water available at the mixing zone where the Carr Powerplant inflows plunge beneath the reservoir's epilimnion. The diurnal fluctuations in the stratification were attributed to insolation and to diurnal fluctuations in release temperatures from Carr Powerplant. Figure 13 clearly shows a strong relationship between Carr Powerplant operations and the reservoir stratification upstream from the tailrace curtain. For example, during intermittent powerplant operations on days 122 to 126, the reservoir temperatures began to warm rapidly. On day 127, when the Carr Powerplant resumed continuous operation, substantial mixing caused a nearly complete breakdown of the thermal stratification. After the curtain was installed on day 130, cold water inflows were established and maintained for the rest of the month of May. For days 141 through 151, figure 13 shows that base load powerplant operations created optimum conditions for curtain performance as demonstrated by the 48 °F inflows.

Continuous temperature profile data collected hourly on both sides of Carr Powerplant tailrace curtain for August 13 through 24, 1994 (calendar days 225 to 236), appear in figure 14. A comparison of these temperature contour plots illustrates the modification to the stratification caused by the temperature control curtain for two types of powerplant operations shown in figure 14a. For base load and partial peaking power operations, temperature profiles collected downstream from the curtain were strongly stratified; the thermocline was located between elevations 1180 and 1200 ft. In figure 14c, variations in thermocline elevation were attributed to peaking power operations and to fluctuations in the vertical expansion of the density current passing under the curtain. Slugs of warmer water that move under the curtain are more buoyant than the hypolimnion and enter the reservoir as an interflow, which displaces the epilimnion downstream. Conversely, when cooler water is released from Carr Powerplant, undercurtain flows enter the hypolimnion as an underflow and the epilimnion moves back upstream. This process was also confirmed by velocity profiles collected downstream from the curtain and by visual observations of curtain shape. When the downstream thermocline was near elevation 1180 ft, the curtain would billow dramatically in the upstream direction under a load generated by the density differential (fig. 15). However, when the thermocline was at elevation 1190 ft or higher, the density loading would equilibrate and the curtain would straighten out. This billowing may have impacted curtain effectiveness because the deformed curtain has a reduced depth, which may allow mixing with warm water downstream.

SPRING CREEK INTAKE CURTAIN PERFORMANCE EVALUATION

Although an extensive monitoring system was installed, few performance data were collected in 1993. During the wet year of 1993, only intermittent diversions passed through Carr Powerplant into Whiskeytown Reservoir during spring and summer. As a result, the water stored in Whiskeytown Reservoir gradually became too warm to be diverted into the Sacramento River.

Figure 16 presents 1994 data that illustrate the curtain's performance for three types of power operations at Carr and Spring Creek Powerplants:

1. During calendar days 220 through 228, the flows through the reservoir were base load power operations, and the average daily discharge was about 3,200 ft^3/s.

2. During days 229 through 241, partial peaking power operations were in effect with 1 turbine on continuously at 1,800 ft^3/s, and peaking was performed with the second turbine operating for 12 to 15 hours a day for a total flow of 3,500 ft^3/s. For this period, the average daily discharge was about 2,900 ft^3/sec.

3. During days 243 through 260, peaking operations were used with 1 and occasionally 2 turbines operating for 6 to 12 hours. For this period, the average daily inflow was about 500 ft^3/sec.

A comparison of average reservoir inflow and outflow temperatures (fig. 16b) indicated a consistent 3.8 °F temperature gain through the reservoir for days 220 through 242 regardless of the two types of powerplant operations. About 2.0 °F of warming occurs upstream from the Carr tailrace curtain and 1.8 °F downstream. Historical data for August 1988 and 1989 show that the temperature gains of Trinity diversions routed through Whiskeytown Reservoir (for similar powerplant operations) were 6.4 and 6.3 °F, respectively. Therefore, the two curtains in Whiskeytown Reservoir were responsible for a 2.5 °F reduction in Spring Creek Powerplant release temperatures. When intermittent peaking operations went in to effect on day 242, a steady increase in inflow temperature was observed (as previously discussed in the Lewiston Curtain Evaluation section). The effects of increased inflow temperatures take some time to show up at the Spring Creek Tunnel intake because the residence time for the average daily flows of 500 ft^3/sec is about 50 days (for the hypolimnion volume below elevation 1110). Consequently, warmer inflows mix into the hypolimnion, producing a gradual increase in hypolimnetic water temperatures and in Spring Creek Powerplant release temperatures.

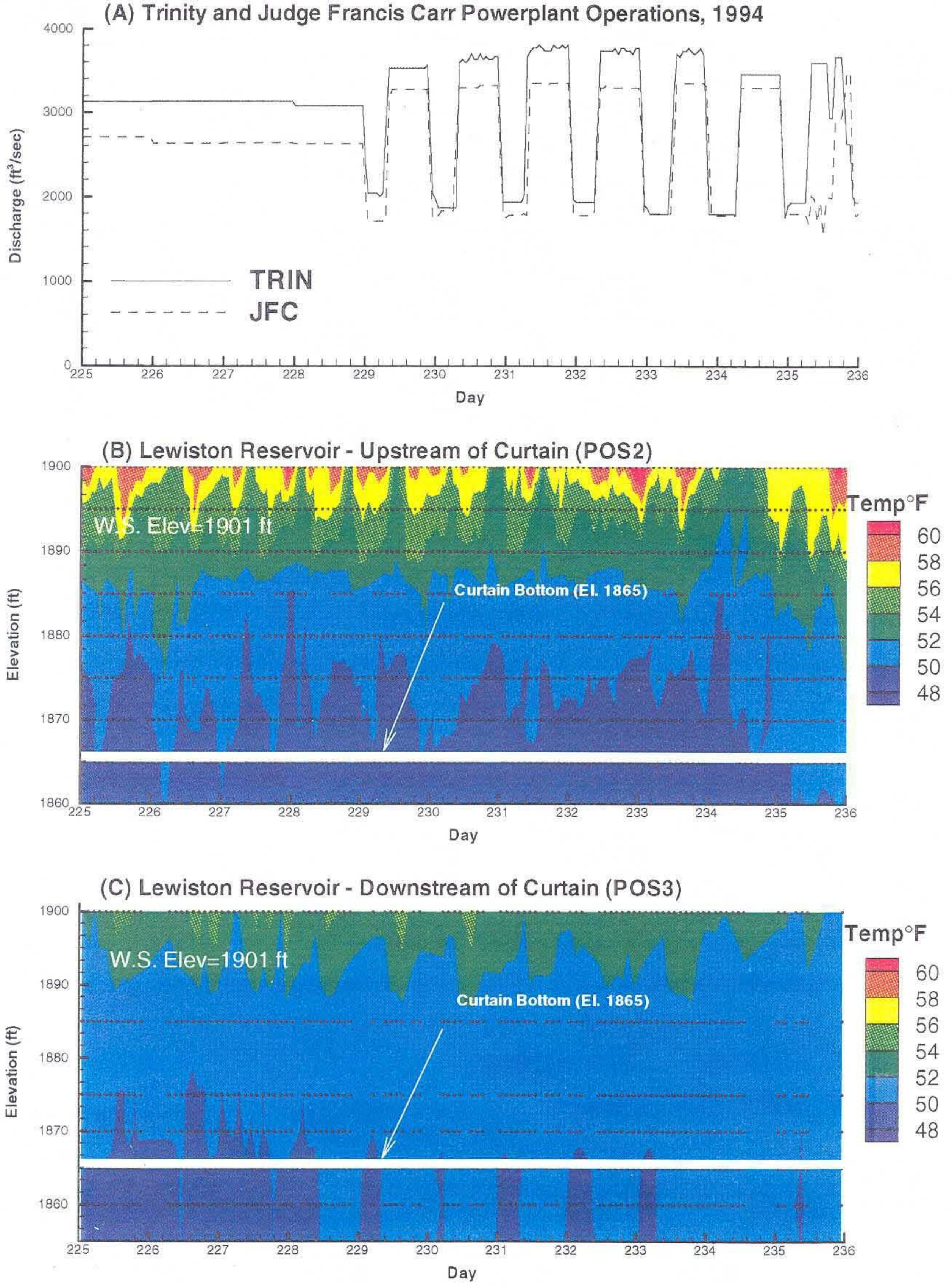
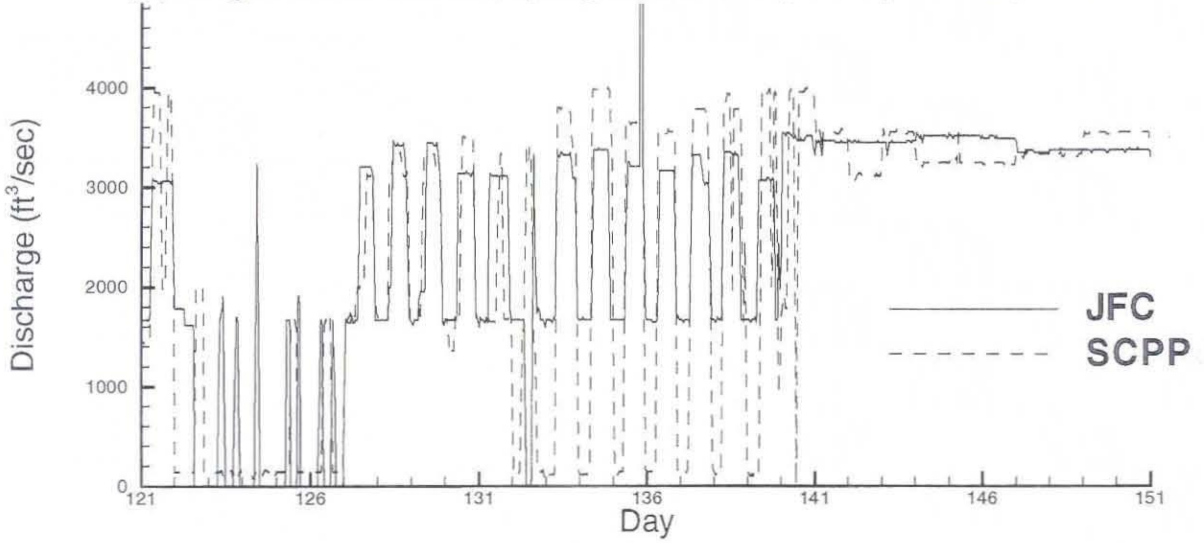


Figure 12. - (a) Lewiston Reservoir operations where Trinity and Judge Francis Carr Powerplants represent inflow and outflow, respectively. (b) Upstream and (c) downstream continuous temperature profile data collected at hourly intervals on both sides of the Lewiston Reservoir curtain for the period of August 12 through 23, 1994. These plots show the modification to the reservoir stratification generated by curtain and reservoir operations. Note: Black dots indicate temperature data points.

(A) Judge Francis Carr and Spring Creek Powerplant Operations, 1994



(B) Whiskeytown Reservoir - Upstream of Carr Tailrace Curtain

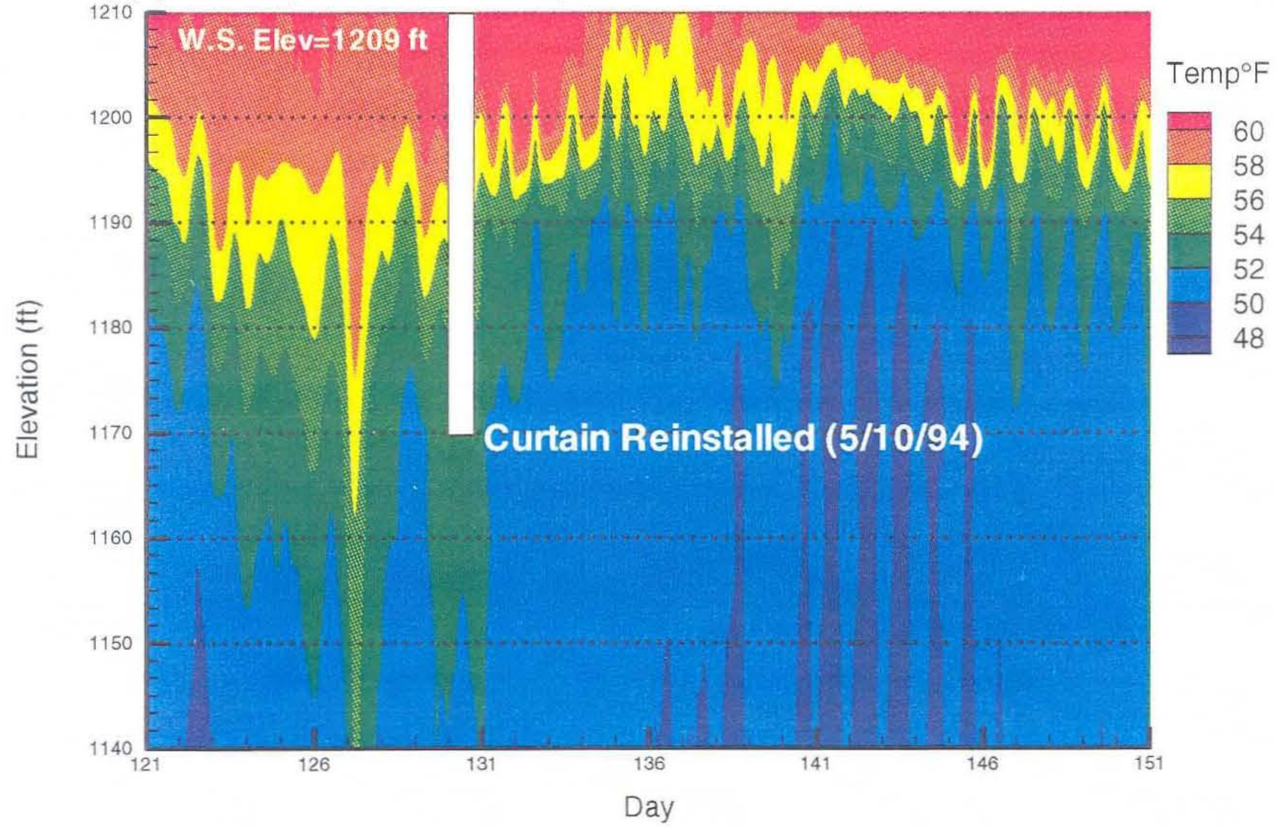
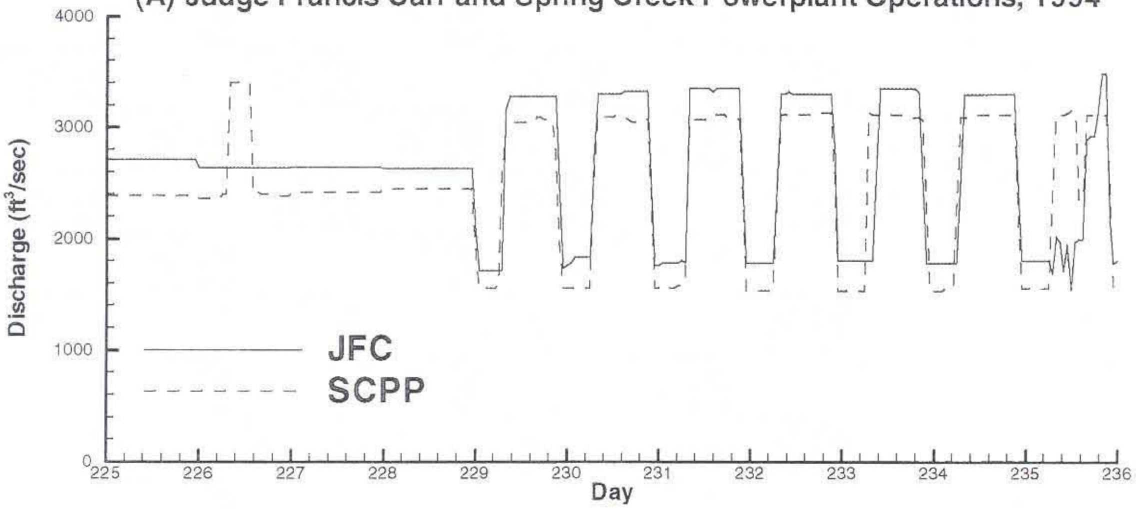
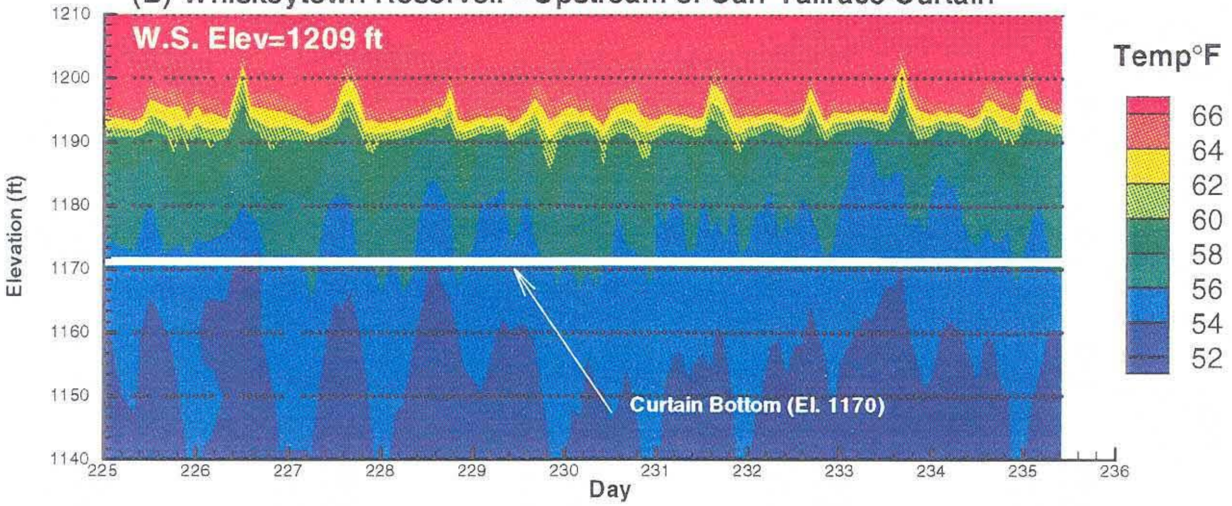


Figure 13. - (a) Judge Francis Carr and Spring Creek Powerplant operations and (b) hourly temperature contours collected at a site upstream from the Carr Powerplant tailrace curtain for May 1994. The Carr tailrace curtain was reinstalled on May 10, 1994. Temperature profiles show an immediate reduction in inflow temperatures by retaining warm water from the mixing zone. Note: the black dots represent temperature data points.

(A) Judge Francis Carr and Spring Creek Powerplant Operations, 1994



(B) Whiskeytown Reservoir - Upstream of Carr Tailrace Curtain



(C) Whiskeytown Reservoir - Downstream of Carr Tailrace Curtain

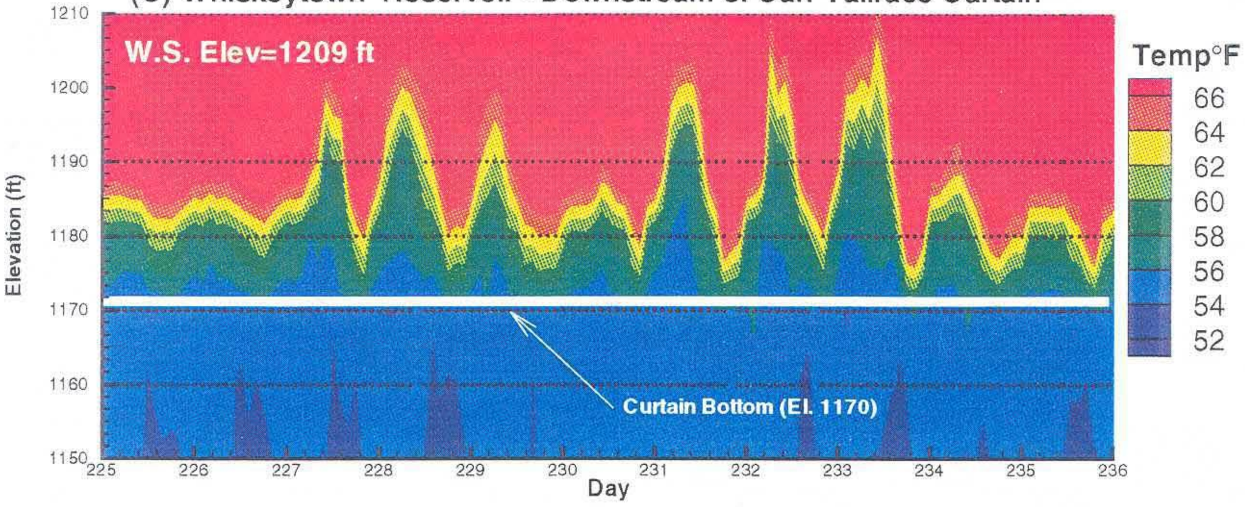
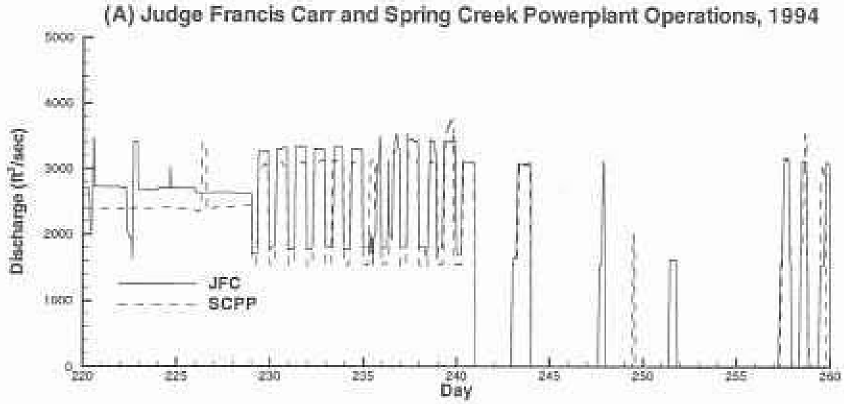


Figure 14. - (a) Whiskeytown Reservoir operations and temperature profiles collected (b) upstream and (c) downstream from the Carr tailrace curtain from August 13 through August 24, 1994. Comparison of upstream and downstream temperature profiles shows how the curtain modified the reservoir stratification. Note: Black dots indicate temperature data points.

Figure 15. - Photograph of the Carr tailrace curtain billowing upstream, which was caused by a large differential density load. Flow from Carr powerplant moves from left to right.



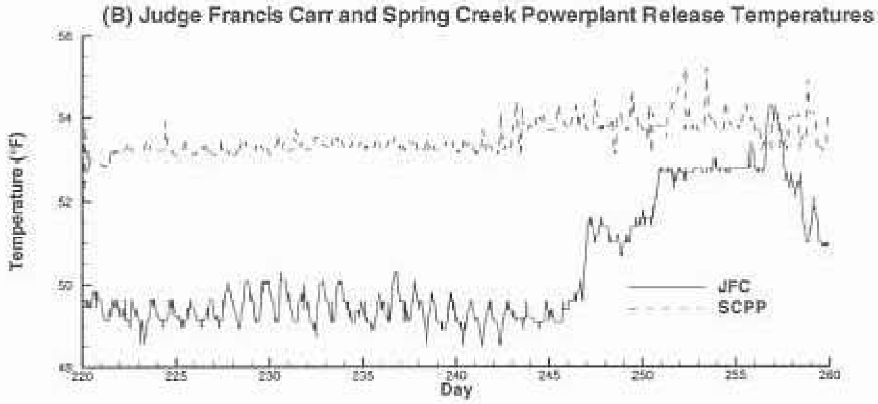


Figure 16. - (a) Whiskeytown Reservoir inflows and outflows and (b) inflow and outflow temperatures illustrate the temperature gains for various reservoir operations during August and September 1994.

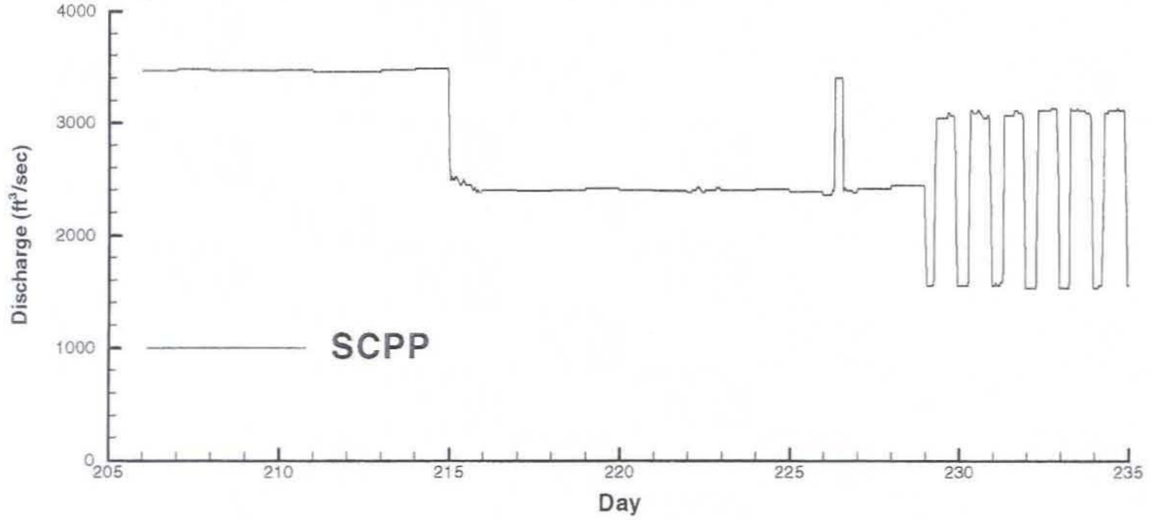
In 1994, bi-hourly temperature profiles were collected to quantify the modified stratification generated by the Spring Creek curtain which surrounds the Spring Creek Tunnel intake structure. The Spring Creek Tunnel intake conveys water into an 18.5-ft-diameter tunnel, and the intake elevation is at elevation 1085 ft. Figure 17a shows Spring Creek powerplant operations, which consisted of two periods of base load and one period of partial peaking powerplant operations. Figures 17b and 17c show two sets of temperature profile data collected from July 24 through August 23, 1994 (days 205 to 235). Temperature profiles were collected on both sides of the curtain using thermistor strings suspended from the water surface; temperature data are indicated on figures 17b and 17c using black dots. In general, the Spring Creek curtain created a small change in the thermal stratification across the curtain. On average, inside the curtain, the epilimnion was slightly warmer (+0.5 °F) and the hypolimnion was cooler (-0.8 °F) than outside the curtain. Warmer temperatures on the surface indicated that warm water accumulated inside the curtain, but it was not withdrawn or exposed to wind mixing. Cooler water in the hypolimnion indicates that cold water which passed under the curtain replaced warmer water which was withdrawn through the Spring Creek Tunnel intake structure. Figure 17c shows a greater volume of cold water inside the curtain. For example, upstream from the curtain, 54 to 56 °F water was located at elevation 1125; downstream, the same temperature water was located at elevation 1140.

Figure 17b illustrates the impact of partial peaking operations (days 229 to 235) on the position of the thermocline. When powerplant discharges were increased, the elevation of the thermocline dropped about 20 ft to elevation 1170. The thermocline drawdown would probably have diminished over time because it was not measured during base load operations at higher discharges (day 205 through day 215). The apparent anomalies which appear on figure 17a (e.g., the flow change on day 226 and the thermocline dip on day 220 during base load operations) are probably attributable to using the powerplant operations *schedules* as the actual powerplant operations, when on occasion the actual operations may have varied. Unfortunately, these schedules were the only source available to determine hourly powerplant discharges.

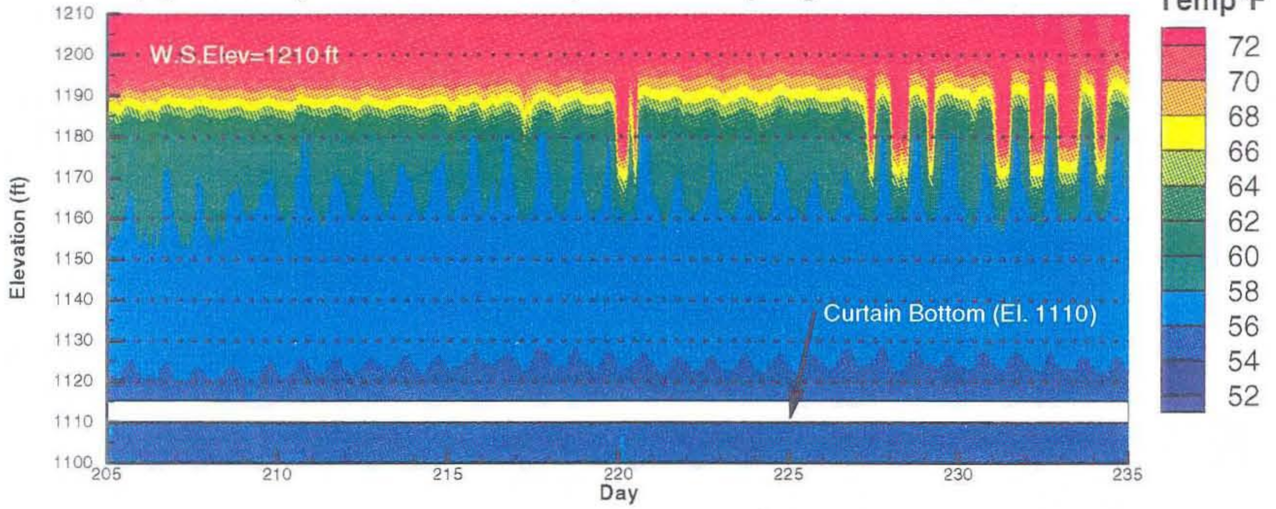
Note that in figures 17b and 17c, the apparent location of the thermocline is exaggerated because the thermistors at elevation 1170 had failed. Consequently, the temperature gradient is distorted between elevations 1180 and 1160 because the temperatures were linearly interpolated. Manual temperature profiles collected bi-monthly showed that the thermocline location was similar on both sides of the Spring Creek curtain during July and August 1994.

To determine how much the curtains changed the thermal structure of Whiskeytown Reservoir, an analysis was performed comparing pre- and post-curtain temperature profiles collected at several US EPA (Environmental Protection Agency) STORET sampling sites. STORET is a nationwide storage and retrieval data base containing water quality data. Two sites were selected for this analysis: SH22, which is located in the main body of Whiskeytown Reservoir 2 miles upstream from Whiskeytown Dam; and SH28, which is located near the Spring Creek Tunnel intake structure. A comparison of July 22, 1994, temperature profiles collected near the Spring Creek tunnel intake was made to pre-curtain profiles collected in July 24, 1992 (fig. 18a). The comparison indicated that the Spring Creek curtain created a warmer epilimnion, a stronger thermocline, and a thicker and nearly isothermal hypolimnion. Likewise, profiles collected at station SH22 showed that both temperature curtains combined to create a warmer epilimnion, a stronger thermocline, and a cooler hypolimnion.

(A) Spring Creek Powerplant Operations, 1994



(B) Whiskeytown Reservoir - Upstream of Spring Creek Curtain



(C) Whiskeytown Reservoir - Downstream of Spring Creek Curtain

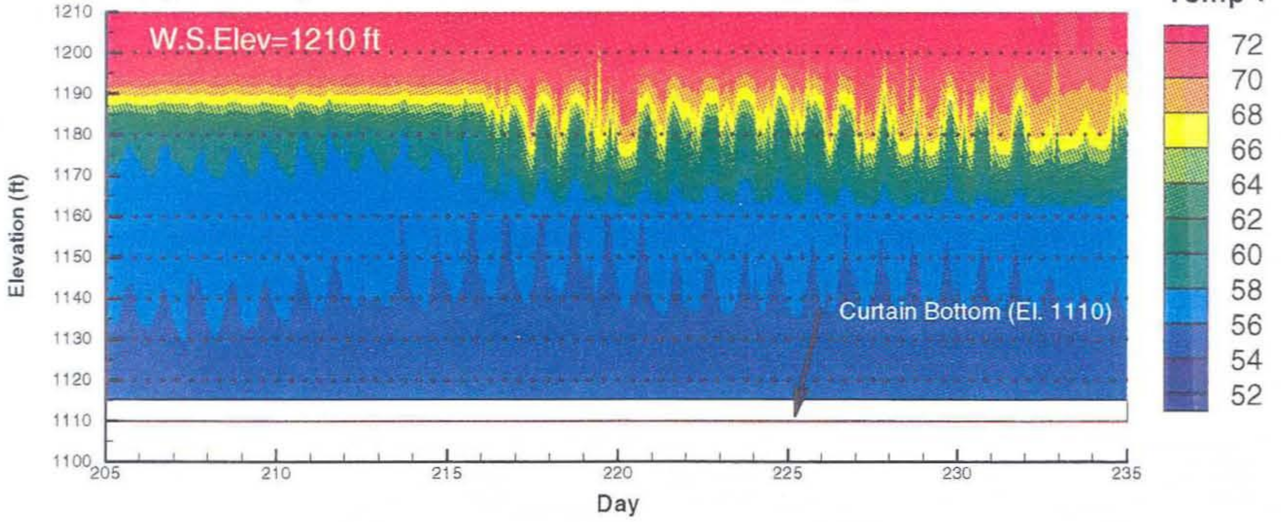


Figure 17. - (a) Whiskeytown Reservoir operations and temperature profiles collected (b) upstream and (c) downstream from the Spring Creek Tunnel intake curtain from July 24 through August 23, 1994. Comparison of upstream and downstream temperature profiles shows how the curtain modified the reservoir stratification. Note: Black dots indicate thermistor locations.

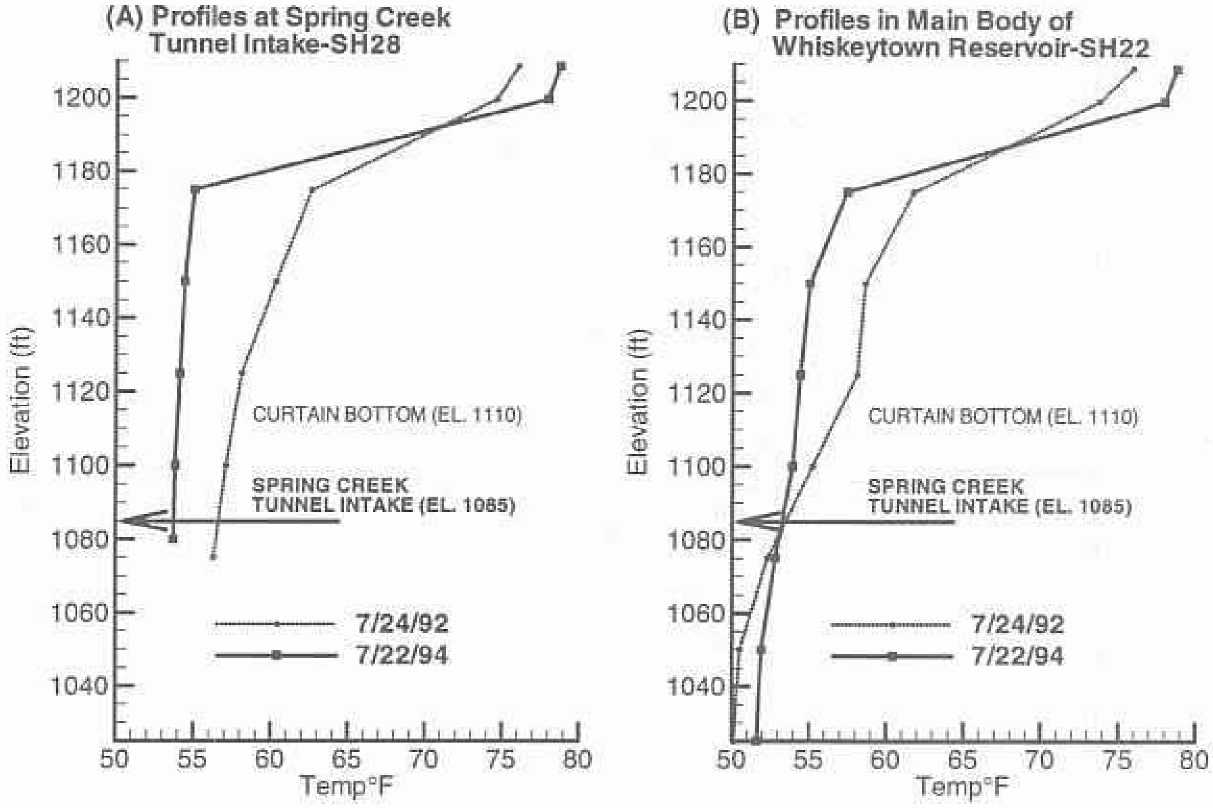


Figure 18. - (a) A comparison of pre- and post-curtain temperature profiles collected near the Spring Creek Tunnel intake, and (b) a comparison of pre- and post-curtain temperature profiles collected in the middle of Whiskeytown Reservoir.

Minor differences in these profiles may be attributed to variations in meteorology and powerplant operations, but this significant modification to the reservoir stratification was typical for several other pre- and post-curtain temperature profile comparisons. The reason for the warmer epilimnion and cooler hypolimnion is that the Carr tailrace curtain limits the supply of epilimnetic water to the plunge zone, which controls the warming associated with mixing and results in cooler water entering the hypolimnion. Likewise, the Carr tailrace curtain generates the warmer epilimnion. The Spring Creek curtain allows only hypolimnetic water to replace withdrawals into the Spring Creek Tunnel intake, thereby creating a nearly isothermal hypolimnion. Another temperature difference occurs below elevation 1075 in figure 18b, where the post-curtain temperatures are warmer than the pre-curtain temperatures. This difference occurred because, for pre-curtain conditions, the Spring Creek intake withdrawal elevation was fixed at elevation 1075, which is the invert elevation of the excavated approach channel (see fig. 7). However, with the curtain, the withdrawal zone extends to the reservoir bottom below the curtain's perimeter, which is elevation 1030. So the Spring Creek curtain not only limits epilimnetic withdrawals, it also creates access to cold water stored between elevation 1030 and 1075, which amounts to 15,000 acre-ft. The warmer water results from removal of cold water and replacement with warmer inflows.

ADCP (ACOUSTIC DOPPLER CURRENT PROFILER) MEASUREMENTS

Acoustic Doppler current profilers were used to document the hydraulic characteristics of flow under two temperature control curtains. Two bottom mounted ADCPs were used for this evaluation. The ADCPs were supplied by the USGS (U.S. Geological Survey) Water Resources Division in Sacramento, California, and were deployed for a period of 56 days from July 27 to September 21, 1994.

ADCP Measurement Techniques

Acoustic Doppler current profilers are state-of-the-art instruments which measure current velocity profiles in oceans, rivers, and lakes. Acoustic Doppler current profilers use the Doppler effect to determine current velocity by measuring velocity of sound reflectors (sediment or plankton) moving with the current. Acoustic Doppler current profilers use the Doppler effect by transmitting sound at a fixed frequency and receiving echoes returning from sound scatterers in the water column. The echoes are referred to as backscattered signals. The frequency shift in the backscattered signal is proportional to the relative velocity between the ADCP and scatterer. An ADCP can only measure the velocity component in the direction of a line between the scatterer and the acoustic transducer. As a result, ADCPs use multiple beams pointed in different directions to measure two or three orthogonal velocity components. Beams are positioned 90 degrees apart horizontally and at an angle of 20 or 30 degrees from vertical (fig. 19).

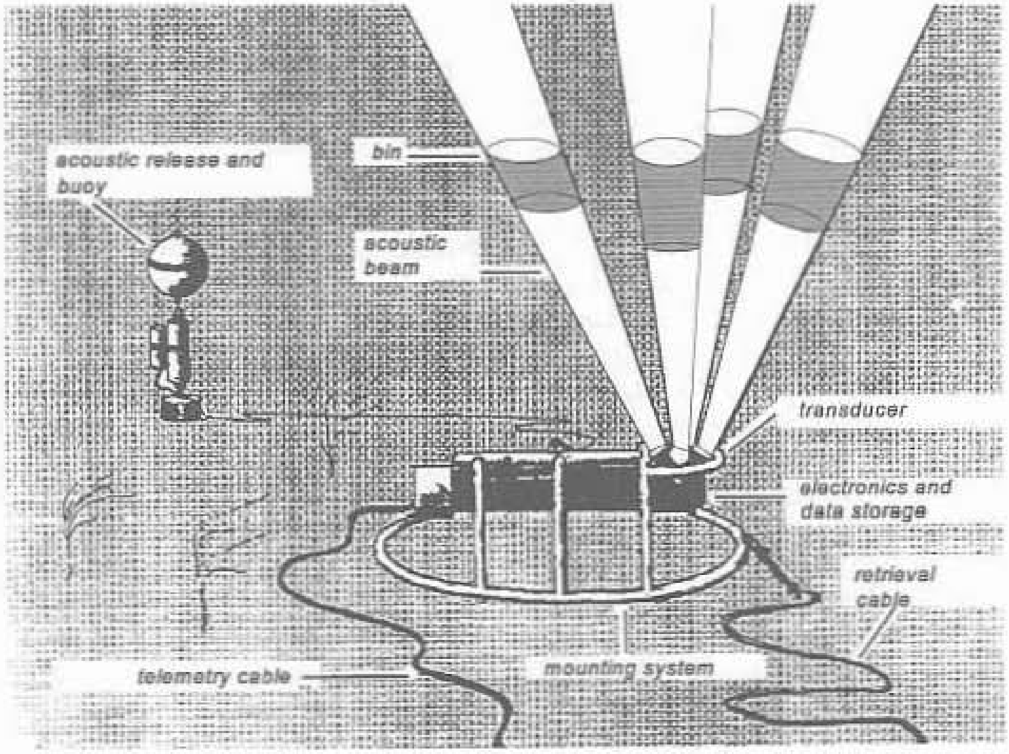


Figure 19. - Bottom-mount deployment and four acoustic beam arrangement. The acoustic Doppler current profiler is anchored to the reservoir bottom and the acoustic beams are projected at a 30° angle from vertical (Burau et al., 1992).

ADCPs break acoustic beams into uniform volumes called depth cells or bins. Each depth cell is comparable to a single current meter measurement, and the ADCP velocity profile is equivalent to a string of evenly spaced current meters. The only difference is that ADCPs measure average velocity over the depth range of each cell, whereas current meters make a point measurement. Profiles are generated by range gating the acoustic pulse. This technique breaks the signal into successive segments and processes each segment independently from the others. Echoes from deep depths take longer to arrive than do echoes from shallow depths. Thus, successive range gates correspond to echoes from increasingly distant depth cells. One problem with this method is that the beams make their measurements at different locations. Therefore, the currents in a horizontal layer must be homogeneous, which, for lakes and oceans, is a reasonable assumption.

Errors associated with ADCP measurements can be attributed to random and bias components. Random errors are a function of transducer frequency, depth cell size, the number of signals or pings averaged together, and beam geometry. Bias errors are a function of temperature, mean current speed, and beam geometry errors. At this time, bias errors cannot be computed, but they are estimated by the manufacturer to be about 0.002 to 0.004 ft/sec. Random error for a single ping is typically around 0.43 ft/sec. However, averaging of several hundred pings is used to reduce the random error to an acceptable level of about 0.006 ft/sec. Averaging can reduce the relatively large random error present in single ping data, but after a certain amount of averaging, the random error becomes less than the bias error. At this point, further averaging will not reduce the overall measurement error.

Another ADCP limitation is the effect of surface reflections on the processing of backscattered acoustic signals. As a result, the ADCP cannot measure water velocities near the water surface. Water velocities near the surface cannot be measured because of side-lobe interference. Side lobes are secondary acoustic signals which are emitted from the transducer. Side-lobe interference causes a corruption of data from the last 10 to 15 percent of the profiling range. Water velocities near the bottom cannot be measured for two reasons: 1) the ADCP is usually secured in a mount above the reservoir bottom, and 2) velocities cannot be measured near the transducer face because a delay is necessary between the send and receive modes of the transducer operation. The blanking distance is usually equal to a single depth cell size.

ADCP DEPLOYMENT IN LEWISTON AND WHISKEYTOWN RESERVOIRS

The ADCP systems used for this study were self-contained, narrow band, 1200-kilohertz ADCPs built by RD Instruments. These ADCPs had a maximum range of 100 ft. One ADCP was deployed on the bottom of Lewiston Reservoir about 100 ft upstream from the reservoir curtain. The purpose of these velocity measurements was to document selective withdrawal characteristics of the temperature control curtain and the curtain's effectiveness at retaining warm surface water as a function of undercurtain flow velocities and stratification. The second ADCP was deployed on the bottom of Whiskeytown Reservoir about 100 ft downstream from the Carr Powerplant tailrace curtain. The purpose of these velocity measurements was to document the density current hydraulics and mixing characteristics near the temperature control curtain.

The ADCPs were deployed for 56 days, from July 27 to September 21, 1994. Velocity profiles were collected every hour, and 6,000 individual profiles, called pings, were averaged to produce a single hourly velocity profile. A group of 6,000 pings is called an ensemble of data. A typical ensemble consists of velocities measured over a 1-m (3.28-ft) depth cell (bin) for a total of 15 to 25 bins depending on water depth. Water temperature data measured at the acoustic transducer were also collected at hourly intervals and were useful in tracking changes in underflow temperatures. Acoustic Doppler current profiler data were stored in an internal storage device and were retrieved after the ADCPs were removed from the reservoirs. ADCP data were processed by USGS personnel and were delivered to Reclamation in a data report. A detailed description of the ADCP data processing was summarized in a report by Burau et al. (1992).

ADCP DATA ANALYSES

Figures 20 and 21 show the powerplant operations and ADCP data collected in Lewiston and Whiskeytown Reservoirs, respectively, from August 13 through August 24, 1994. This period was chosen for analysis because it had two types of powerplant operations, base load and partial peaking, and the average daily flows over this 11-day period were the same. The Lewiston Reservoir curtain data illustrate how velocity profiles upstream from the curtain change with diurnal fluctuations in the approach flow temperatures (days 225 through 228) and with partial peaking powerplant operations (days 229 through 236). The ADCP data showed the upper limit of the withdrawal zone fluctuated between elevation 1880 and 1890 (fig. 20b), which is 15 to 25 ft above the bottom of the curtain. During base load powerplant operations, the velocity data showed diurnal fluctuations in the upper limit of withdrawal. The withdrawal zone contracted during the middle of the day as the stratification intensified, and it expanded as the stratification broke down in the early morning (temperature profiles are shown in fig. 12b). During partial peaking operations, the withdrawal zone fluctuations are amplified when flow changes are coincident with the diurnal temperature changes.

The Carr tailrace curtain data (fig. 21) illustrate how velocity profiles downstream from the curtain change with diurnal fluctuations in Carr Powerplant release temperatures (days 225 through 228) and with partial peaking power operations (days 229 through 236). Several observations were made by analyzing ADCP data, which are summarized as follows:

- In the early morning hours of days 225, 226, and 227, the underflow detached from the reservoir bottom and became an interflow. These flow changes are attributable to diurnal fluctuations in inflow temperatures (see fig. 14b). For this discharge, the warmest water diverted from Lewiston Reservoir arrived at the Carr tailrace curtain around midnight the following day and entered the reservoir as an interflow. Conversely, the coldest water arrived around noon and entered the hypolimnion as a underflow or density current.

- The vertical extent of the curtain underflow seldom exceeded the bottom of the curtain (El. 1170), which is evidence that little mixing of the underflow with epilimnetic water occurred downstream from the curtain.

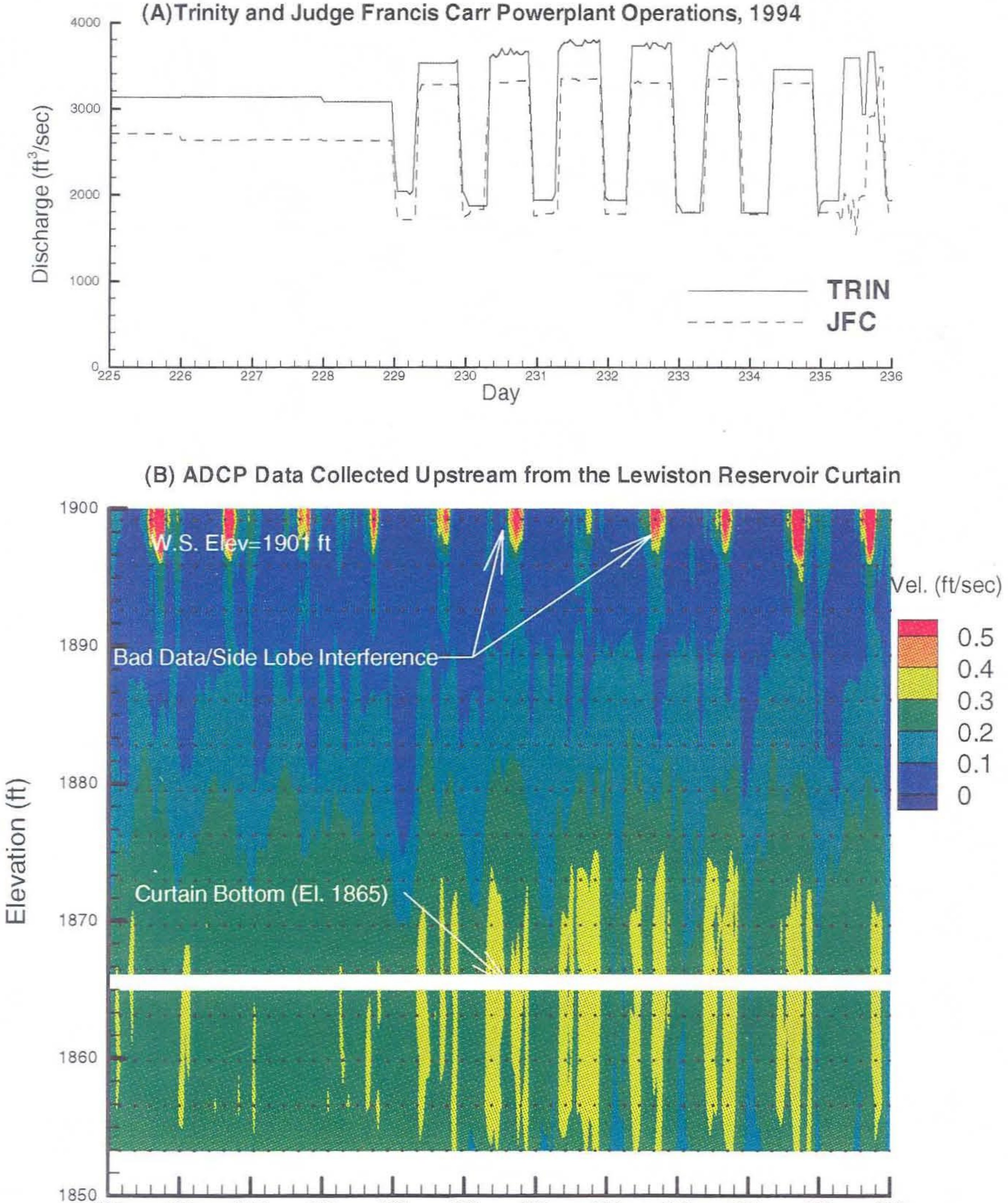
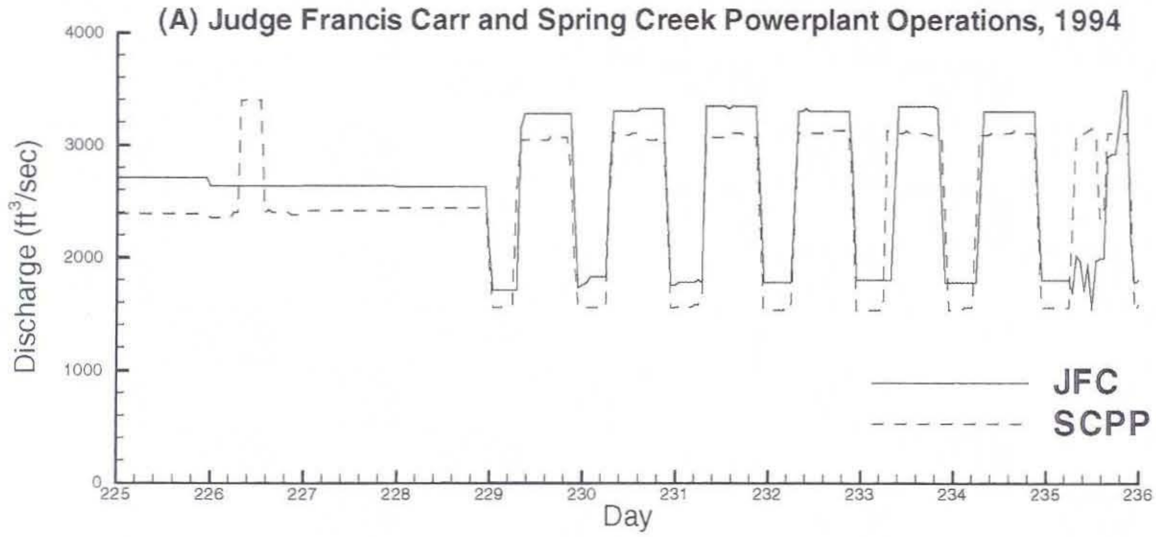
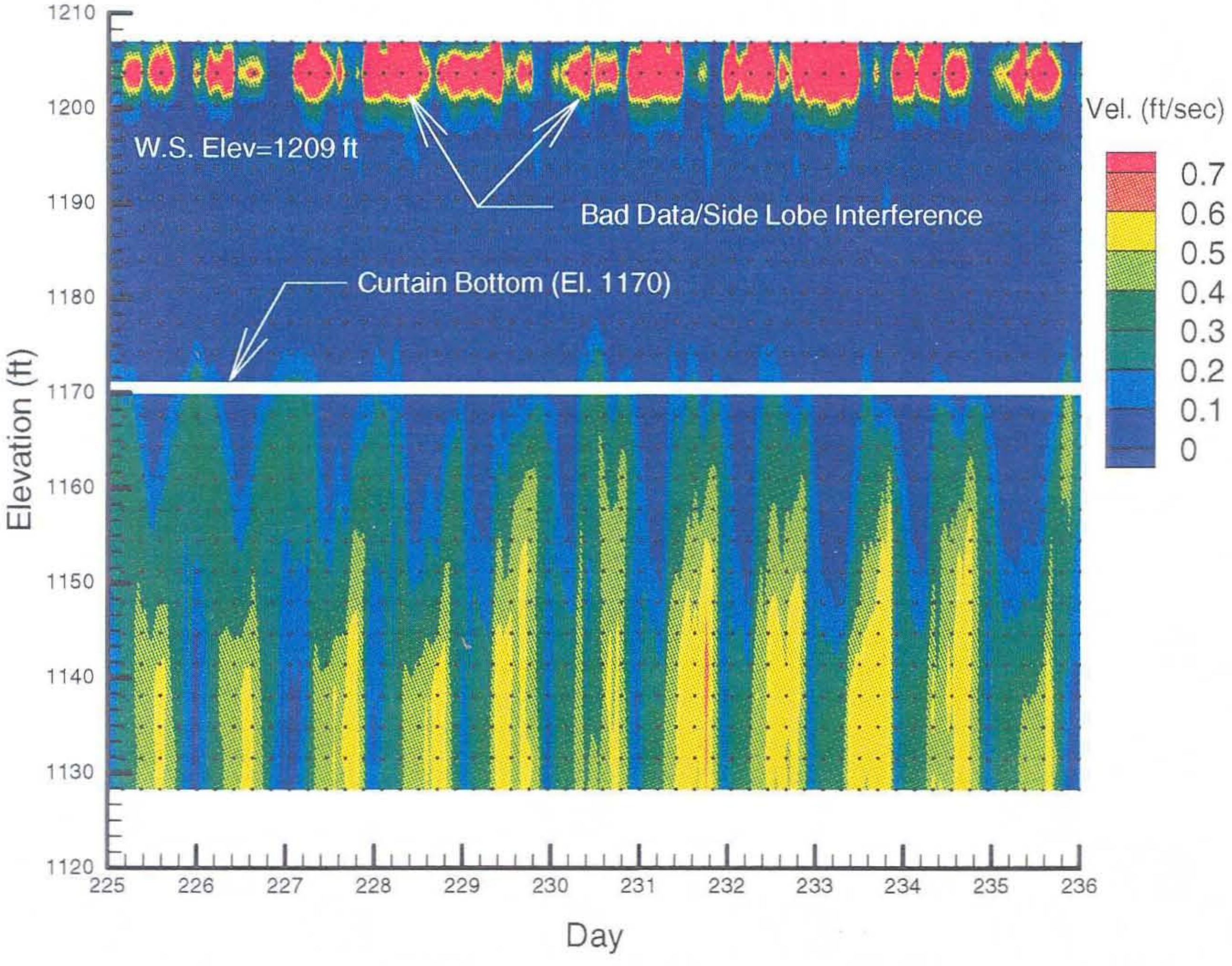


Figure 20. - (a) Lewiston Reservoir operations, and (b) ADCP isovel data collected upstream from the Lewiston Reservoir curtain. Note: the black dots represent the ADCP depth cell locations.



(A) Judge Francis Carr and Spring Creek Powerplant Operations, 1994

(B) ADCP Data Collected Downstream from the Carr Tailrace Curtain



W.S. Elev=1209 ft

Bad Data/Side Lobe Interference

Curtain Bottom (El. 1170)

Figure 21. - (a) Whiskeytown Reservoir operations and (b) ADCP isovel data collected downstream from the Carr Powerplant tailrace curtain. Note: the black dots represent the ADCP depth cell locations.

- During partial peaking operations (days 229 to 236), the underflow appeared to be unaffected by the curtain when flows were reduced to 1,800 ft^3/sec. During this period, the vertical extent of the underflow appeared to be 20 to 25 ft below the curtain bottom. In addition, around midnight, when power releases were reduced, the underflow current slowed considerably (about 0.1 to 0.2 ft/sec), then slowly recovered to about 0.4 ft/sec. These flow conditions were confirmed by field observations that the curtain was heavily loaded during midday (high flows) and was slack during the early morning (low flows).

- The apparent high velocities measured near the water surface were corrupt because of side lobe interference and were not good velocity measurements.

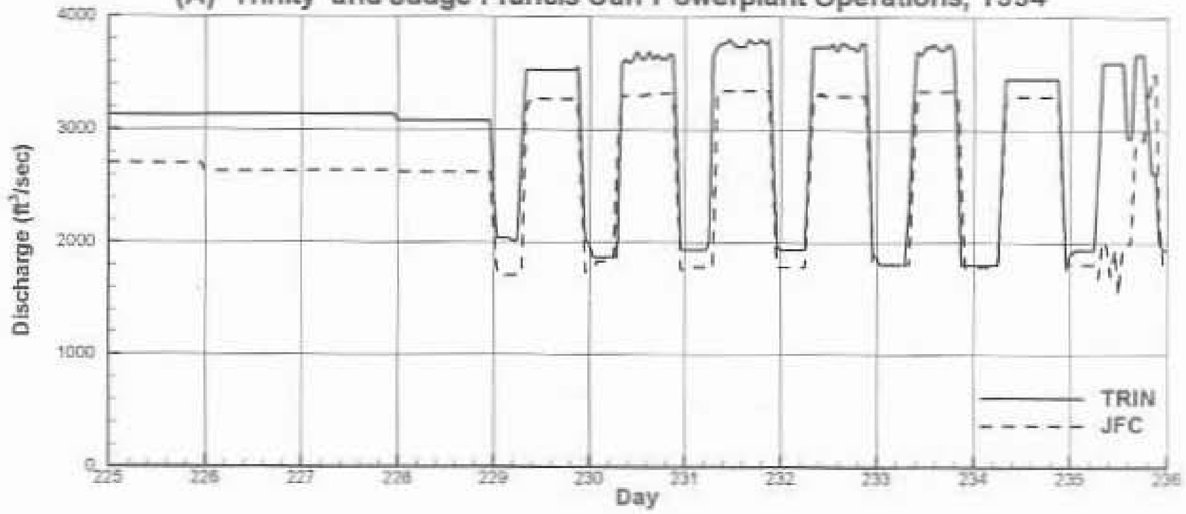
Figures 22 and 23 show in more detail the effects of underflow temperatures on the velocities measured near the reservoir bottom and near the curtain bottom for the Lewiston Reservoir and Carr Powerplant tailrace curtains, respectively. Figure 22a shows Lewiston Reservoir operations, figure 22b shows ADCP transducer temperatures, and figure 22c shows ADCP velocities measured at elevations 1850 and 1882. These plots show how flow rate and water temperature affect curtain underflow hydraulics. For base load operations, velocities at the reservoir bottom, elevation 1850, were relatively uniform at 0.25 ft/sec and were only slightly affected by water temperature changes. ADCP transducer temperatures were used as an indication of underflow water temperatures, and they fluctuated between 47.5 and 48.2 °F. Velocities measured 17 ft above the curtain bottom, at elevation 1882, were mostly uniform at 0.10 ft/sec but were notably affected by water temperature changes. For example, as inflowing water temperature increased from 47.5 to 48.2 °F, velocity increased from 0.10 to 0.16 ft/sec. The withdrawal zone expanded because the inflow grew warmer as it approached the curtain as a result of mixing with the epilimnion. As the density difference between inflow and water near the thermocline was reduced, withdrawal from higher in the water column increased.

For partial peaking operations, velocities at both elevations would increase and decrease with fluctuations in flow rate, but bottom velocities were more sensitive to flow rate. Flow rate fluctuations hindered determination of the influence of temperature variations on the underflow velocities. However, a pronounced warming trend occurred from days 229 through 231, after which an equilibrium was reached. The average temperature gain attributed to an expanded withdrawal zone was 0.4 °F, but a portion of this gain may have been a result of warmer air temperatures or wind mixing.

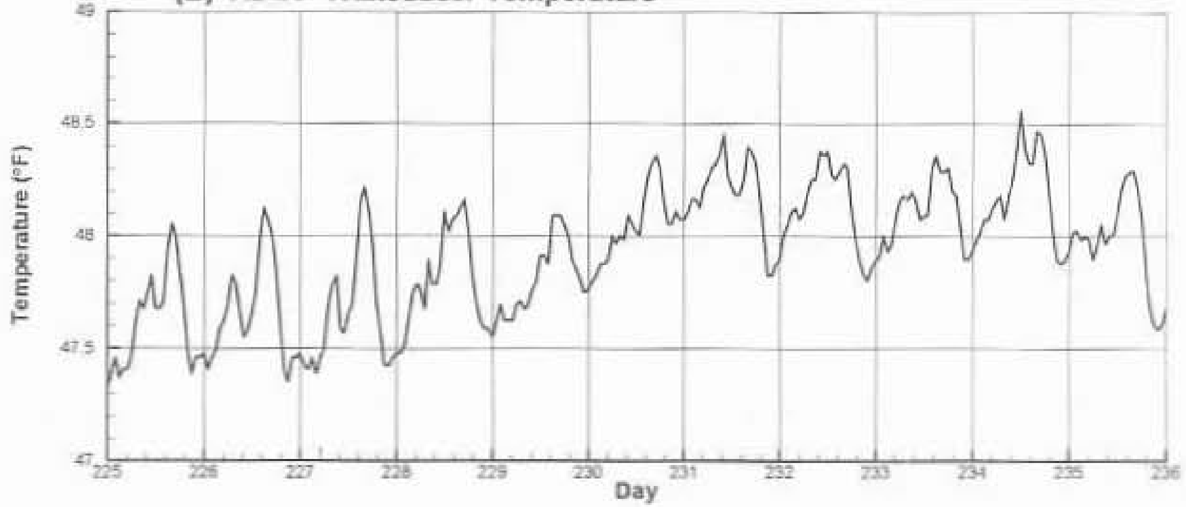
During a period of full peaking operations, days 244 to 260 (not shown on figure 22), the underflow temperatures increased to 52 °F. The large temperature gain resulted from a period of no diversions, which allowed a large volume of warm water to accumulate in the reservoir. When diversions were resumed, the underflow temperatures increased as the warm water was flushed from Lewiston Reservoir. After several days of consistent peaking operations, underflow temperatures decreased to about 49.5 °F by day 259.

Figure 23a shows Whiskeytown Reservoir operations, 23b is a plot of ADCP transducer temperatures, and 23c shows ADCP velocities at elevations 1130 and 1163. For base load operations, velocities along the reservoir bottom, elevation 1130, varied from 0.05 to over 0.5 ft/sec and were inversely related to fluctuations in underflow water temperature. Likewise, as underflow water temperatures increased from 50.5 to 52 °F, the velocity at elevation 1163

(A) Trinity and Judge Francis Carr Powerplant Operations, 1994



(B) ADCP Transducer Temperature



(C) ADCP Velocity Measurements

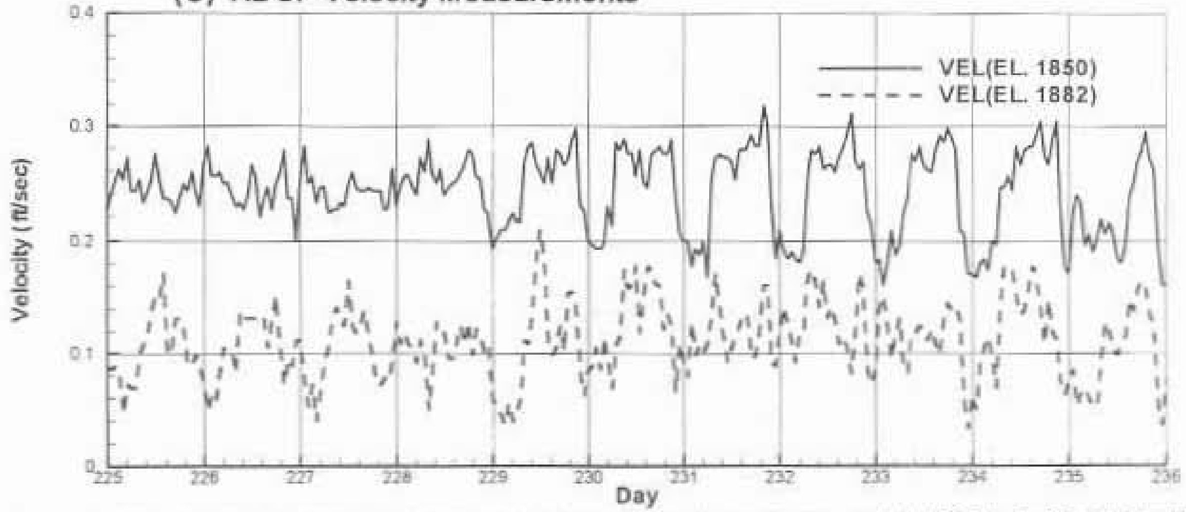


Figure 22. - (a) Lewiston Reservoir operations, (b) ADCP transducer temperatures, and (c) ADCP velocities at elevations 1850 and 1882.

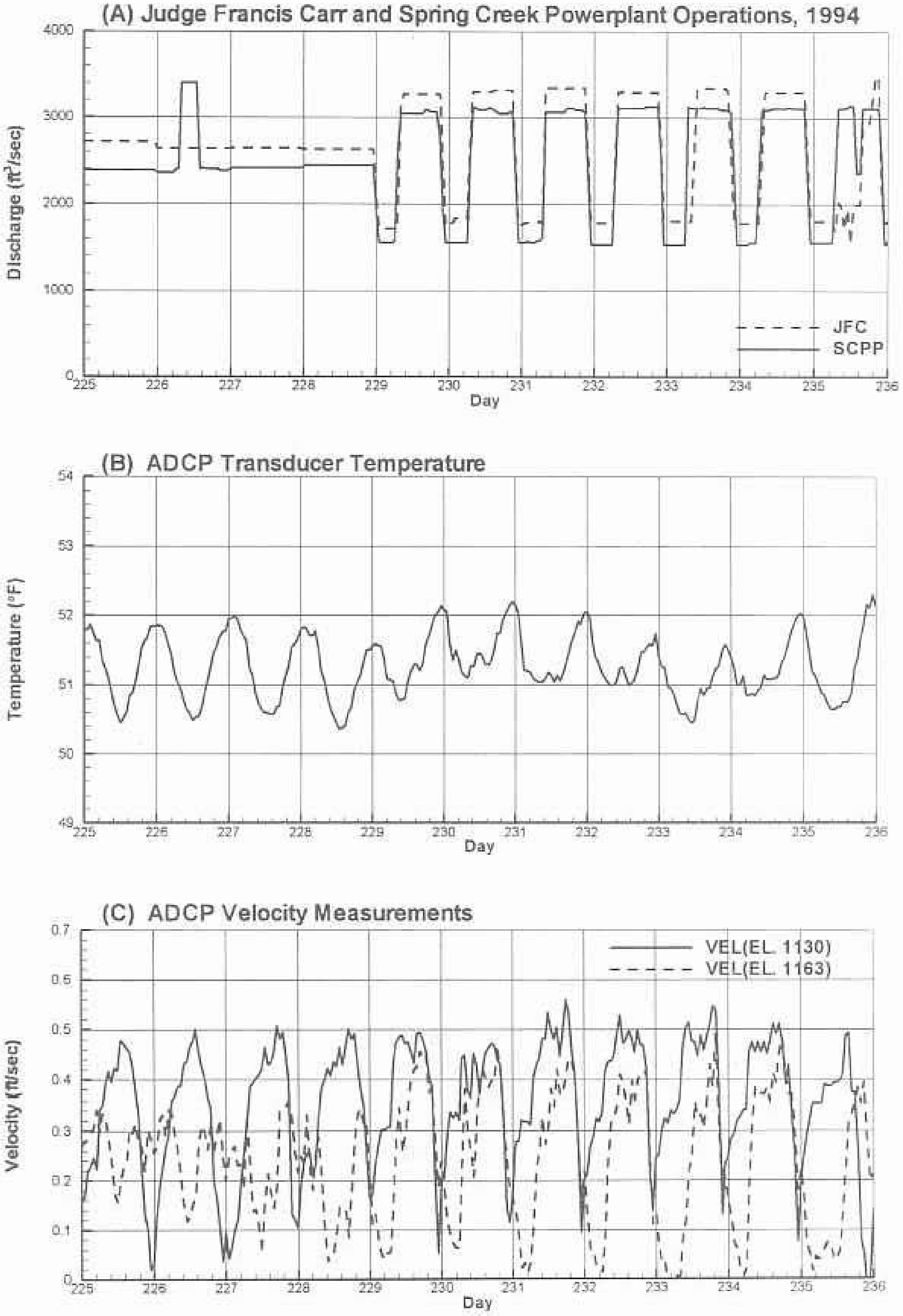


Figure 23. - (a) Whiskeytown Reservoir operations, (b) ADCP transducer temperatures, and (c) ADCP velocities at elevations 1130 and 1163.

increased from 0.05 to 0.3 ft/sec. Velocities measured near the curtain bottom (El. 1163) varied directly with change in underflow temperature. As previously described, the warmer underflow was forced under the curtain and was more buoyant (less dense) than the ambient hypolimnion, and it was buoyed upward and would detach from the reservoir bottom. As colder water inflows arrived at the curtain, the underflow would remain attached to the reservoir bottom, and velocity at elevation 1130 increased. During partial peaking operations, the impact of temperature fluctuations on velocities measured at elevation 1163 was overwhelmed by fluctuations in flow rate. Interestingly, average underflow temperatures did not increase significantly with partial peaking operations; the average increase was only 0.1 °F. This small change was unexpected because the average temperature did not reflect the 0.4 °F temperature gain measured in Lewiston Reservoir. A possible explanation is that partial peaking operations change the degree of mixing which occurred in the plunge zone.

During a period of full peaking operations, days 244 to 260 (not shown on figure 23), the underflow temperatures increased from 51 to 54 °F. The large temperature gain was caused by a period of 6 days with no diversions, which allowed the stratification to equilibrate across the Carr tailrace curtain. In fact, manual temperature profiles collected on both sides of the curtain showed more warm water upstream from the curtain than downstream. This unusual condition was attributed to warm water which flowed upstream through the boat passage, which skimmed the top 6 feet of the epilimnion. During this period, the curtain was observed to billow downstream. When daily diversions were resumed on day 257, underflow temperatures increased as warm water was entrained in the mixing zone, where the inflow plunges beneath the epilimnion. ADCP data showed that during this period, the underflow entered the hypolimnion as an interflow. After several days of consistent peaking operations, underflow temperatures began to fluctuate between 52 and 54 °F.

CURTAIN DESIGN EQUATIONS

As previously described, the curtain site selection was based on a simple energy balance given in equation 1. The energy balance approach was selected for curtain design because it was easily applied to the limited field data available at the time of design. The design underflow velocities for the Lewiston Reservoir and Carr Tailrace curtains were 0.25 and 0.36 ft/sec, respectively. Acoustic Doppler current profiler data confirmed that the maximum underflow velocities were very similar to the design values. The underflow velocities did exceed the design values for periods of high flows coupled with a strong reservoir stratification.

The complete set of monitoring data (flows, temperature and velocity profiles) at Lewiston Reservoir was used to develop an improved description of temperature control curtain hydraulics. Using equation 1 and the monitoring data, the potential energy required to displace epilimnetic water was on average four times greater than the kinetic energy associated with curtain underflows for a wide range of flow rates and powerplant operations. This analysis showed that equation 1 was very sensitive to unsteady flow conditions (peaking power operations) and diurnal fluctuations in reservoir stratification. Equation 2 is a modified form of equation 1 which best describes the Lewiston Reservoir curtain site.

$$\frac{V_o^2}{2g} = C\,Y\,\frac{\Delta\rho}{\rho_o} \qquad (2)$$

where:

V_o = mean flow velocity under the barrier, ft/sec
Y = vertical distance from the bottom of the barrier to the bottom of the epilimnion, ft
$\Delta\rho$ = $\rho_o - \rho_a$, slugs/ft^3
ρ_o = mean density between the bottom of the epilimnion and the bottom of the curtain, slugs/ft^3
ρ_a = representative epilimnion density, slugs/ft^3
C = A coefficient which balances the kinetic and potential energy for the Lewiston Reservoir curtain site. The average coefficient was found to be equal to 0.23 with a standard deviation of ±0.12.
g = gravitational constant, ft/sec^2

An improved description of curtain hydraulics was found by modifying an equation describing selective withdrawal hydraulics for a skimming weir (Bohan and Grace, 1973). Equation 3 is a modified form of the Bohan and Grace weir equation which describes the hydraulic characteristics for flow under a curtain. The coefficient in the Bohan and Grace weir equation was 0.32, and the average coefficient for the Lewiston Reservoir curtain was found to be equal to 0.32 with a standard deviation of ±0.09. The empirical coefficient, *C*, was determined for a wide range of flow rates (1,800 to 4,000 ft^3/sec) and powerplant operations (base load, partial, and full peaking) and for the months of August and September 1994.

$$V_c = C\frac{Y+H_c}{H_c}\sqrt{\frac{\Delta\rho_c}{\rho_c}gY} \tag{3}$$

where:

C = an empirical coefficient
V_c = mean flow velocity under the curtain, ft/sec
Y = vertical distance from curtain bottom to upper limit of the withdrawal zone, ft
$\Delta\rho_c$ = $\rho_c - \rho_a$, density difference of the water between the curtain bottom and the upper limit of the withdrawal zone, slugs/ft^3
ρ_c = density of water at the curtain bottom, slugs/ft^3
ρ_a = density of water at the upper limit of the withdrawal zone, slugs/ft^3
H_c = depth from reservoir bed to curtain bottom, ft
g = gravitational constant, ft/sec^2

A similar analysis was attempted to describe the underflow hydraulics for the Carr Tailrace curtain. However, the highly unsteady underflows were difficult to define because curtain underflows varied from a density current to an interflow because of diurnal fluctuations in underflow temperatures (densities). Likewise, cyclical loading on the curtain hindered definition of the curtain bottom elevation.

OPERATION AND MAINTENANCE

Operation and maintenance costs for the four curtains over the years of 1993 to 1995 have been about $160,000. This cost includes installing and breaching the Carr tailrace curtain in the spring and fall, maintaining safety lighting at the boat passage, and conducting the temperature monitoring. As of 1995, the Lewiston curtains have required no maintenance or repairs.

A few structural components have failed because of extreme loads from temperature differentials or wear and tear associated with wave action. Significant failures are listed below:

- A top boom floating tank at the Carr Powerplant tailrace curtain failed under extreme loading. The end-cap weld failed as shown in fig. 24. Also, curtain components like chains and shackles have deformed under extreme loads (fig. 25).

- A top boom floating tank at the Spring Creek Tunnel intake curtain failed from wear because two adjacent tanks were rubbing against each other under wave loading. Cost of these 1995 repairs was $15,000.

- Curtain fabric tears have occurred on both the Carr tailrace and Spring Creek curtains when large changes in reservoir elevation caused the curtain fabric to drag along the ground. Tears were several feet long and occurred near the bottom of the curtain, so leakage effects are minimal. Fabric tears occurred at the Spring Creek Tunnel intake curtain where the top of the curtain end was supported by chains. Curtain loads coupled with wave action caused abrasion which wore through the Hypalon fabric. Abrasion damage was minimized by fixing the curtain to the chain at closer intervals. The cost associated with this 1995 repair was $30,000.

- Coatings on the steel components have failed in locations where birds roost and where abrasion occurs. Recoating will likely be necessary in 1998 or 1999 at an estimated cost of $500,000.

APPLICATIONS

Curtain structures have many potential applications in lakes and reservoirs:

- Curtains can be used to increase or decrease mixing in reservoirs to improve reservoir or release water quality.

- Curtains can provide selective withdrawal or the ability to release water of a select quality from a stratified reservoir.

- Curtains can be used to create a warm water fishery inside a cold water fishery by containing a warm water inflow behind a curtain. Or vice versa, a cold water fishery can be maintained throughout the summer months if a bottom-sealed curtain is used to prevent cold water withdrawal.

- Curtains have been proposed by the U.S. Army Corps of Engineers to divert downstream migrating fish from entering hydro-power intake structures. The curtains would be used to guide fish to a new or existing fish bypass facility. They have also proposed using curtains to control reservoir temperatures at a pump-storage project in Georgia.

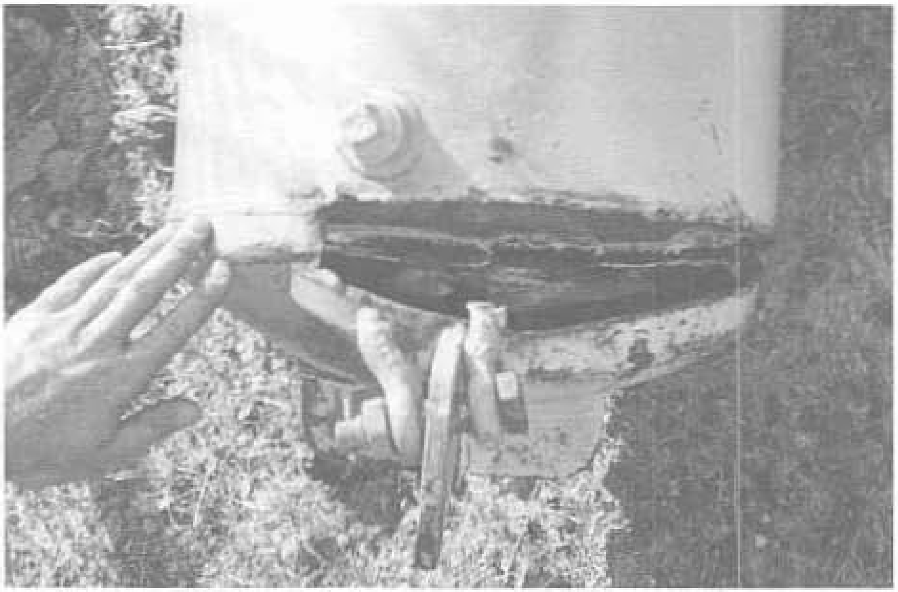


Figure 24. - Photograph of a failed weld on a Carr tailrace curtain top boom floating tank.

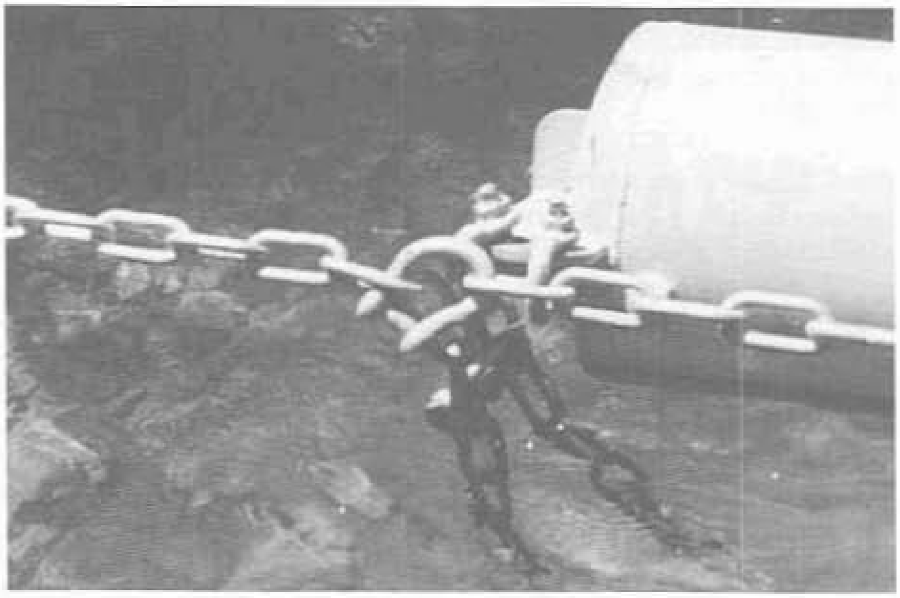


Figure 25. - Photograph of a deformed shackle used to connect the Carr tailrace curtain to a shore anchor.

- Curtains can be used for selective withdrawal when water quality parameters other than temperature are an issue. For example, curtains can be used for surface withdrawals from a reservoir with depleted dissolved oxygen at the intake elevation.

- Submerged curtains could be used to redirect density currents laden with sediment to a specific location in a reservoir—away from an intake structure, for example.

- Various curtain-like structures have been used to enclose dredging and underwater construction sites to keep environmental impacts to a minimum.

Both the performance of the curtain structure and the curtain's influence on flow patterns and reservoir hydrodynamics depend on the curtain design and the kinetic and density characteristics of the flow. This study showed that curtain performance and hydrodynamic responses are complex and not easily characterized. The objective of this report was to document specific observed performance and, where possible, generalize findings which would guide development of future curtain applications and designs. For designs that deviate significantly from this application, use of physical modeling and/or prototype testing is strongly recommended to support the curtain design process and to achieve the project objectives.

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