Control of Release Water Temperatures in Reclamation’s Central Valley Project

by

Perry L. Johnson

Presented in Japan
by Darrell W. Webber

November 1991
CONTROL OF RELEASE WATER TEMPERATURES IN RECLAMATION'S CENTRAL VALLEY PROJECT

by Darrell W. Webber
Assistant Commissioner-Engineering and Research
United States Bureau of Reclamation

INTRODUCTION

California's Central Valley Basin includes two major watersheds, the Sacramento River on the north and the San Joaquin River on the south (figure 1). The combined watersheds extend nearly 800 kilometers (500 miles) in a northwest-southeast direction and range from about 100 to 160 kilometers (60 to 100 miles) in width. The valley floor occupies about one-third of the basin; the other two thirds are mountainous. The Sacramento River and its tributaries flow southward, draining the northern part of the basin. The San Joaquin River and its tributaries flow northward, draining the central southern portion. These two river systems join at the Sacramento-San Joaquin Delta, flow into San Francisco Bay and the Pacific Ocean.

The Central Valley Project, one of the United States major water developments, extends over much of the basin. Although developed primarily for irrigation, this multiple-purpose project also provides flood control, improves Sacramento River navigation, supplies domestic and industrial water, generates electric power, creates opportunities for recreation, controls salt water encroachment, and conserves fish and wildlife. The project annually delivers between 3.7 billion and 4.9 billion cubic meters (3 and 4 million acre-feet) of water for irrigation use on nearly 8 billion square meters (2 million acres) of land. Also approximately 390 cubic meters (320,000 acre-feet) of water is delivered to communities for municipal and industrial use. Annual power generation is in excess of 5.5 billion kilowatt-hours. Water releases are also used to control salt water encroachment from San Francisco Bay upon the Sacramento-San Joaquin Delta which endangers the cropland and could inhibit industrial development. In addition Reclamation is committed to maintaining fishery habitat with releases being modified, on occasion, specifically for this objective.

The Sacramento River system is the largest in California yielding 35 percent of the states water supply and providing the most important salmon habitat in the state. Chinook salmon from the Sacramento River account for over half of the commercial catch for Northern California. Since the early 1970's, the chinook salmon population in the Sacramento River has been on the decline. Numerous studies and corrective actions have been undertaken by State and Federal agencies to protect and enhance the fisheries.

River temperatures are one of the most critical factors limiting habitat. Table 1 shows desired temperature ranges for various chinook life stages.
Table 1. Preferred water temperatures (°C) for various chinook salmon life stages

<table>
<thead>
<tr>
<th>Life Stage</th>
<th>Preferred Range</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spawning</td>
<td>5.5 - 13.9</td>
<td>*temperatures in excess of 14.4 begin to be lethal</td>
</tr>
<tr>
<td>Incubation</td>
<td>6.1 - 14.4</td>
<td>*temperatures in excess of 16.7 yield 100% mortality</td>
</tr>
<tr>
<td>Juvenile rearing</td>
<td>7.2 - 14.4</td>
<td>*12.2 is optimum *temperatures in excess of 14.4 begin to be lethal</td>
</tr>
<tr>
<td>Adult migration:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>9.4 - 14.2</td>
<td></td>
</tr>
<tr>
<td>Fall</td>
<td>10.6 - 19.4</td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>3.3 - 13.3</td>
<td></td>
</tr>
</tbody>
</table>

As shown in figure 2, four major runs occur on the Sacramento River. Fish are present, spawning, incubating, and rearing in the river year round. At present, chinook salmon in the Sacramento River are adversely impacted by water temperatures that are too warm during the summer and fall for optimum egg and fry survival and too cold during the spring months for optimum growth.

Construction of Keswick Dam (the re-regulation dam for Shasta and Spring Creek Powerplants) and Shasta Dam truncated the salmon runs on the mainstem Sacramento. Significant spawning now occurs on the river between Red Bluff and Keswick Dam a distance of approximately 100 river kilometers (60 miles). River water temperatures in this reach are influenced by release water temperatures at Shasta and Keswick as well as by the temperature of water diverted from the Trinity River to the Sacramento River through Clear Creek Tunnel, Whiskeytown Reservoir and Spring Creek Tunnel (figure 3).

Shasta Dam is a 183 m (602 ft) high concrete gravity structure which was completed in 1945 (figures 4 and 5). The dam includes an extensive outlet works structure with intakes at elevation 287, 257, and 226 m (942, 842, and 742 ft). The dam has a gated spillway with a crest elevation of 316 m (1037 ft). The power penstock intakes sit on the right abutment with a centerline elevation of 248 m (815 ft), approximately 76 m (250 ft) above the bottom of the reservoir. The power plant includes five turbines with a combined rated capacity of 539 Mw. Currently, units are being upgraded with
future additional upgrades expected. The current discharge capacity of the powerplant is 498 m$^3$/s (17600 ft$^3$/s). Expected upgrades will increase the discharge capacity to 552 m$^3$/s (19500 ft$^3$/s).

Shasta Dam is the primary source of flow for the reach of river of concern. Shasta Powerplant is operated in a peaking mode with releases varying hourly, daily, and seasonally as a function of power and water demand. In the late summer and fall, significant additional flows are also diverted from the Trinity River and Clair Engle Reservoir through Whiskeytown Reservoir and Spring Creek Powerplant to Keswick Reservoir and the Sacramento River. Also several minor tributaries contribute to the river between Keswick and Red Bluff. The diverted and tributary flows influence both river discharge and river water temperature.

Lake Shasta receives its largest inflows during winter and spring storm events and with snow melt runoff. Inflows during these periods are turbid. The turbidity is caused by very fine sediment which settles and clears over weeks and months. Control of turbidity in releases is a secondary water quality objective.

Heaviest draw on the reservoir occurs during the late spring and summer. During this period, the reservoir water surface falls and the water in the upper levels of the reservoir warms due to climatic and inflow influences. In most years, but in particular in low water or drought years, the water at the penstock intakes warms substantially through the summer months. When this warming is coupled with downstream warming in the river (due to atmospheric and tributary influences), by August optimum water temperatures may be exceeded over portions of the river reach of concern. River water temperatures can be lowered by accessing and releasing deeper, colder water from Lake Shasta. Currently this requires use of the low level (elevation 226 m) outlet works which bypasses the turbines and results in lost power revenues. Replacement power must then be purchased from alternate sources due to contractual commitments. This was done in 1987, 1988, and 1989 with a total cost of approximately $6 million.

Reclamation has conducted studies to identify and evaluate ways to both manage cold water reserves in the reservoir and access deeper cold water for power release. A value engineering study completed in November of 1987 identified several structural alternatives that could function as temperature control devices (TCD). A study had also been done earlier by the engineering consulting firm of CH2M Hill that had identified a light weight flexible curtain barrier that would function as a TCD and control release temperatures. In all cases the structures identified achieved temperature control through selective withdrawal.

SELECTIVE WITHDRAWAL

When a reservoir is density (and water quality) stratified, it is possible to withdraw water from distinct layers. The vertical position and thickness of the withdrawal layer depends on the
vertical position of the intake, the size and orientation of the intake, the withdrawal discharge, the density stratification profile, and reservoir geometry. Positioning intakes at various elevations in the reservoir allows selection of the horizontal layer from which water is withdrawn. Numerous studies have been conducted to define upper and lower bounds and thus the vertical thickness of the withdrawal layer \([4,5,6,7]\). These studies were done in stratified laboratory reservoirs (typically in rectangular flumes) with simplified intake and reservoir geometry. The laboratory findings have been at least generally confirmed by field observations. There are however variations between theories which indicate uncertainties. In addition, secondary currents and site specific geometry influenced flow features are generated in Shasta Reservoir that do not occur in laboratory flumes. Thus, variations away from the withdrawal layer bounds predicted by simplified theory can be expected. However, it should be noted that the reservoir math models used in this study have been fit to Shasta Reservoir based on field data. Thus the withdrawal layer theory included in these models has been adjusted to give a true representation.

In general the theory shows that if the discharge is increased the withdrawal layer thickness will also be increased. Thus with peaking power operation, water will be drawn from thicker vertical layers as more units are used at Shasta Powerplant. Likewise the theory shows that when withdrawals are made from zones with strong temperature and density gradients the withdrawal layer will be thinner. Typically gradients tend to be stronger at the surface and weaker at depth and thus withdrawal layers will tend to be thinner at the surface and thicker at depth. When no temperature gradient exists in the reservoir, as is the case in the winter after turnover, the withdrawal will be from the full depth of the reservoir.

Reclamation has constructed numerous dams with multi-level intakes and selective withdrawal capabilities. Typically these capabilities are supplied either by independent intakes set at various elevations, free-standing reinforced concrete multi-level intake towers, or inclined conduits with multi-level intakes. These structures are well suited for new construction but are not well suited for retrofits. Likewise the cost of these traditional structures is substantial.

MATHEMATICAL MODELING

The TCD can be thought of as an interface between the reservoir and the downstream river. Depending on how the TCD is operated and depending on the withdrawal characteristics of the TCD, withdrawals will be made from specific layers of the reservoir. Depending on inflows and climatic influences; these withdrawals will reduce reservoir storage; reduce cold water reserves; and generally modify reservoir temperature, dissolved oxygen and turbidity stratification patterns. The withdrawal characteristics of alternative designs was described by the theory which was modified
and confirmed through use of a physical model study. Reservoir and TCD interaction was evaluated through use of computer models. The reservoir computer model, WQRRS [2], was used in this study. The model had been previously applied to Lake Shasta with its accuracy verified by historic data. The math model was used to evaluate TCD effectiveness when operating with various reservoir elevations, hydrologic conditions, and climatic conditions. Historic data from wet, dry, and typical years were used. Various TCD configurations (with alternative withdrawal locations) were evaluated. The math model selected appropriate withdrawal elevations, as available, to both met downstream temperature objectives and to conserve cold water reserves within the reservoir. The math model in turn yielded predictions of resulting release temperatures and resulting stratified reservoir water quality conditions throughout the year of interest. Thus the model shows the potential effectiveness of various TCD designs, guides operation of the TCD to optimize release water quality (temperature) throughout the year, and allows determination of TCD effectiveness when operating under a broad variety of conditions.

Also studied was the influence of the TCD operation on river temperatures between Shasta Dam and Red Bluff. As previously noted river temperatures are a function of release temperatures and discharge magnitudes at Shasta Dam, diversion and tributary flow temperatures and discharge magnitudes, river morphology, and climatic influences. A release discharge and temperature that easily meets downstream temperature requirements in May could fall well short of meeting the requirements in August. Again the best available tool for analysis of this flow and determination of water temperature at various river stations is a computer model. A Reclamation developed model [3] which had previously been applied to, and verified for this reach of river was used. Use of this model shows the downstream influence of various TCD designs and operations. It also shows the limitations of downstream temperature control that can be achieved through use of the TCD.

Findings from the computer model studies showed that:

1. Use of a TCD offers an effective way to manage water supplies in Lake Shasta with the objective of improving water temperatures in the upper Sacramento River.

2. Solely adding deep water access capabilities to the existing power intakes will yield river cooling for only a limited time duration in low water years. In the 10 percentile low water years (a low water year that would occur approximately once in every 10 years) the addition of deep water access reduces the length of time that release and river water temperatures exceed the basin plan water quality objectives from approximately two months to one month. However, maximum release temperatures will equal or exceed historic maximum release temperatures made through the existing intakes for similar conditions. The problem is that if releases are made through the existing intakes until river temperatures exceed criteria and then deeper water is accessed, in lower water years,
insufficient cold water reserves are available to meet late summer and early fall water demands.

3. Use of a temperature control device (TCD) that allows high level withdrawal (from elevation 290 to 319 m) early in the season and deep withdrawal (from elevation 198 to 229 m) later in the season offers optimum potential for release and river cooling. By releasing from high in the reservoir during spring, river temperatures which are 0.5 to 1.0°C warmer than historic can be achieved. This is of benefit in that historically spring river temperatures are too cold for optimum incubation and fish growth. High level releases allow cold water reserves to be saved and used to achieve release and river cooling during the late summer and early fall. In 10 percentile low water years, late summer release temperatures can be reduced by 2.8°C with resulting 0.5 to 2.2°C reductions in river temperatures. In 3 percentile low water years, mid-summer release temperatures could be reduced by 5.6 to 6.7°C with up to 3.3°C reduction in river temperatures. However in these critical low water years, even with optimum cold water management, insufficient cold water reserves would be available to sustain cold water releases through the late summer and fall. Consequently, either late summer and fall release temperatures would rebound and be comparable to historic temperatures or early summer releases would have to be managed for something less than optimum river temperatures. In high water years use of high and low TCD intakes would allow optimum river temperatures to be sustained over the entire river reach between Keswick and Red Bluff.

4. Access of the deep cold water reserves (that cannot be accessed with the existing power intakes) is of particular importance in extreme low water years. Conservation of cold water reserves through use of high level intakes in the spring significantly improves performance in all years. Use of high level TCD intakes with the existing 248 m (815 ft) power intakes (but with no deep water access) produces comparable release temperature control to a TCD with both high and deep intakes in years when reservoir elevations are equal to or higher than those of the 10 percentile low water year. This reflects the importance of using the high level withdrawal in the spring and conservation of large volumes of cold water. However, in critical low water years, up to a 2.8°C release cooling and 1.1°C river cooling for a one to two month period is lost if deep intakes are not included.

5. The top of the TCD should be positioned above frequently occurring reservoir high water elevations to prevent overdraw generated by flow entrainment within the TCD. Based on reservoir math model findings, raising the top of the TCD from elevation 290 m (950 ft) to elevation 319 m (1045 ft) in an effort to further increase cold water reserves does not significantly improve TCD performance. However physical model study findings show that internal mixing and flow generated head losses within the TCD will cause entrainment of high level withdrawal (overdraw) water into the release (even if the objective is to withdraw totally through the low level intakes). This is particularly the case at higher
discharges. Findings indicate that to totally exclude overdraw a physical blockage should be used (buoyancy of the warm surface water in itself will not do the job). One option is to extend the top of the TCD to or above the reservoir surface to obtain this control.

6. Because of operational limitations it was recommended that the TCD structure be placed over all five power intakes. Based on the 10 percentile low water year, if the TCD were placed over only three intakes, only a slight reduction in temperature control performance would result. This assumes that the TCD modified units would be the first used and that the un-modified units would be used only for peaking. Thus placement of the TCD over a limited number of units would change operating procedures. Likewise temperature control would suffer if modified units were down for maintenance. For this reason placement of the TCD over less than all five units was not further considered.

7. Again because of operational limitations, deep water access capabilities should be available for all five units. Having deep water access capabilities with three units produced comparable performance to having deep water access capabilities with all five units, even in low water years. If deep water access was limited to two units river warming of 0.3 to 0.5°C would result (as compared to five unit access). If deep withdrawal is limited to one unit, warming of 0.5 to 0.8°C would result (particularly in low water years). If individual units were modified for deep water access then the same operational restrictions mentioned above would occur. Historic operation shows that in late summer and fall simultaneous use of more than three units will generally not occur.

PHYSICAL MODEL STUDIES

The hydraulic characteristics of the various TCD concepts are complex. Factors to be considered include intake coefficients, internal headloss, density influences on vertically displaced flows, vertical mixing and flow entrainment, and resulting density profiles inside the TCD and their influence on net head differential across the structure. The three dimensional flow problem that the TCD presents is best addressed using a density stratified physical model. Consequently a scale model was constructed and tested in the Hydraulic Laboratory of Reclamation's Denver Office.

A 1:72 scale physical model was used to study the alternative TCD concepts. Included in the model were all five penstock intakes, a simplified representation of the trashrack structures, and a 1300 ft by 2000 ft area of reservoir topography surrounding the penstock intakes. The large area of reservoir topography and corresponding large reservoir volume were included in the model to at least partially eliminate boundary effects and simulate the very large prototype reservoir. To maintain a constant reservoir elevation during a test, water drawn from the reservoir and into the power intakes was recirculated and returned to the back of the model.
When the model was operated with a temperature stratification, the recirculated water was generally not returned to the horizontal layer in the model reservoir from which it was drawn. Consequently during a test, with time, the temperature stratification profile in the model would become distorted. The time duration allowed for testing without recirculation generated distortions was discharge dependent. Because of the large reservoir in the model, the time duration varied from 20 minutes to over an hour.

The 1:72 scale was selected primarily to allow inclusion of the large reservoir in the model. At this scale headloss associated with flow around structural members, vortex formation, and turbulent air entrainment all experience distorted scaling. These potential distortions were considered and compensated for as laboratory test results were interpreted.

The reservoir in the physical model was temperature and therefore density stratified. Stratification was achieved with refrigeration coils set in the lower back of the model (extending from the bottom of the reservoir to approximately elevation 259 m). The refrigeration coils maintained cold deep water while surface water was warmed by the ambient air. At times in an effort to further strengthen the stratification, warm air was blown across the surface of the model reservoir and surface emersion heaters were used. Temperature stratifications as strong as those experienced in the reservoir in May were duplicated. As temperature gradients increased, vertical heat transfer in the model could not be overcome. Consequently late summer stratifications could not be duplicated. Sufficient stratification was created to define temperature profile shifts across the TCD and how these profile shifts varied with operation, to evaluate the upper and lower bounds of generated withdrawal layers and determine structure configuration or topography influences, and to define density influences on the withdrawal characteristics of the TCD.

The head loss characteristics of the TCD intakes were found to be dependent on discharge and on intake size and configuration and independent of density influences. Consequently intake losses could be evaluated with no stratification of the model reservoir. For these tests, testing duration was not limited by stratification distortions, therefore, back-to-back tests over extended periods were conducted.

Temperature profiles in both the model reservoir and between the TCD and the dam were monitored using columns of thermistors which were scanned by a data acquisition computer. Discharges were monitored using an ultrasonic flow meter that had been calibrated in the laboratory pipe stand. Headlosses were measured using a high accuracy differential manometer. Upper and lower bounds of withdrawal layers were determined visually by observing displacements in vertical dye streaks.
HYDRAULIC CHARACTERISTICS

The TCD placed in front of the power intakes will typically modify the vertical position of flow withdrawal away from the centerline of the existing power penstock intakes. Use of the TCD can yield withdrawal from one elevation or from multiple elevations depending on TCD intakes used. In either case withdrawal layers will be generated at each withdrawal point. These withdrawal layers may be independent or they may overlap. The withdrawal layer theory discussed above can be used to define the resulting layers. The influence of overlapping layers is superimposed.

When wicket gates are opened and a discharge is initiated through a turbine or turbines, a discharge through the TCD is also initiated. Depending on gate or orifice openings in the TCD as well as gate and orifice coefficients and internal losses (due to structure geometry, structural members or internal roughness, and internal flow constrictions), a net headloss associated with the particular discharge and particular flow path results. In addition to head losses, energy may be required to either lift cold dense water up to the penstock intake or pull warm buoyant water down to the intake. The head required to overcome buoyant effects and pull the warm surface water down to the intake equals the difference between the pressure head at the penstock intake elevation in the reservoir and the pressure head at the penstock intake elevation between the TCD and the dam. The pressure head is obtained by integrating the product of the water density and the vertical depth increment from the water surface to the intakes.

With traditional selective withdrawal structures the elevation or elevations of withdrawal are selected and controlled through use of the gates. However, most of the TCD alternatives considered for Shasta, when submerged, are open to the reservoir at the top. This was the case either because it was impractical to enclose the top of the TCD (as with the large curtain concepts) or that by enclosing the top, excessive transient loads are created inside the TCD with start up and/or load rejection. With an open top there is no structural means to exclude flow when the top of the TCD is submerged. Overdraw could be structurally excluded when the reservoir water surface drops below the top of the TCD. To obtain positive control with an open topped structure the TCD could be extended to higher elevations yielding a positive barrier at all but the highest reservoirs. During high water years, large quantities of cold water are available and thus total exclusion of overdraw and optimum management of cold water reserves would likely not be required.

Alternative operations for the open topped TCDs when submerged include: total overdraw with all intermediate and low level intakes closed, predominately intermediate level withdrawal with intermediate level intakes (when available) open and with low level intakes closed, predominately low level withdrawal or underdraw which would occur with warm surface water and with intermediate levels gates closed while the low level intakes are full open, and
Large Curtain TCDs

The physical model was used evaluate the hydraulic performance of a large curtain TCD (figures and ). As shown in figure , the top of the curtain was at elevation 290 m (950 ft) and the bottom of the curtain extended to the topography. Water could be drawn over the top of the curtain in overdraw around the entire curtain perimeter. Likewise, the bottom of the panel between the guyed support tower and the dam could be raised to allow access to the deepest water in the reservoir in underdraw. The hydraulic performance of this curtain was evaluated both with the underdraw panel open and closed.

During each test temperature profiles were measured at two stations in the reservoir and at one station between the curtain and the dam. Since the reservoir was quiet with little vertical mixing, the profiles measured at the two reservoir stations were identical. Considerable three-dimensional mixing occurs between the curtain and the dam. As a result, strong vertical and lateral gradients or transitions occur. Because of the profile variations, it is difficult to select representative temperature profiles inside the curtain to compare with the free reservoir (to determine density loads or to determine density generated differentials that will influence withdrawal distribution). Temperature profiles inside the curtain were consistently measured at one, arbitrarily selected, station throughout the curtain studies. For each test, temperature profile data were collected and corresponding water densities computed. These densities were then integrated over each water column (inside and outside the curtain) to define the density influenced pressure fields. These pressure fields and the shift between them yield both static loading on the curtain and the head differential required to generate the underdraw.

With the top of the curtain submerged and with all flow drawn over the curtain (overdraw), it was found that the withdrawal layer in the main reservoir sheared with the warm surface water above. The shearing action pulled surface water over the curtain and into the inner reservoir zone. An equilibrium state resulted with a thickened surface water layer inside the curtain and with a fairly static surface water layer in the main reservoir (once the equilibrium state is reached surface water flow over the curtain was small). The strength of this action was dependent on submergence. With shallow submergence of the top of the curtain the withdrawal layer extend to the surface and surface water was actively passed. With moderate submergence the flow conditions described above were maximized. With large submergence (with the top of the curtain substantially below the warm surface water layer) circulation in the surface layer relieves the tendency for thickening. With moderate submergence, the withdrawal flow (beneath the surface layer) drops from the top of the curtain into the inner reservoir. The flow drops as a supercritical density flow until it reaches water of similar density. At that point the jet diffuses or an internal hydraulic jump results. The mixing entrains both surface water from above and cold water leakage from below.
Typically there was a zone inside the curtain below the mixing and below the penstock intakes that contained fairly stagnant cold water. The penstock intakes then draw water from this modified stratification (thick surface layer, mixed transition layer, cold stagnant layer). The withdrawal layer from this inner reservoir (into the penstock intakes) appears to follow withdrawal layer theory with compensation for boundary influences.

With total overdraw, the zone between the curtain and the dam is filled with warmer water while the bulk of the reservoir profile remains cold. This difference in profiles maximizes density generated loading. Differences between the predicted and vertically integrated model profiles indicate the potential for pressure differentials across the curtain to exceed 73 mm (0.25 ft) of water. When this load is applied over the large surface area of the curtain, the density generated loading becomes a major design consideration. On the other hand analysis shows that if properly operated with low overdraw and underdraw velocities, dynamic headlosses across large curtain TCD's are less than 6 mm (0.02 feet) of water at 498 m$^3$/s (17600 ft$^3$/s). Consequently density generated pressure differentials yielded the dominant design load for the large curtain.

Conversely when efforts were made to draw all flow under the curtain (underdraw) relatively small temperature and density profile shifts resulted. Basically the cold water in the main reservoir, below the penstock intake elevation, was of similar temperature to the cold underdraw flow which fills the lower inner reservoir between the bottom of the curtain and the penstock intakes. A differential across the curtain is required to generate the underdraw flow. If the top of the curtain is submerged the differential can be created by a density profile shift. If the differential required (depending on the underdraw cross-section and discharge) exceeds what can be generated by a temperature profile shift (depends on vertical water column height and temperature differentials) water is drawn both over and under the curtain. If the top of the curtain is at the reservoir surface a physical blockage to overdraw, except for leakage, is present and greater differentials are possible. This, however creates the potential for miss operation where excessive curtain control could yield differentials that exceed the design capacity of the curtain.

The mixing that occurs between the curtain and the dam not only influences temperature profile shifts across the curtain but also yields entrainment of underdraw and overdraw flows into the releases. For example: if the objective is to release solely deep cold water and if the top of the curtain is submerged (thus the curtain does not supply a physical blockage to overdraw), underdraw generated currents will mix with and entrain overdraw flows which will amount to at least 10 to 20 percent of the total release even though theoretically there is enough buoyancy in the surface water to exclude its withdrawal. Because surface temperatures are much warmer than deep water temperatures this entrainment can substantially reduce curtain effectiveness. Again withdrawal from
the inner reservoir is approximately described by available withdrawal layer theory. It is possible that by increasing intake areas and thus reducing flow velocities, mixing could be weakened and entrainment reduced.

Leakage was also a concern. The curtain would attach to the dam face and would seat against the bottom topography. It was expected that leakage free attachments were not possible at either surface although closer tolerances could be achieved at the dam face. For various flow conditions (high level withdrawal, low level withdrawal, combined high and low level withdrawal) efforts were directed towards evaluating leakage discharge, distribution, and determining what constitutes acceptable leakage. Leakage discharge was dependent both on cross-sectional area and geometry of the leakage path and on local differential across the curtain. Differential was a function of curtain design, withdrawal operation, and temperature profile shifts (in particular with strong temperature gradients and large vertical water column heights). Differentials generated by dynamic effects are modified vertically by differences between the integrated density profiles on both sides of the curtain.

A final concern was dynamic loading on the curtain. It was noted that a flexible curtain might develop a periodic response to dynamic loading. In turn this curtain oscillation might case either fabric or support structure failure. Although it was not possible to exactly model the structural characteristics of the curtain, a very light weight flexible curtain was installed and observed for dynamic response. Noting physical model limitations indicated by reduced model Reynolds Numbers, no dynamic response was observed for the conditions tested. Detailed dynamic response tests have not been done and consequently curtain oscillation remains a uncertainty. As noted, development of the Shasta curtain found differentials generated in overdraw to be the controlling design load. The curtain was designed for a maximum differential of 73 mm (0.25 ft) of water. To minimize oscillation potential, underdraw cross-sections were sized to yield maximum velocities of 0.3 m/s (1.0 ft/s). The stagnation pressure generated by the 0.3 m/s (1.0 ft/s) velocity is approximately 1/15 of the design load.

Final Curtain Concepts

Smaller TCDs which are rigid or which contain rigid elements (figure ) produce similar temperature profile shifts to those generated by the large curtain, however mixing is more controlled and thus temperature gradients inside the TCD are more abrupt. As a result the plunging action with the thickened surface layer is less pronounced and very strong temperature gradients tend to result at the elevation of the existing power intakes. Because intake and internal velocities are substantially higher than with the large curtain, dynamic losses become a significant factor which increases the design load on the structure.

Rigid Selective Withdrawal Structure
Both the mathematical and the physical model studies indicate that use of a rigid TCD will yield effective management of water supplies in Lake Shasta. This is primarily because the rigid TCD has good flexibility in selection of withdrawal elevation, and is less susceptible to leakage and internal flow entrainment than the curtain concepts.

The rigid TCD functions more as a conduit. Vertical mixing inside the rigid TCD is limited by the near proximity of the TCD walls. As a result temperature gradients inside the TCD, when intake flows from different sources merge, are more abrupt than with the curtain. Likewise when operating in overdraw the top of the TCD functions as an upward facing intake and consequently plunging supercritical density flows were not observed. As a result the temperature profiles inside the TCD were predictable given gate operation, total discharge, and reservoir temperature profile. The reduced vertical mixing also reduced the potential for entrainment of overdraw flows. However the physical model shows that when withdrawals are made solely from the 219 m (720 ft) level with the top of the TCD submerged, if the withdrawal exceeds 8,000 to 10,000 ft³/s, overdraw flow will be entrained. This would be the case even in late summer with strong surface buoyancy.

Depending on submergence and discharge a potential exists to draw air into the penstocks when the TCD is operated in a total overdraw mode or when gates with shallow submergence are used. Entrained air may yield either blowback or rough turbine operation and thus should be avoided. Although the physical model scale was not ideal to set submergence criteria, it was recommended that with a maximum discharge the upper gates should be lowered when the reservoir elevation drops below 323 m (1059 ft). When submergence on the lowered upper gates is less than 30 ft, it was recommended that the next lower level of gates (or at least a portion of the next lower level of gates) be opened. Minimum submergence criteria is based on maximum possible discharge and assumes that gate position will not be changed with daily peaking (the gate design will not allow changes in gate setting with plant peaking). This criteria was somewhat confirmed by experience at Flaming Gorge Dam which has a similar rigid structure. It was recommended that this criteria be reviewed and modified, if needed, through observation of the operating prototype structure. When overdraw is occurring over lowered upper shutters; or when with a low reservoir, the intermediate gates are being used in an overdraw mode, a more concentrated, higher velocity flow is generated. Consequently the discharge generated by a specific differential decreases and the potential for vortex formation and air entrainment increases. Additional submergence is required to control air entrainment.

Noting that the bottom intake of the TCD is at elevation 219 m (720 ft) which is 49 m (160 ft) above the reservoir bottom, a withdrawal layer predictive equation calibrated through use of the physical model for Shasta Dam with the rigid TCD, predicts that the volume of unaccessed water (the volume of cold water that could not be accessed and released in late summer) varies from \(3.3 \times 10^7 \text{ m}^3\) (27000
acre-ft) at a discharge of 113 m³/s (4000 ft³/s) to $8.9 \times 10^6$ m³ (7200 acre-ft) at a withdrawal discharge of 552 m³/s (19500 ft³/s). These volumes are considered small and indicate that most of the cold water in the reservoir could be accessed. Predicted volumes of unaccessed cold water are conservatively high in that a shear exists between the withdrawal layer and the cold water below. This shear in conjunction with the mixing influence of the peaking operation should mix and gradually entrain the deeper water into the withdrawal.

Although, under normal operating conditions, the TCD will be exposed to differential pressure loading resulting from wave loads and from flow generated velocity heads, head losses, and density influences; it was found that the loading due to transient flow conditions (turbine start-up and load rejection) controlled much of the structural design. Numerous analyses were done to evaluate the influence on resulting transient loads of TCD size, spacing off of dam, top elevation, intake size, and possible use of a fixed top or cover. Use of a cover on the TCD was inviting because it would allow absolute control of overdraw, even when the top of the TCD was submerged. Use of a cover would also allow the top of the structure to be lowered to elevation 305 m (1000 ft) or lower without concern for associated overdraw problems. Unfortunately, covering the structure created an extended closed conduit which substantially increased transient loads. Thus it was concluded that the top of the structure would be kept open.

The design selected included adjustable gates or weirs which allowed the top face of the main structure to be set as low as elevation 305 m (1000 ft) or as high as elevation 319 m (1045 ft). This allowed overdraw, or at least partial overdraw in the spring of all but the critical low water years. Two sets of intermediate gates were included in the structure. One set of five gates, one gate in each 15 m (50 ft) wide section, was placed across the face of the TCD and extended from elevation 274 m (900 ft) to elevation 288 m (945 ft) and one set of five gates was placed across the face of the TCD and extended from elevation 244 m (800 ft) to elevation 252 m (827 ft). Because the TCD was not designed to withstand full hydro-static load (with reservoir head on one side and a dewatered or partially dewatered chamber on the inside), pressure relief panels were included in the 244-252 gates to prevent structure collapse in case the structure was miss-operated or in case of high transient related surges.

TEMPERATURE CONTROL ON THE TRINITY DIVERSION

Studies are currently underway in Reclamation's Mid-Pacific Regional Office to identify alternatives for reducing the temperature of the Trinity River water diverted to the upper Sacramento River. These studies are an extension of a previous value engineering study ( ). Because the diverted flow passes through numerous structures (figure 3) including the Trinity Dam Outlet, Clear Creek Tunnel Intake, Carr Powerplant Tailrace, and Clear Creek Tunnel Intake; there are several alternatives for
structural and/or operational control of release temperatures. One of these options, use of a curtain barrier at the Clear Creek Tunnel Intake is currently being studied through use of a physical model.

In addition because feasibility designs have shown the cost of curtain structures to be less than half the cost of a conventional rigid structure, Reclamation has a current active research program which is oriented at developing and proving the curtain barrier concept. Because of uncertainties about hydraulic performance, deployment, operation, maintenance, and reliability; a conventional structure design was selected for installation at Shasta. Reclamation's intent is to install and instrument a prototype which would be used to resolve various materials, fabrication, installation, loading, and operations questions.

REFERENCES

1. Bureau of Reclamation - "Shasta Dam Temperature Modification Value Engineering Study September 1987"