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Temperature Control Device for Shasta Dam

by

Perry L. Johnson
Richard LaFond
Darrell W. Webber

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by Perry L. Johnson[1], Richard LaFond[2], and Darrell W. Webber[3]

INTRODUCTION

Shasta Dam and Reservoir are located on the Sacramento River in northern California (figure 1). Shasta Dam is a major feature of the U.S. Bureau of Reclamation's Central Valley Project. This 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. 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.

Four major salmon 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 (a reregulation dam) downstream of Shasta Dam truncated the salmon runs on the Sacramento River. Significant spawning now occurs on the river below Keswick Dam. River water temperatures in this reach are primarily influenced by release water temperatures at Shasta Dam.

Shasta Dam, completed in 1945, is a 183-m (602-ft)-high curved concrete gravity structure with a crest length of 1055 m (3460 ft)

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[1] Hydraulic Engineer, U.S. Bureau of Reclamation

[2] Structural Engineer, U.S. Bureau of Reclamation

[3] Assistant Commissioner - Engineering and Research, U.S. Bureau of Reclamation

(figures 2 and 3). The dam includes an extensive outlet works structure with intakes at three elevations and a gated spillway. The five power penstock intakes sit on the right abutment approximately 73 m (240 ft) above the bottom of the reservoir near the center of the dam but only 8 m (25 ft) from the reservoir bottom directly in front of the intakes. The powerplant includes five turbines with a combined rated capacity of 539 MW. The discharge capacity of the powerplant is 498 m^3/s (17 600 ft^3/s). The powerplant is operated in a peaking mode with releases varying hourly, daily, and seasonally as a function of power and water demand.

Largest releases from the reservoir occur 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, optimum water temperatures for fish habitat may be exceeded over portions of the river reach of concern by late summer.

River water temperatures can be lowered by accessing and releasing deeper, colder water from Lake Shasta. Currently, this requires use of the low level 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, 1989, 1990, and 1991 with a total cost of approximately $13 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 [1] that could function as temperature control devices (TCD). A study had also been done earlier by the engineering firm of CH2M Hill [2] that identified a lightweight, 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. Reservoirs can be stratified with regard to temperature, turbidity, and dissolved oxygen. 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.

Withdrawal layer 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 layers as more units are used. 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 are stronger at the surface and weaker at depth and, thus, withdrawal layers will tend to be thinner at the surface and thicker at depth. With no temperature gradient, as is the case in the winter after turnover, the withdrawal will be from the full reservoir depth.

Reclamation has constructed numerous dams with multilevel intakes and selective withdrawal capabilities. Typically, these capabilities are supplied either by independent intakes set at various elevations, free-standing reinforced concrete multilevel intake towers, or inclined conduits with multilevel intakes. These structures are well suited for new construction, but are not well suited for modifications to existing facilities where evacuation of the reservoir is not feasible and construction must not severely impact powerplant operations. Likewise, the cost of these traditional structures is substantial.

MATHEMATICAL MODEL STUDIES

The TCD can be thought of as an interface between the reservoir and the downstream river. Reservoir and TCD interaction, and TCD and river interaction were evaluated through use of mathematical (computer) models [3,4]. Using historic data from wet, dry, and typical years, the math models were used to evaluate the potential effectiveness of various TCD designs, and provide an indication of TCD operation that would optimize release water quality (temperature) throughout the year.

The mathematical model studies [5] showed that:

1. Use of a TCD offers a potentially 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. If releases are made through the existing intakes until river temperatures exceed criteria and then deeper water is accessed, insufficient cold water reserves are available to meet late summer and early fall water demands.

3. Use of a TCD that allows high level withdrawal early in the season and deep withdrawal later in the season offers optimum

potential for release and river cooling. 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.

4. In critical low water years, even with optimum cold water management, sufficient cold water reserves will not be available to sustain optimum river water temperatures through the late summer and fall.

PHYSICAL MODEL STUDIES

The hydraulic characteristics of the various TCD concepts are complex. Factors to be considered include intake coefficients, internal head loss, density influences, vertical mixing, and flow entrainment. The three-dimensional flow problem that the TCD presents is best addressed using a density stratified physical model. Consequently, a 1:72 scale model (figure 4) was constructed and tested in the Hydraulic Laboratory of Reclamation's Denver Office.

The physical model study [5] showed that:

1. The TCD placed in front of the penstock 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 operation (figure 5).

2. Depending on gate or orifice openings in the TCD, internal losses due to structure geometry, structural members or internal roughness, and internal flow constrictions, a net head loss associated with the particular discharge and particular flow path results. In addition to these head losses, energy is required to either lift cold dense water up to the penstock intake or pull warm buoyant water down to the intake.

3. When multiple TCD intakes are being used, the energy equation can be evaluated along each flow path (from the reservoir to the penstock intakes through each of the operating TCD intakes) and equated to determine the discharge distribution between intakes.

4. Mixing inside the TCD with resulting entrainment of overdraw (flow over the top of the TCD) can reduce TCD effectiveness. Control of overdraw is a concern because the TCD alternatives considered for Shasta are open at the top, either because it was impractical to enclose the top or because by enclosing the top excessive transient loads caused by turbine start up or load rejection resulted. Thus, when the top of the TCD is submerged there is no structural means to exclude flow. Buoyancy of warm surface water was not sufficient to totally exclude overdraw. Studies indicated that the top of the TCD should be positioned high enough to exclude overdraw for all but high water years.

PRELIMINARY TCD CONCEPTS

The initial effort to provide temperature control for the penstocks at Shasta Dam focused on the temporary curtain study by CH2M Hill [2] as modified by information gained from the math models of the reservoir and river. Model studies revealed that for best management of river temperatures a device should be used that restricts cold water release early in the year. This conservation of cold water is accomplished by providing high level withdrawal capability. Access to the cold water is accomplished by providing low level withdrawal capability. During transition from total high level (warmer water) to total low level (colder water) withdrawal, the ability to mix the two and access intermediate water levels permit optimum use of the cold water resource.

The initial concept (figure 6) consisted of an impermeable, flexible curtain made of reinforced Hypalon, supported by steel cables, and adjusted by operation of variable buoyant tanks attached to the top and bottom booms. The reinforced Hypalon material was selected for its flexibility, weather resistance, high tear resistance, and ease of seaming. Conservation of the cold water was achieved by sealing the bottom of the curtain to the bottom of the reservoir and drawing the water over the top. By pumping air into the bottom boom tanks, an aperture could be created to access the cold water.

As preliminary designs proceeded, concerns with the mechanical operation and structural support arose. The device would require large quantities of submerged valves and pneumatic hose. These items were considered to be susceptible to damage, would require frequent maintenance, and would be difficult to repair underwater. Support of the approximately 22 300-m^2 (240 000-ft^2)-curtain was also complicated by its height [approximately 95 m (310 ft) at its highest point], magnitude of applied load, reservoir topography, underwater depth, and potential for a 70-m (230-ft)-fluctuation of the reservoir water surface.

It became apparent that the mechanical operation and structural support of the curtain would dictate whether a flexible curtain could be safely operated at this site. For mechanical operation, it was decided that hoists would provide a reliable means of adjustment. To improve structural integrity, it was decided to reduce the area of the curtain to the minimum required for selective withdrawal, while maintaining a safe distance between the flexible curtain material and the trashracks surrounding the penstock intakes. To this end, flexible curtain concepts, with reduced curtain area and positive support from the dam and reservoir bottom were considered. However, even with these reductions in curtain area, the concepts still required over 11 500 m^2 (125 000 ft^2) of flexible curtain material to be suspended in front of the penstock intakes.

The estimated construction costs for these smaller curtain concepts ranged from \$13.5 million to \$15.5 million. Although these costs made the concepts financially desirable, the lack of historical reference for underwater curtains of this size prompted the decision to seek other "more traditional" concepts. The major concerns associated with the installation and operation of a flexible curtain at Shasta Dam are: the size of curtain required for the design discharge, extreme underwater depths of operation, large fluctuation of reservoir water surface and its impact on curtain and anchorage, possibility of damage from floating or submerged debris, and potential for tremendous economic loss in case of catastrophic curtain failure leading to failure of one or more of the existing trashracks.

Several "traditional" concepts were investigated. They included modification of the existing diversion tunnel, manifolding the lower tier of outlet works to the existing penstocks, and excavating a new penstock intake through the dam. All would supply low level power withdrawal. For all cases the existing trashrack structure would be modified to permit withdrawal from higher reservoir levels. These concepts were abandoned due to the excessive underwater construction, high head losses, and/or excessive excavation of the existing dam.

FINAL TCD CONCEPT

One of the "traditional" concepts that was investigated required the installation of a steel selective withdrawal structure on the upstream face of the dam. This concept was modeled after a similar structure installed at Reclamation's Flaming Gorge Dam in the late 1970's. The Flaming Gorge structure has a maximum discharge capacity of 120 m^3/s (4 260 ft^3/s). However, unlike the Flaming Gorge installation, where only high level selective withdrawal was required, the installation at Shasta Dam was also required to access the lower, colder water in the reservoir. This difference in operational criteria, as well as the larger design discharge, greatly influenced the shape and size of the structure and caused the installation at Shasta Dam to be much larger than the installation at Flaming Gorge Dam.

The final TCD (figures 4 and 7) consists of a steel shutter structure and low level intake structure that are attached to the upstream face of Shasta Dam. The device encloses all five power penstock intakes, which gives maximum power operations flexibility. Based on a comparison of the alternative TCDs with respect to durability, reliability, operational flexibility, ease of operation, maintenance, head loss, and ability to optimize the cold water resource, this TCD was selected for final design [6].

The shutter structure consists of a series of fixed panels and adjustable shutters that permit access to water levels at and above the existing intake elevation. The 76-m (250-ft)-wide by 91-m (300-ft)-high shutter structure is composed of five separate units that will be individually assembled and attached to the dam around each penstock intake. These units will project 15 m (50 ft) upstream from the face of the dam and will be open between units to permit crossflow through the shutter structure. The adjustable shutters are operated by hoists, and pressure relief panels prevent excessive differential pressure across the TCD that could be caused by turbine startup or shutdown, or improper TCD operation. Trashracks on the upstream face of the TCD prevent debris accumulation within the device.

Attached to the side of the shutter structure, is the low level intake structure. This structure projects 15 m (50 ft) upstream from the face of the dam and acts as a conduit extension to access the deeper, colder water near the center of the dam. The 46-m (150-ft)-wide by 49-m (160-ft)-high, low level intake structure is composed of three separate intake units that will be individually assembled and attached to the dam. The low level intakes have inverted openings at EL. 219 m (720 ft) and two slide gates, mounted on the side of the shutter structure, control the flow from the low level intake structure to the shutter structure.

The design of the final TCD is complicated by its size, magnitude of applied loads, and attempt to minimize underwater construction. Of the analyzed load combinations for dead and live loads, earthquake, wave, head loss and density effects, transient flow conditions, and wind loads; transient flow conditions (turbine startup and load rejection) controlled much of the structural design. Designs attempt to minimize the amount and complexity of underwater construction in order to keep construction costs low and minimize impact to powerplant operation. However, the requirement to drill and grout a large number of anchor bolts into the dam face, to support the vertical and lateral loads, could not be avoided.

The construction and construction inspection of the TCD will be challenging. It is anticipated that each of the eight individual units that form the shutter and low level intake structures will be individually assembled on the shore of the lake, floated and sunk into position, then attached to the dam. Once attached to the dam, the units will be connected to each other to form one monolithic structure. The handling and positioning of the eight structures with estimated weights ranging from 318-770 metric tons (350-850 tons) will require equipment specifically designed for this purpose. Actual installation procedure of the TCD will be determined by the contractor and approved by Reclamation. Inspection of underwater construction activities which may be required at depths exceeding 91 m (300 ft) will be aided by the use of a remote operated vehicle (ROV) equipped with a video camera.

The primary purpose of the shutter structure is to optimize the cold water resource by allowing withdrawal from the selected levels of the reservoir. Conservation of the cold water pool is achieved by forcing withdrawal from the highest elevation possible. To that end, the shutters would be operated to access the highest permissible level of withdrawal based on the reservoir water surface elevation and downstream water quality objectives.

When downstream water temperature objectives can no longer be satisfied by accessing water through the shutter structure intakes, the slide gates between the low level intake structure and shutter structure will be raised. The gates in the shutter structure will then be positioned to exclude withdrawal from higher in the reservoir. Total exclusion of overdraw flow is possible for reservoir water surfaces 8 m (27 ft) above the normal water surface.

The mathematical and physical models [5] showed that:

1. The use of the final TCD will yield effective management of water supplies in Lake Shasta. This is primarily because it has good flexibility in selection of withdrawal elevation, and is less susceptible to leakage and internal flow entrainment than the flexible curtain concepts.

2. Vertical mixing inside the TCD is limited by the near proximity of the TCD to the dam face. This reduced vertical mixing reduces the potential for entrainment of overdraw flows. However, the physical model shows that if the top of the TCD is submerged and withdrawals are made solely from the low level intake, overdraw flows will be entrained if the total discharge exceeds approximately one-half of the design discharge.

3. Depending on submergence and discharge, a potential exists to draw air into the penstocks when the shutter structure is operated in total overdraw or when gates with shallow submergence are used. Entrained air may yield either blowback or rough turbine operation and should be avoided. Preliminary submergence criteria was set based on physical model observations. It was recommended that the submergence criteria be reviewed and modified, through observation of the operating prototype structure.

4. Noting that the lowest intake of the TCD is 44 m (145 ft) above the reservoir bottom, a withdrawal layer predictive equation calibrated for the final TCD at Shasta Dam was used to predict the volume of cold water that could not be accessed and released in late summer. The calculated volumes which vary with discharge, and thus peaking operation, are considered small in comparison to the capacity of the reservoir.

CURRENT TCD STATUS

Reclamation is awaiting funds to complete the designs for the temperature control device at Shasta Dam. It is hoped that the device will be operational by late 1995.

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 the curtain barrier concept. Reclamation's intent is to install and instrument a prototype curtain which would be used to answer various material, fabrication, installation, loading, and operational questions. The installation, operation and maintenance of this curtain would be of great value in establishing future design parameters.

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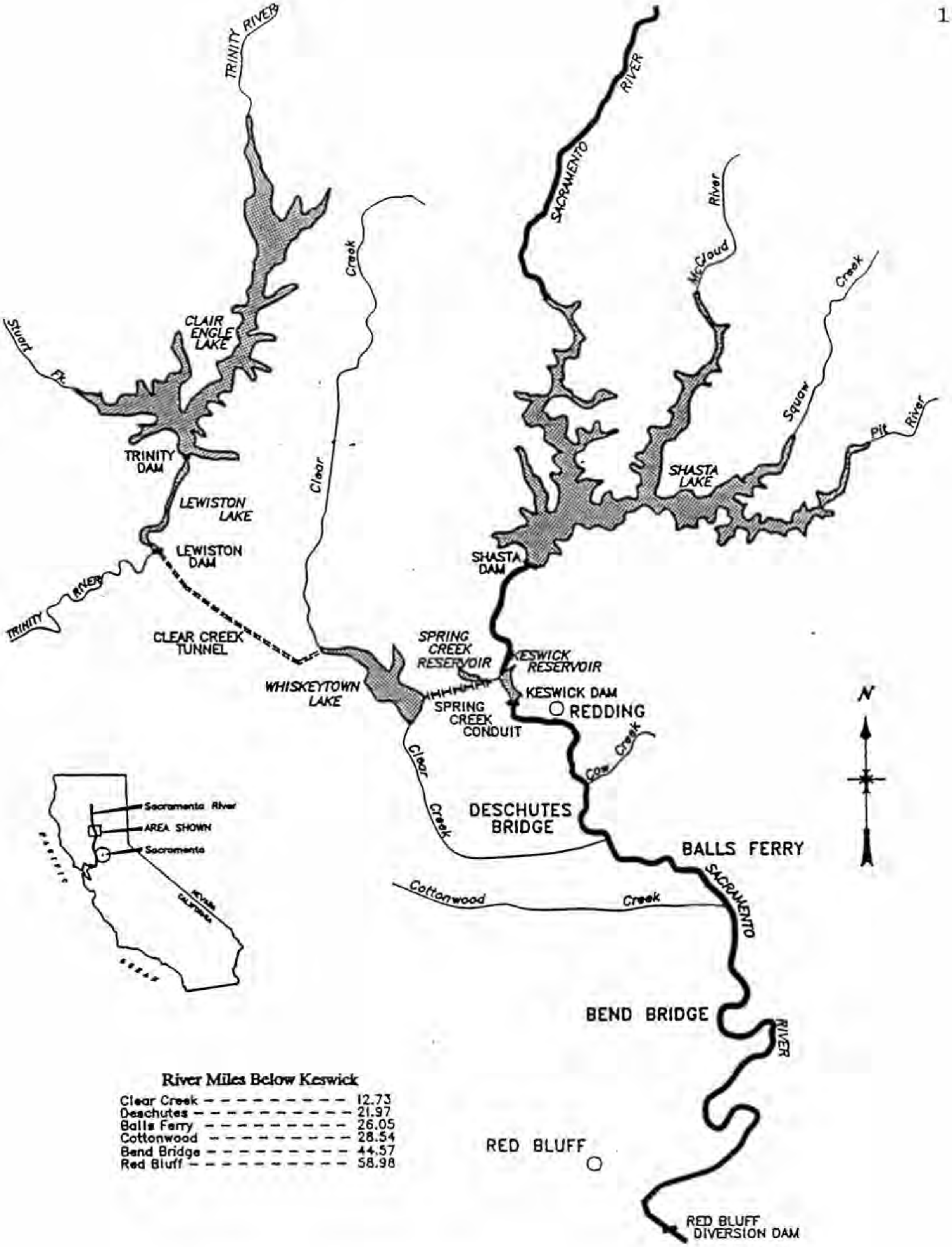

Fig. 1. Central Valley Project Map

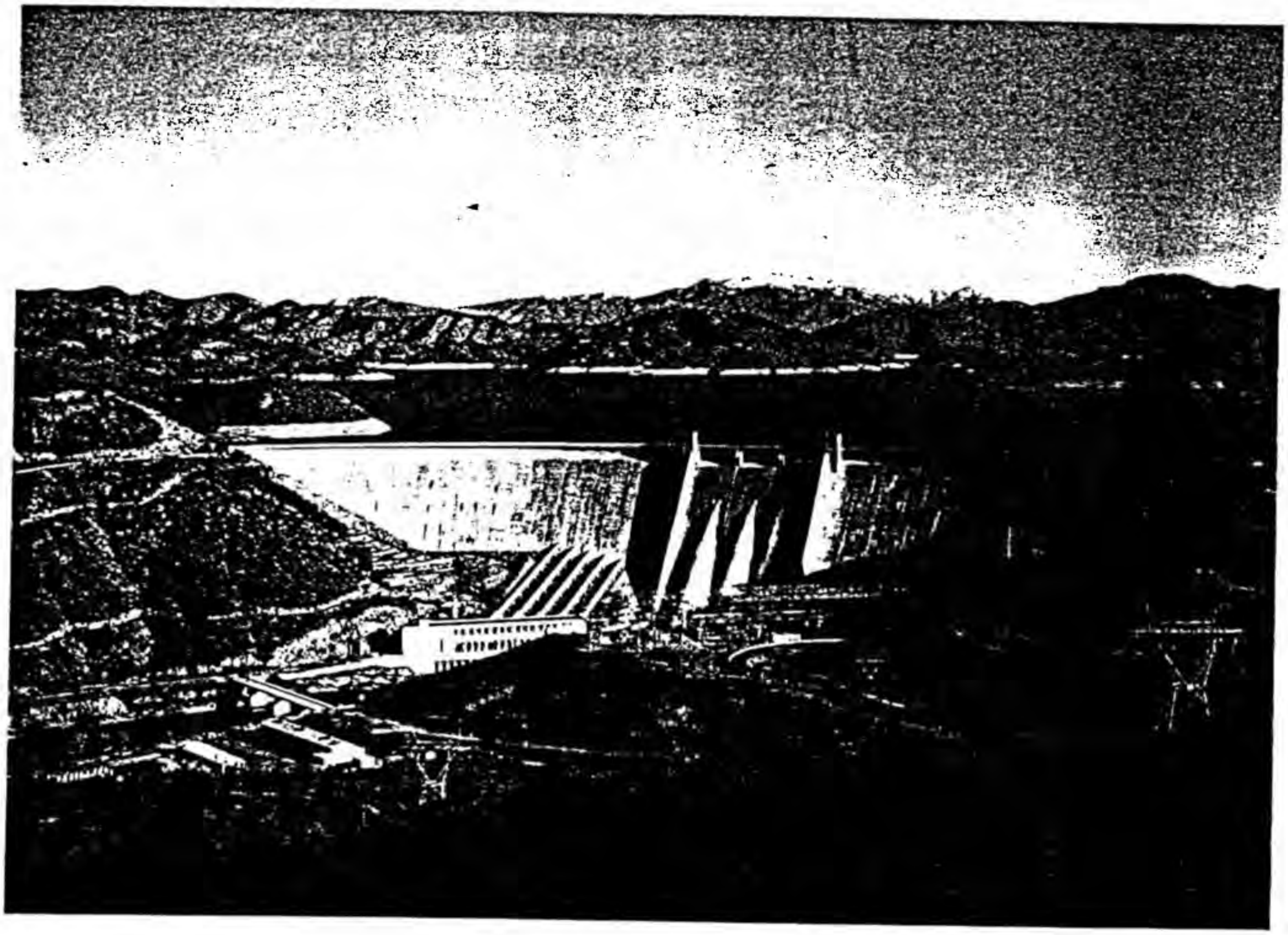

Fig. 2. Shasta Dam

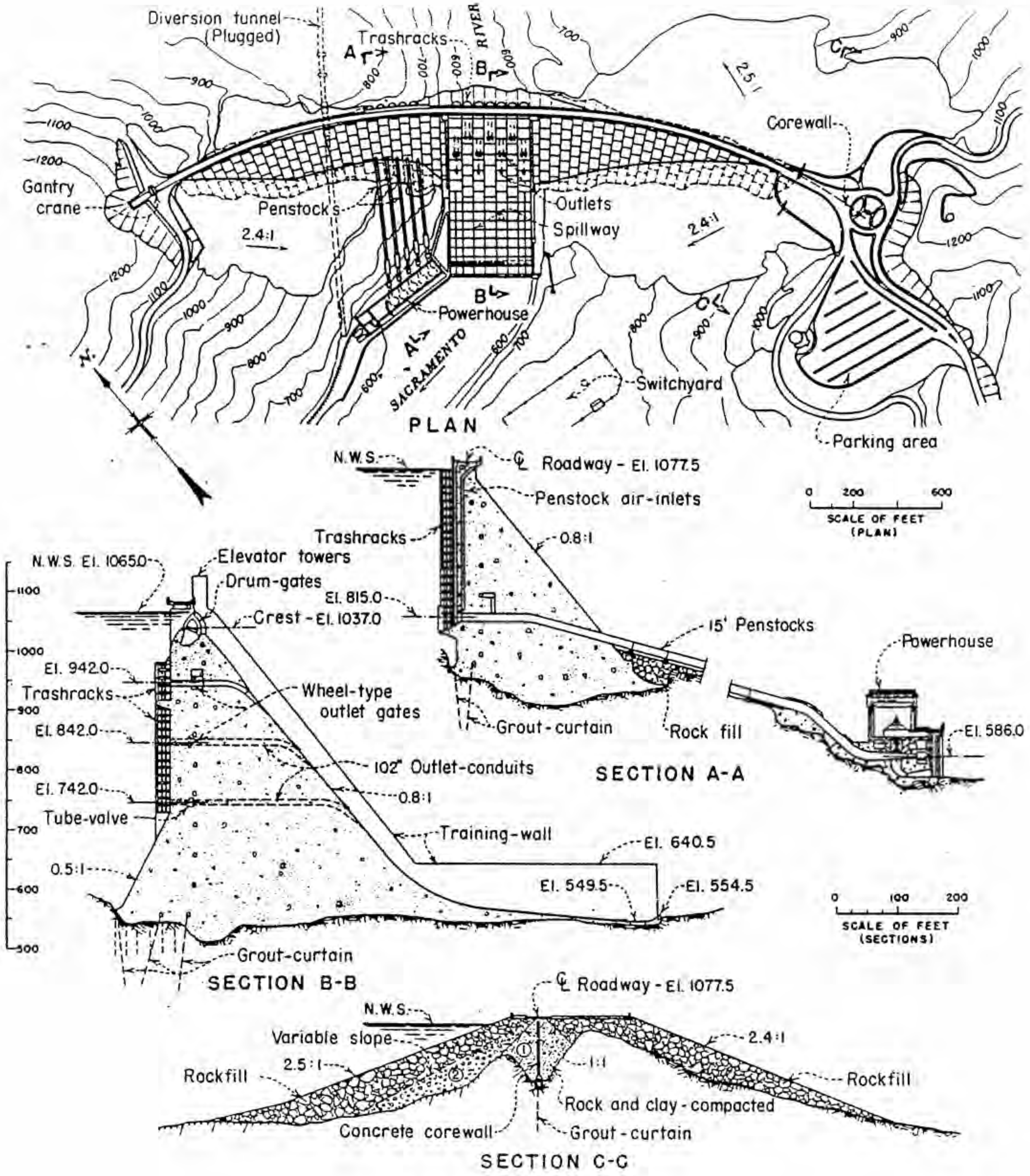

Fig. 3. Shasta Dam, Plan and Sections

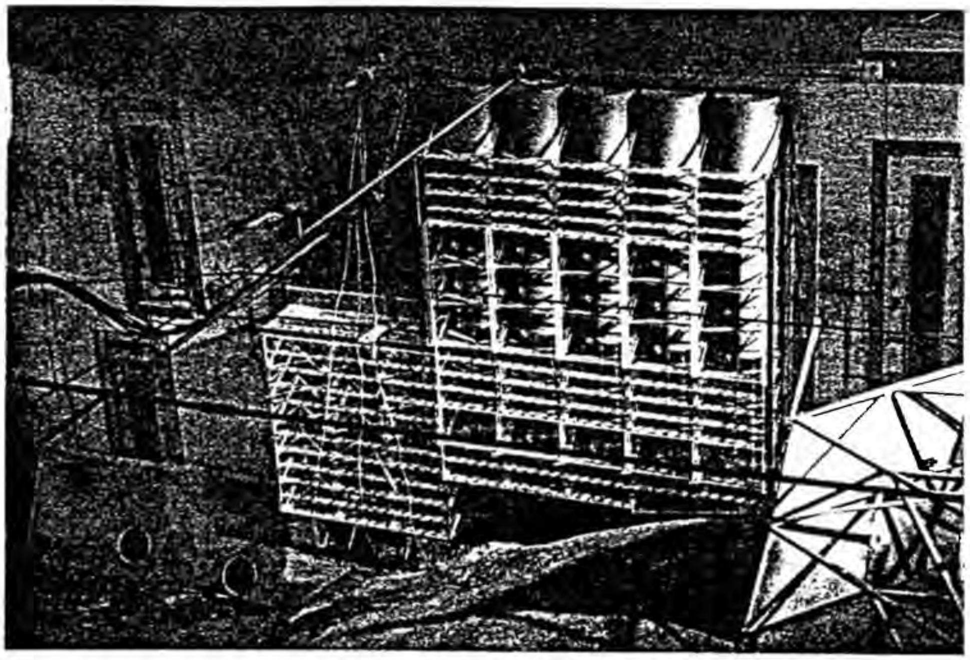

Fig. 4. Physical Model with Final TCD

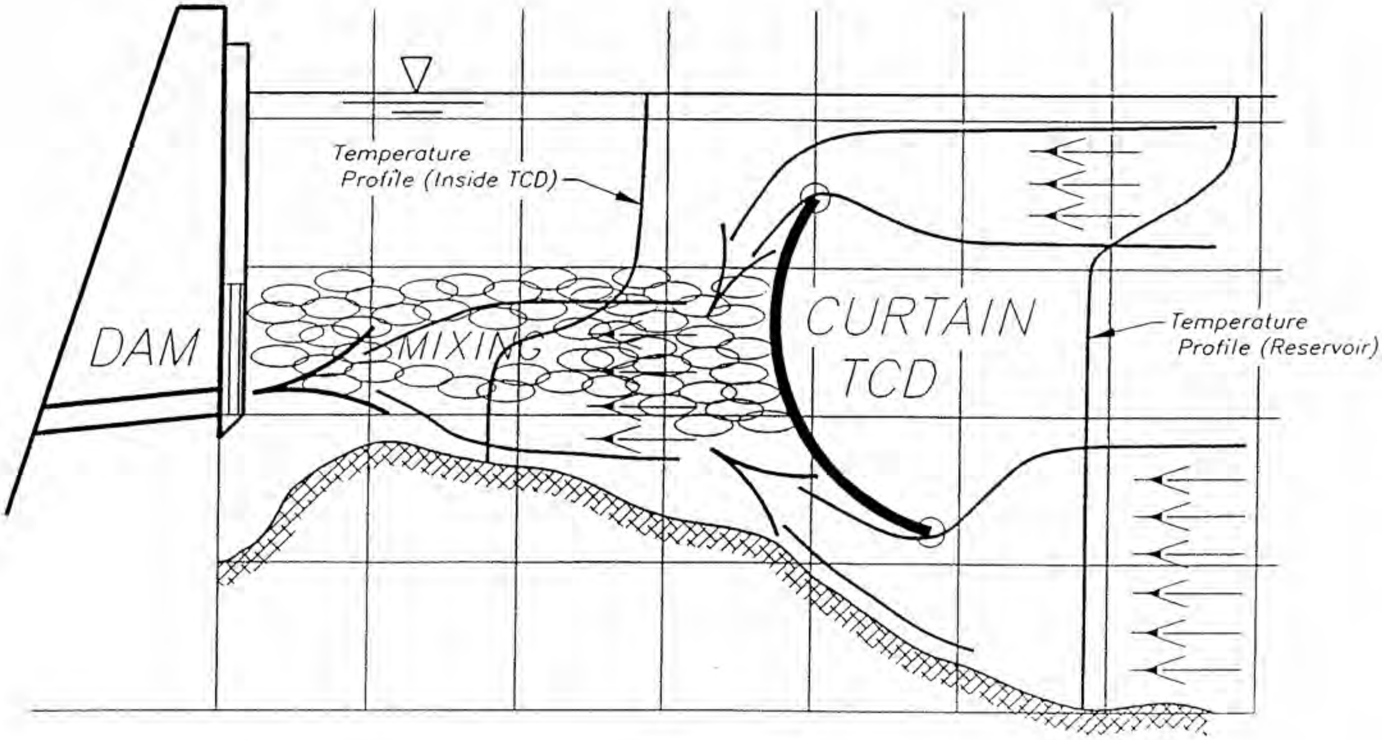

Fig. 5. Schematic of Curtain TCD with Multiple Withdrawals

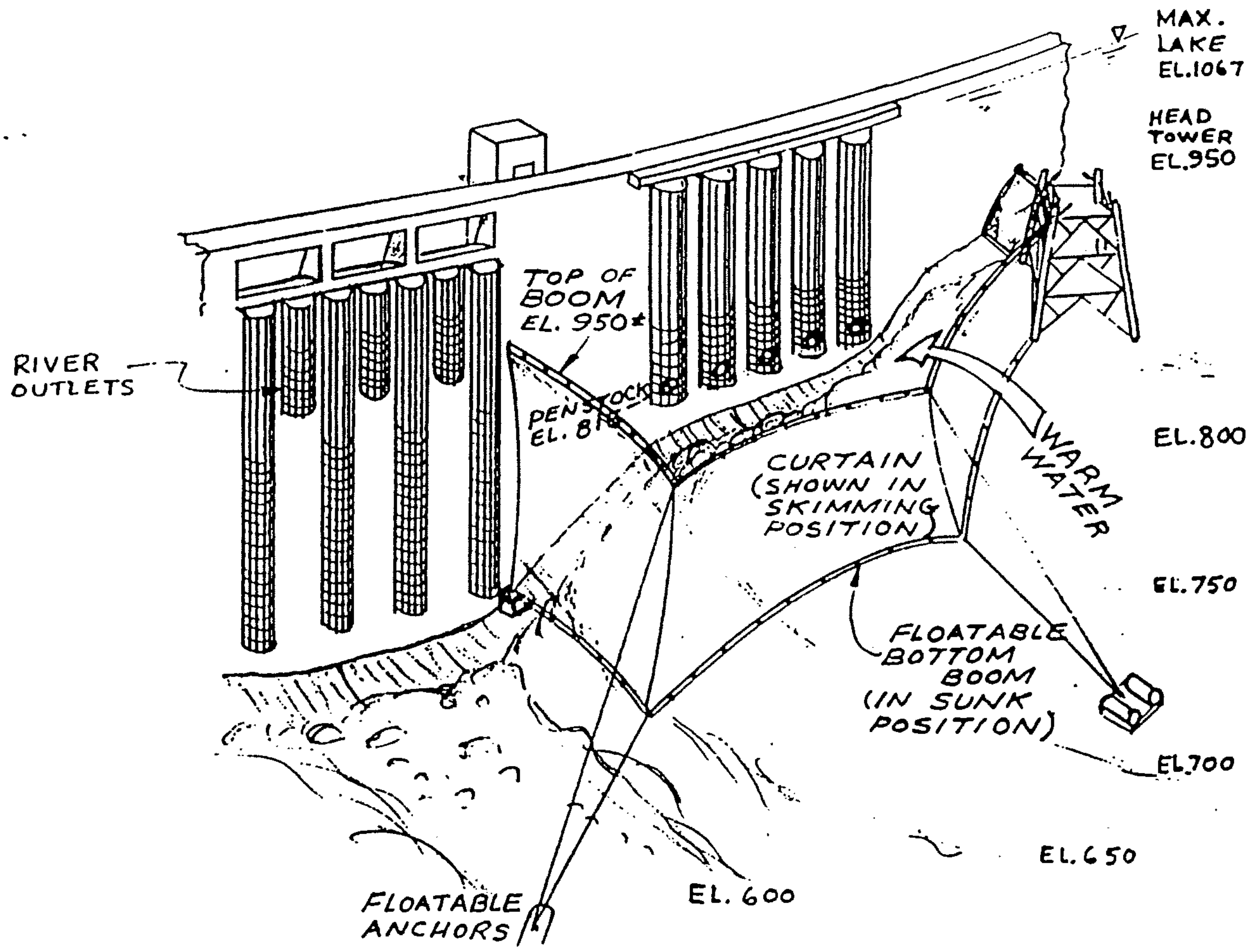

Fig. 6. Flexible Curtain TCD

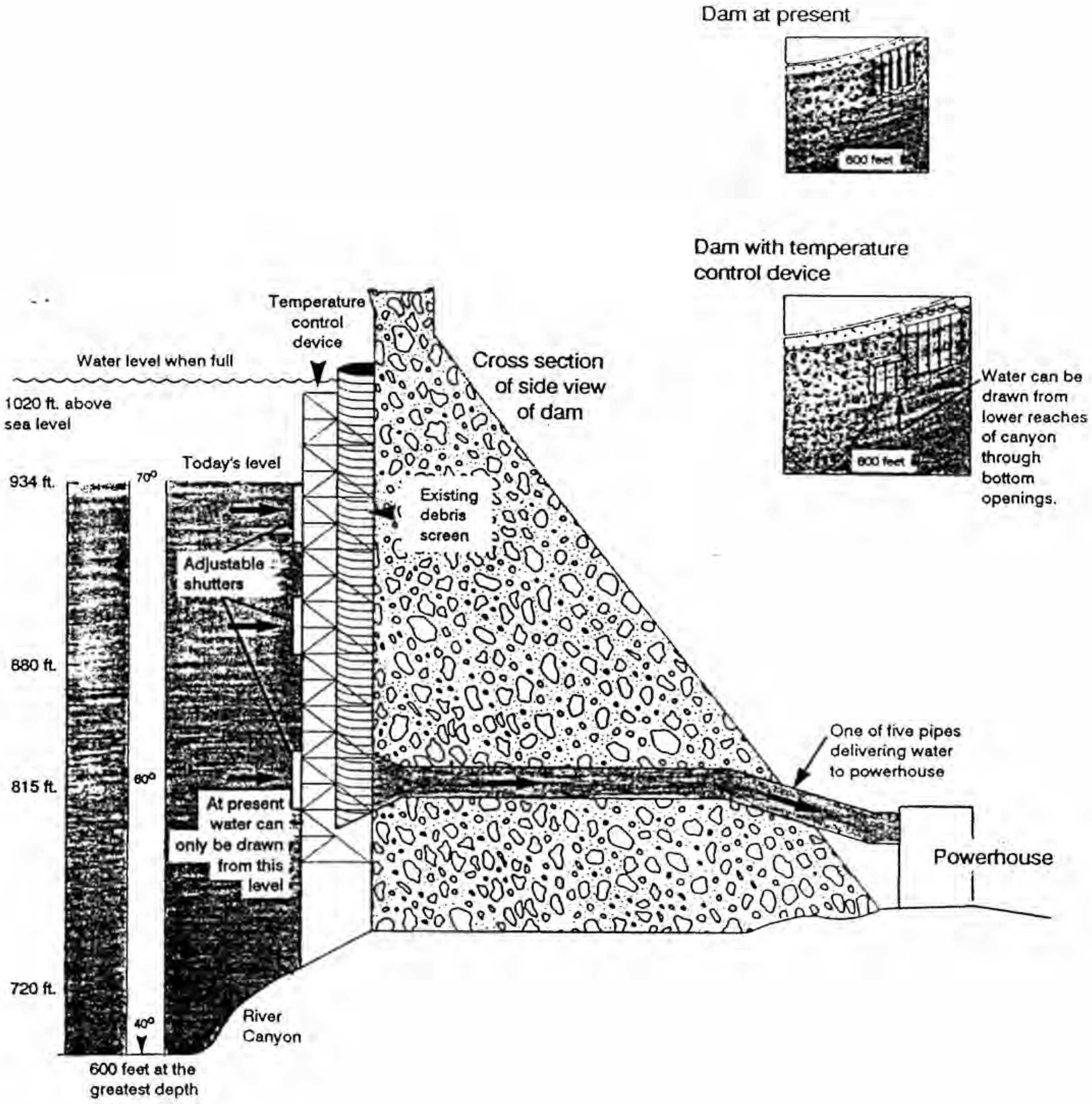

Fig. 7. Final TCD