R-95-07

PRATTVILLE INTAKE, LAKE ALMANOR, CALIFORNIA, HYDRAULIC MODEL STUDY ON SELECTIVE WITHDRAWAL MODIFICATIONS

July 1995

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Technical Service Center
Water Resources Services
Water Resources Research Laboratory

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1995	Final

4. TITLE AND SUBTITLE
Prattville Intake, Lake Almanor, California,
Hydraulic Model Study on
Selective Withdrawal Modifications

5. FUNDING NUMBERS
PR

6. AUTHOR(S)
Tracy Vermeyen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
Technical Service Center
Denver CO 80225

8. PERFORMING ORGANIZATION REPORT NUMBER
R-95-07

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
Denver Federal Center
PO Box 25007
Denver CO 80225-0007

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DIBR

11. SUPPLEMENTARY NOTES
Microfiche and hard copy available at the Technical Service Center, Denver, Colorado

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Available from the National Technical Information Service,
Operations Division, 5285 Port Royal Road, Springfield, Virginia 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Reclamation (Bureau of Reclamation) conducted this hydraulic model study to provide Pacific Gas and Electric Company with an evaluation of several selective withdrawal structures that are being considered to reduce intake flow temperatures through the Prattville Intake at Lake Almanor, California. Release temperature control using selective withdrawal structures is being considered in an effort to improve the cold-water fishery in the North Fork of the Feather River.

14. SUBJECT TERMS--selective withdrawal/ stratified flow/ hydraulic model study/ structural modifications/

15. NUMBER OF PAGES
41

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UL	UL	UL	UL

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by

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Denver, Colorado

July 1995

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

ACKNOWLEDGMENTS

This study was conducted in cooperation with Pacific Gas and Electric Company, with assistance from Wing Lee, Larry Harrison, and Scott Tu. Brent Mefford, Head, Hydraulic Structures Section, and hydraulic engineers Perry Johnson and Joe Kubitschek, provided technical support throughout this study.

Wayne Lambert provided photographic services; Lee Elgin assisted with instrumentation, and Tom Hovland was the technical editor.

U.S. Department of the Interior
Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

This research of selective withdrawal structures in reservoirs was conducted for Pacific Gas and Electric Company in Reclamation's Hydraulic Laboratory under task agreement pursuant to provisions of Master Agreement No. Z-19-2-196-91.

The cooperative research and development master agreement between Pacific Gas and Electric Company and the Bureau of Reclamation provides for cooperative research in areas of hydroelectric power and water resources.

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PURPOSE

This model study will provide Pacific Gas and Electric Company with an evaluation of several selective withdrawal structures that are being considered to reduce intake flow temperatures through the Prattville Intake at Lake Almanor, California. Release temperature control using selective withdrawal structures is being considered in an effort to improve the cold-water fishery in the North Fork of the Feather River.

INTRODUCTION

The Prattville Intake is located on the southwest shore of Lake Almanor, Plumas County, California. It is owned and operated by PG&E (Pacific Gas and Electric Company) and is part of PG&E's North Fork of the Feather River Project (FERC license No. 2105). The intake diverts water through the Prattville Tunnel to Butt Valley Powerhouse and Reservoir. Subsequent releases from Butt Valley flow downstream through a series of hydroelectric facilities (fig. 1).

Studies by PG&E and California Department of Fish and Game concluded that water temperatures in the NFFR (North Fork of the Feather River), between June and September, are warmer than optimum for trout habitat. In 1985, PG&E hired Woodward-Clyde Consultants to study the NFFR and identify means to reduce the river water temperatures during the summer months. Woodward-Clyde concluded that release temperatures through the Prattville Intake could be lowered by selectively withdrawing water from the hypolimnion (cool bottom stratum) in Lake Almanor.

Woodward-Clyde proposed a rigid curtain wall placed around the Prattville Intake, which would block the warm surface water from entering the intake structure. However, PG&E elected to test a flexible curtain structure. A second alternative proposed by PG&E was a hooded pipe inlet with three 12-ft-diameter pipes carrying water from the reservoir body to the Prattville Intake. In addition to the two initial alternatives, early study results indicated that enlarging the existing approach channel might also provide effective selective withdrawal.

PG&E and Reclamation's Water Resources Research Laboratory in Denver, Colorado, entered into an agreement to perform a hydraulic model study. Reclamation was asked to conduct this research under the CRDA (Cooperative Research and Development Master Agreement) with PG&E because of the experience gained in developing selective withdrawal devices for Shasta Dam and Lewiston Lake (Johnson 1991a, 1991b; Johnson et al., 1991; LaFond, 1991; O'Haver, 1992).

The hydraulic model was used to evaluate the potential of the proposed selective withdrawal structures to reduce intake release temperatures based on the following parameters:

- Existing Prattville Intake geometry
- Near- and far-field topographic influences
- Discharge requirements
- Variable reservoir level
- Reservoir stratification data
- Costs

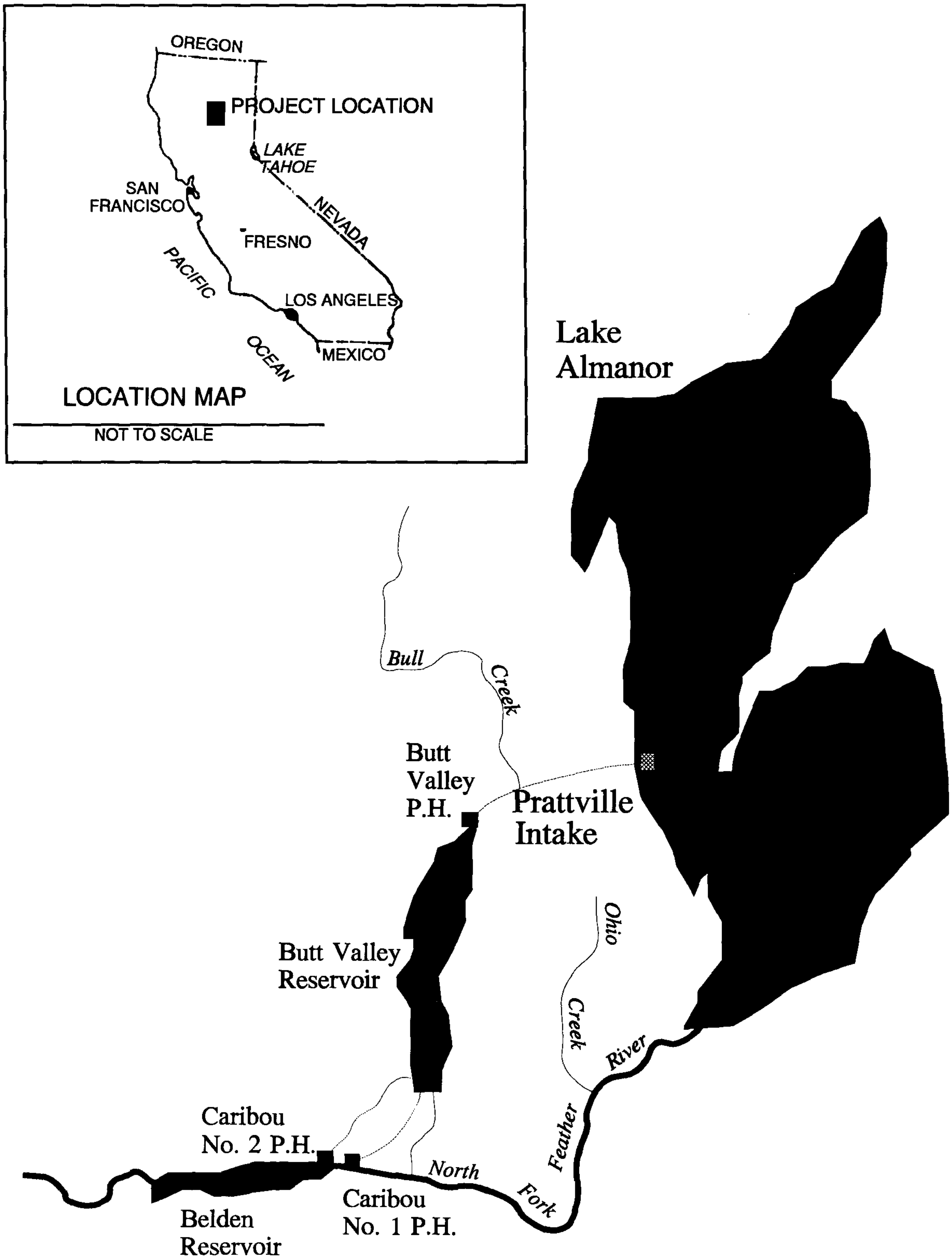


Figure 1. - Location map for the North Fork of the Feather River Project.

PG&E supplied Reclamation with drawings necessary to design and construct the model and a scope of work, which contained the testing components and operational requirements.

CONCLUSIONS

1. For most test cases, the hooded pipe inlet was most effective at minimizing the metalimnion entrainment rates. The hooded pipe inlet developed the weakest withdrawal layer because it was located in a portion of the reservoir where horizontal flow was not restricted by surrounding high ground. As a result, the inlet could withdraw unimpeded from all directions, which keeps the inlet velocities small and vertical withdrawal to a minimum. In addition, performance of the hooded pipe inlet was enhanced because once the flow entered the pipes, it was confined and could not entrain surrounding water as it was conveyed to the intake. For all other options tested, metalimnion water was entrained along the entire withdrawal layer interface. This mixing is an integral mechanism responsible for warming Prattville releases. By eliminating the interfacial entrainment, the hooded pipe inlet had a distinct advantage over the other options.

2. For all structures tested, the selective withdrawal performance was substantially better for discharges of 800 ft^3/s when compared to 1,600 ft^3/s. Likewise, little difference in performance existed between various selective withdrawal structures for discharges of 800 ft^3/s. As a result, Prattville release temperatures appear to be nearly independent of withdrawal structure geometry for discharges at or below 800 ft^3/s. This finding indicates that release temperatures can be reduced by operating at or below 800 ft^3/s during periods when temperature control is required.

3. For a modified hood configuration, flow distribution around the hood's perimeter was reasonably uniform, and had an average entrance velocity (normal to the perimeter of the hood) of 0.37 ft/s at elevation 4480 and a flowrate of 1,600 ft^3/s. For flows of 800 and 1,600 ft^3/s, velocities in each of the three conduits were evenly distributed. The maximum deviation from average velocity was ± 10 pct. However, the reservoir bottom in the vicinity of the hooded pipe inlet could be excavated to further improve the uniformity of flow entering the hooded structure. Excavation may also improve the flow distribution into the pipes.

4. The original flexible curtain design did not prevent metalimnion entrainment because the kinetic energy (velocity head) of flow under the curtain was sufficient to entrain large quantities of warm water from the metalimnion and epilimnion. Consequently, an extended curtain was designed so that the open area beneath the curtain was the same as the hooded pipe inlet structure (4710 ft^2). The extended curtain design showed improved performance with respect to the original design. Improved performance was the result of increased flow area beneath the curtain. However, the extended curtain did not perform as well as the hooded pipe inlet or excavated channel options. Depending on the economics of the other selective withdrawal structures, an extended curtain may provide adequate selective withdrawal.

5. The enlarged approach channel option performed slightly better than the extended curtain option. Although the excavated approach channel option would require a large amount of dredging, it would be a low maintenance, no head-loss alternative which may provide an adequate level of selective withdrawal.

6. An equilibrium condition could not be achieved because of the model's finite volume of water; therefore, data from the hydraulic model could not be used to estimate the magnitude of cooling for Prattville Intake's outflows. However, model data could be used to calibrate an existing mathematical model of Lake Almanor and the Prattville Intake. This procedure would require scaling of the mathematical model to represent the same area of Lake Almanor as the hydraulic model. Model data could be used to evaluate the mathematical model's prediction of reservoir response. Once calibrated, the math model's limits could be restored to full scale to represent all of Lake Almanor.

THE MODEL

A 1:40 scale, undistorted physical model was constructed, and included the Prattville Intake and about 1400 by 800 ft of the prototype reservoir topography (fig. 2). A 1:40 scale was chosen to include, in a limited laboratory space, the selective withdrawal alternatives and adjacent topography which exerts a strong influence on withdrawal characteristics.

Similitude and Test Discharges

The Prattville Intake model was designed to a 1:40 geometric scale using Froude law relationships. The Froude number was chosen because the hydraulic performance of the model/prototype structures primarily depend on gravitational and inertial forces. However, for density stratified modeling a modified Froude number is used which accounts for the modified gravity force ($\Delta\rho/\rho g$). The modified Froude number is called the densimetric Froude number and is defined by equation 1, which is valid for a linearly stratified reservoir.

$$F_D = \frac{Q}{D^3\ N} \qquad (1)$$

where:

$$N = \sqrt{\frac{g}{\rho}\frac{d\rho}{dz}}$$

and:

Q = *withdrawal flow rate*
D = *withdrawal layer thickness*
N = *buoyancy frequency*
$\frac{d\rho}{dz}$ = *density gradient*

A concern for this model study was the low Reynolds numbers for this model scale. Prattville model Reynolds numbers ranged from 2,200 to 4,500, which are in the transitional region between laminar and turbulent flow. To minimize the effects of a low Reynolds number, which causes an overestimation of boundary shear stress, the model was constructed with smooth boundaries. In general, the effects of turbulence were not precisely modeled; therefore, the model was used to obtain a qualitative comparison of the selective withdrawal structures.

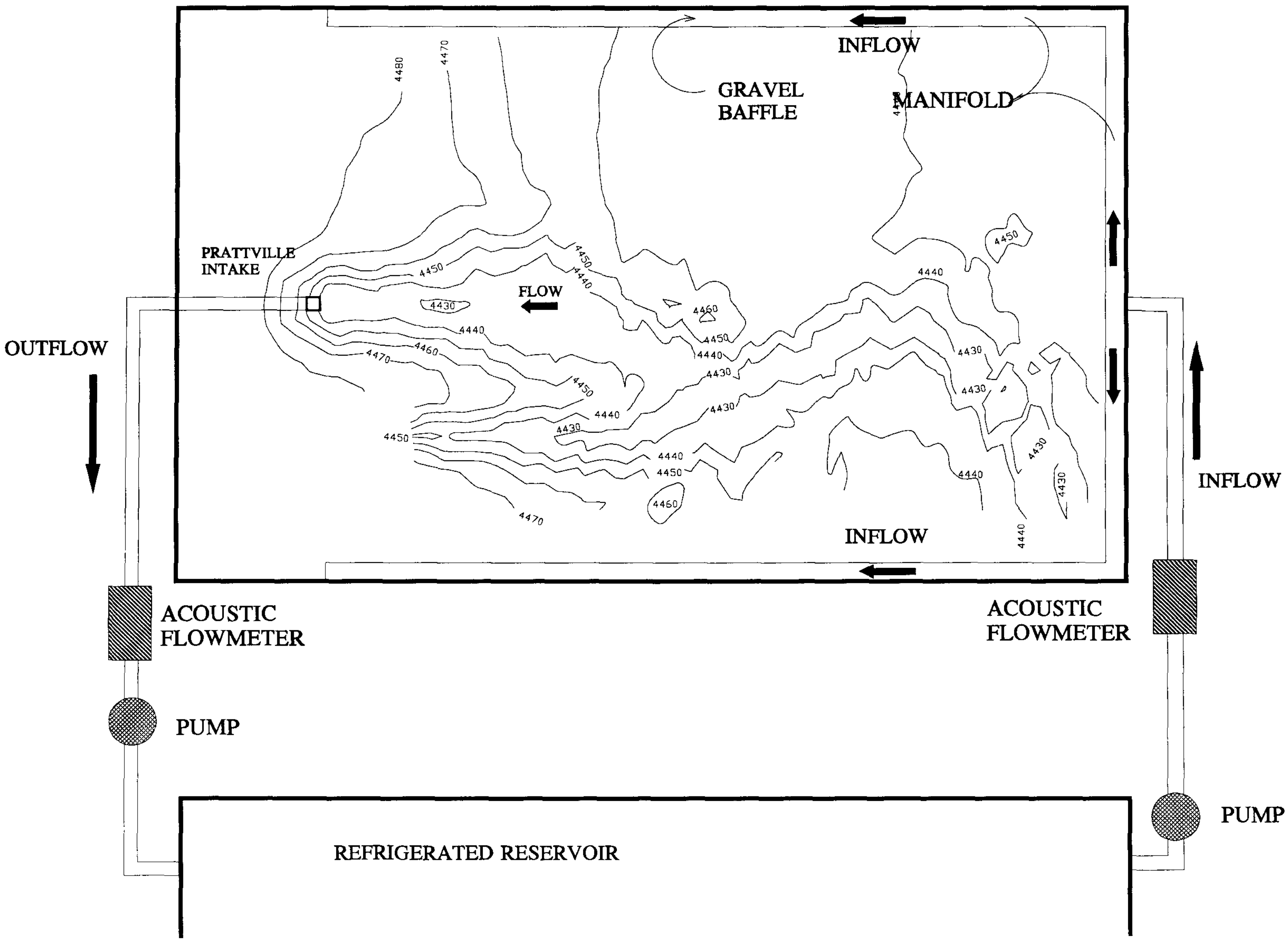


Figure 2. - Schematic of Prattville hydraulic model. Model scale is 1:40; model is 35 ft by 20 ft (NOTE: This schematic is not to scale).

The 1:40 scale model has the following scaling relations which are used to convert model and prototype variables:

Length ratio	$L_r = L_m/L_p$ = 1:40
Area ratio	$A_r = L_r^2 = (1:40)^2$ = 1:1,600
Velocity ratio	$V_r = L_r^{1/2} = (1:40)^{1/2}$ = 1:6.33
Discharge ratio	$Q_r = L_r^{5/2} = (1:40)^{5/2}$ = 1:10,119.3
Time ratio	$t_r = L_r^{1/2} = (1:40)^{1/2}$ = 1:6.33
Density ratio	$\rho_r = 1$ (no correction)

Reservoir Stratification

Stratified temperature profiles for the hydraulic model were generated using cold water stored in an adjacent hydraulic model which was cooled using a refrigeration system. Cold water was slowly discharged into the model through a manifold and gravel baffle (fig. 2). A stratified reservoir formed as a warm water layer floated above the cold water. Once the thermal profile was established for the proper reservoir level, the inflow was stopped and the temperature profile was allowed to stabilize for about 30 minutes.

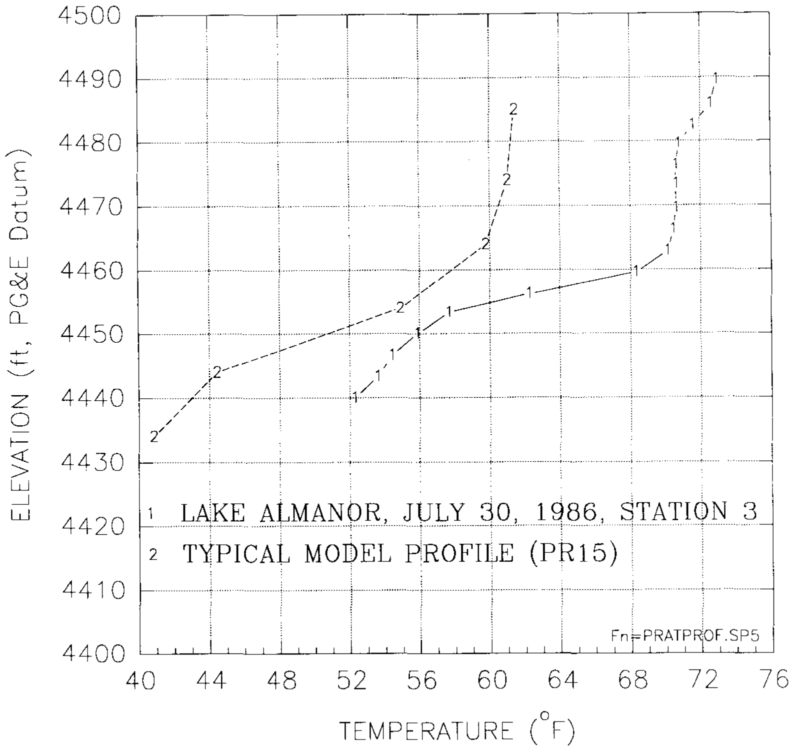
PG&E personnel specified a typical temperature profile to be studied. However, because of the low ambient temperatures in the laboratory, this temperature profile could not be achieved. A cooler, but similarly shaped, profile was used for the testing (fig. 3a). Figure 3b shows a comparison of the relative density profiles for the model and prototype. Ideally, these model and prototype profiles should be identical, but they begin to deviate above elevation 4455, with the prototype profile being less dense at the surface. During testing, the model's relative density profile should result in the formation of a thicker withdrawal layer for a fixed discharge and reservoir elevation. As a result, the model should provide a conservative evaluation of the selective withdrawal potential for each structure tested. In this case, a linear approximation of the reservoir stratification would be conservative by a factor of two, with respect to relative density.

Ideally, the same initial reservoir stratification should be established for each test. However, because of variable laboratory temperatures, establishing similar initial stratifications for successive tests was difficult. Likewise, the refrigeration system was not capable of restoring the cold water temperatures in the overnight recovery period between tests. This problem could not be avoided but was taken into consideration in the data analyses.

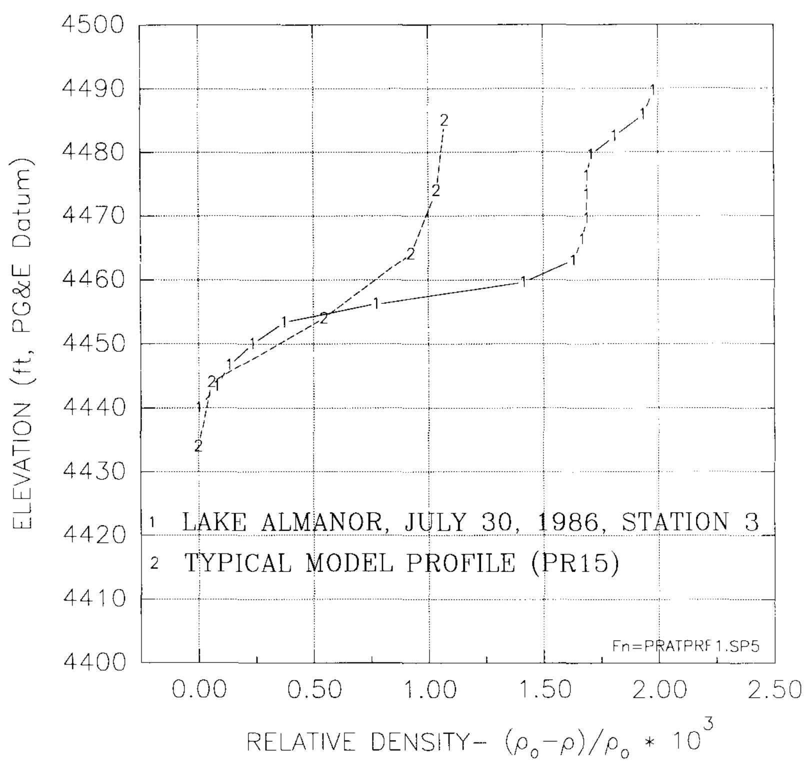
Model Operation

After a reservoir stratification was established, tests were started by withdrawing a constant flow rate through the Prattville Intake structure which was recirculated into the refrigerated model, while the same flow rate of refrigerated water was pumped into the upstream end of the model through a gravel baffle diffuser system (fig. 2). The cold water inflow represents the cold water available in Lake Almanor's hypolimnion.

Inflow and outflow were measured using a strap-on acoustic flowmeter, which was calibrated using a weigh tank. The acoustic flowmeter was used to set the flow rates to within ±1 pct of the known discharge.



(a)



(b)

Figure 3. - (a) Prattville model/prototype temperature profile. (b) model/prototype relative density profile. Prototype profile at Lake Almanor - Station 3, July 30, 1986 (Woodward-Clyde, 1987).

A typical test length was 2 to 3 hours, which allowed a quasi-steady-state condition to be established. Because of the limited model size, a steady-state condition could not be established because the finite warm water layers (metalimnion and epilimnion) in the model reservoir eroded slowly as the test progressed. This limited warm water supply is contrary to the large volume of warm water available from Lake Almanor's metalimnion and epilimnion. As a result, the model was used to compare selective withdrawal structure performance based on the metalimnion entrainment rates.

A quasi-steady-state condition was established when the average withdrawal temperature through the Prattville Intake reached a constant value for two to three consecutive time steps (20 to 30 minutes). Generally, steady-state conditions were established after 90 to 120 minutes of testing. Once steady-state conditions were established and data were collected the testing was stopped.

Testing and Data Acquisition

Testing and data acquisition for this model study included measuring temperature profiles at three locations for baseline conditions; a fourth location was added for curtain and hooded pipe inlet tests (fig. 4). Temperature data were also collected in the inlet manifold and intake structure to measure average inflow and outflow temperatures, respectively. The four sampling locations were designated as poles A through D. The position of poles A and B was fixed for all tests. However, poles C and D were positioned around the selective withdrawal structure to measure the near-field temperature profiles. In general, pole A provided the best indication of the far-field reservoir response to the various selective withdrawal options, whereas poles B, C, and D provided information on the near-field response. However, for the hooded pipe inlet tests, pole A was close to the intake structure, so for these tests pole B was used to evaluate the far-field responses.

Temperature profiles were measured using thermistors, which were mounted vertically at 10-ft intervals (prototype). For excavated channel tests thermistor poles A and B were combined to create a new pole A with thermistor spacing of 5 ft prototype. Thermistors were individually calibrated using a constant temperature water bath and a thermometer accurate to 0.1 °F, traceable to NIST (National Institute of Standards and Technology). Temperature profiles were collected using an automated data acquisition system which sampled each thermistor, applied the individual calibration equation, and stored the temperature measurements to a data file. Temperature profiles were collected every 10 minutes (hourly in prototype time scale). A time step of 10 minutes was selected after review of several trial runs.

Reservoir levels were held constant (± 0.25 ft prototype) with a level sensor, which controlled a valve that regulated a cold water supply to the model. Cold water was supplied from the refrigerated reservoir.

Mirrors, dye streaks, and staff gages were used for flow visualization and to estimate withdrawal layer thicknesses. Flow visualization was very important in locating areas of vertical mixing, topographical influences on withdrawal layer development, and evaluating selective withdrawal structure performance.

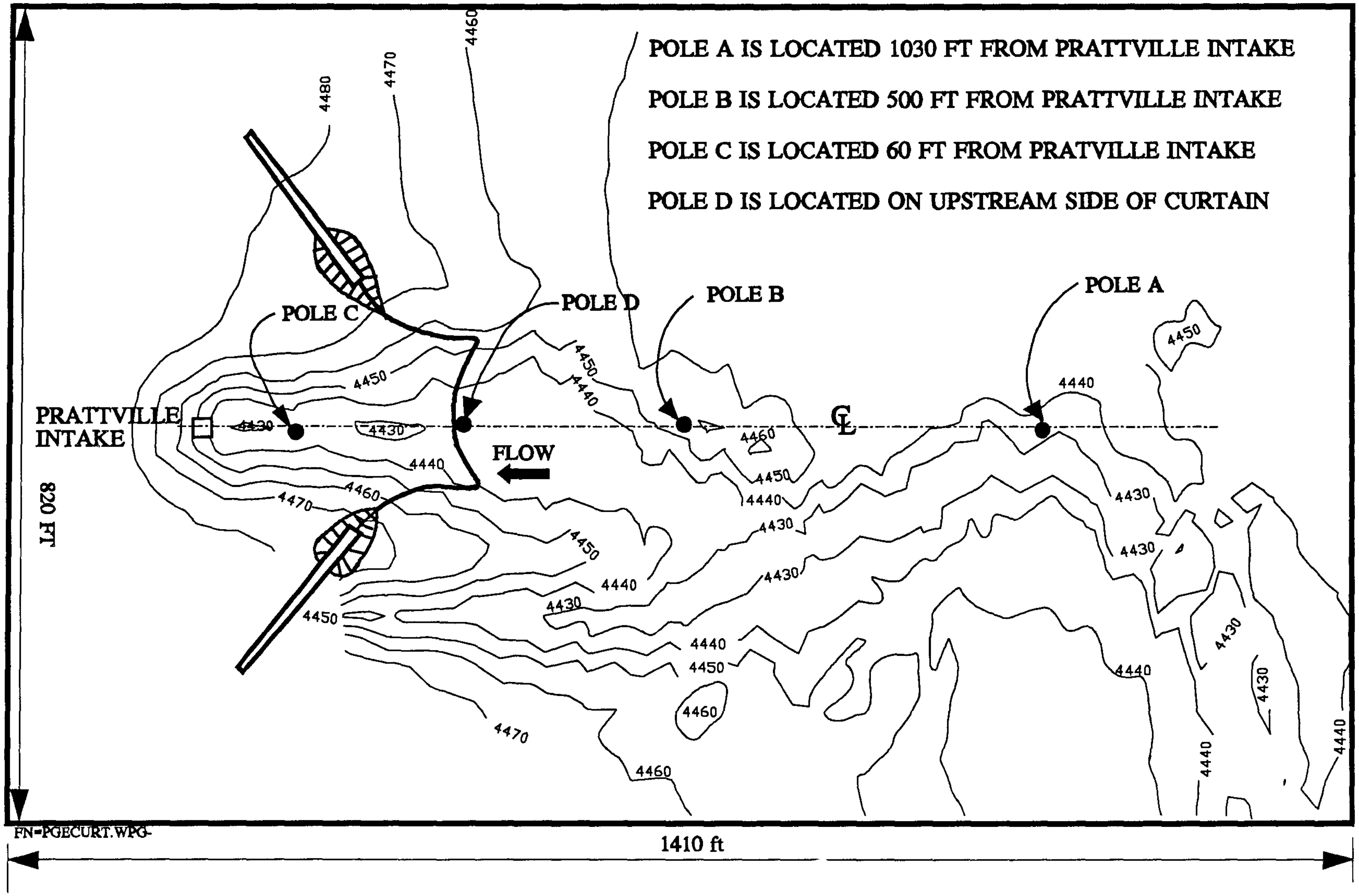


Figure 4. - Plan view of the original PG&E flexible curtain option.

PHYSICAL MODEL STUDY

The physical model study included the following elements:

- **Calibration of Model Temperature Stratification -** Model stratification was developed which approximated Lake Almanor's temperature stratification measured at station 3 on July 30, 1986.

- **Baseline Withdrawal Characteristics** - This task included measuring withdrawal layer thickness, entrainment rates, and modifications to density stratification. PG&E specified three test cases (table 1). Flow rates of 800 and 1,600 ft^3/s correspond to normal operation of hydraulic generators. Tests 1a and 3a were not requested by PG&E, but were conducted to gain further insight on selective withdrawal characteristics. Tests of baseline conditions were identified with the abbreviation PR, followed by the test number, e.g., PR1 was the first baseline test.

Table 1. - Test cases for the Prattville Intake physical model.

Test Case	Lake Elevation* (ft)	Flow Rate (ft^3/s)	Thermal Profile
1	4490	1,600	July 30, 1986
1a	4490	800	July 30, 1986
2	4485	800	July 30, 1986
3	4480	1,600	July 30, 1986
3a	4480	800	July 30, 1986

* Elevations are referenced to PG&E's datum (PG&E datum = USGS datum - 10.2 ft)

- **Flexible Curtain** - The selective withdrawal performance of a 400-ft-long, 40-ft-deep curtain surrounding the Prattville Intake (fig. 4) was evaluated. A modified curtain design was also tested. The modified curtain was 1250 ft long and 40 ft deep at maximum lake elevation (fig. 5 and fig. A.1.). Flexible curtain tests were identified with the abbreviation PR, followed by the test number and a C to designate the curtain, e.g., PR11C was the eleventh baseline test with the curtain installed. For the original curtain tests, the model was operated for a period of 40 to 60 minutes prior to installing the curtain. As a result, withdrawal characteristics were measured for both baseline and curtain conditions. The modified curtain design was too large to install during a test, so it was in place throughout the entire test. These tests were identified by PRAC, followed by the test number.

- **Hooded Pipe Inlet -** The selective withdrawal performance of three 12-ft-diameter pipes which extend 750 ft into Lake Almanor was evaluated. The three pipes were connected to a modified intake structure (fig. 6 and fig. A.2.). This alternative was later modified by extending the two outside pipes 10 ft farther into the hooded structure. Tests of the hooded pipe inlet were identified with the abbreviation PRH, followed by the test number.

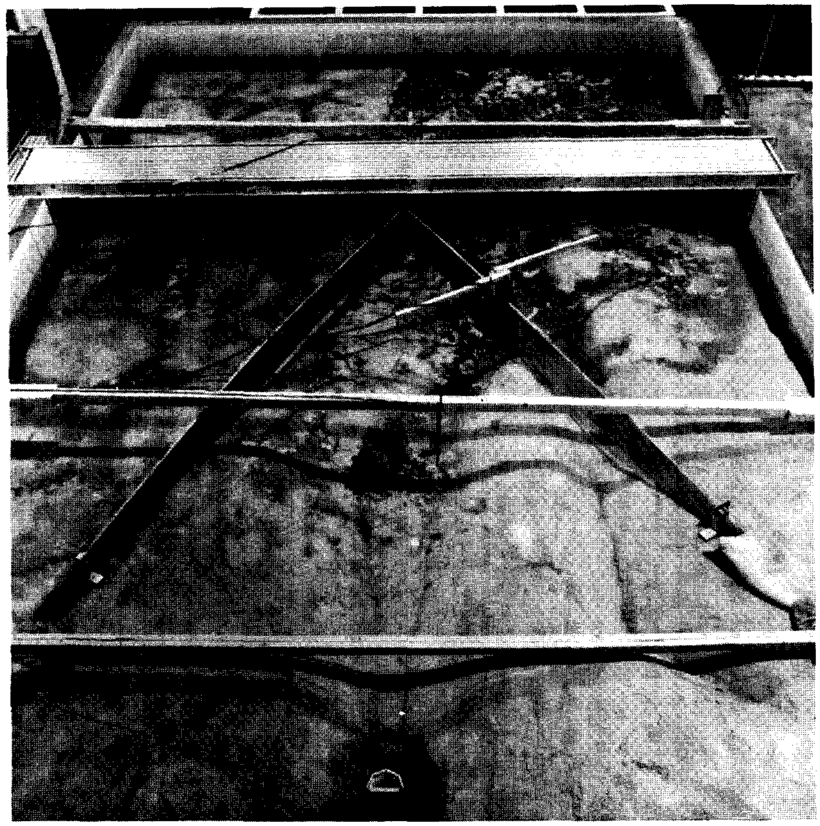


Figure 5. - Photograph of hydraulic model with extended curtain. A schematic of this option appears in appendix figure A.1

- **Excavated Approach Channel** - The selective withdrawal performance of an approach channel excavated to an invert elevation of 4410[1] was evaluated. The excavated channel would be about 1000 ft long and would enlarge the existing channel (fig. 7 and fig. A.3.). Tests of the excavated channel were identified with the abbreviation PREC, followed by the test number.

Calibration of Model Temperature Stratification

Several tests were conducted to determine the filling procedure necessary to develop the proper reservoir stratification. This procedure involved a determination of an initial water surface elevation prior to filling, and the filling rate.

Baseline Withdrawal Characteristics

The Prattville Intake in its present condition was tested to determine the baseline withdrawal characteristics. Results from these tests were used to compare the performance of the proposed selective withdrawal structures.

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[1]All elevations reported are referenced to PG&E's datum (PG&E datum = USGS datum - 10.2 ft).

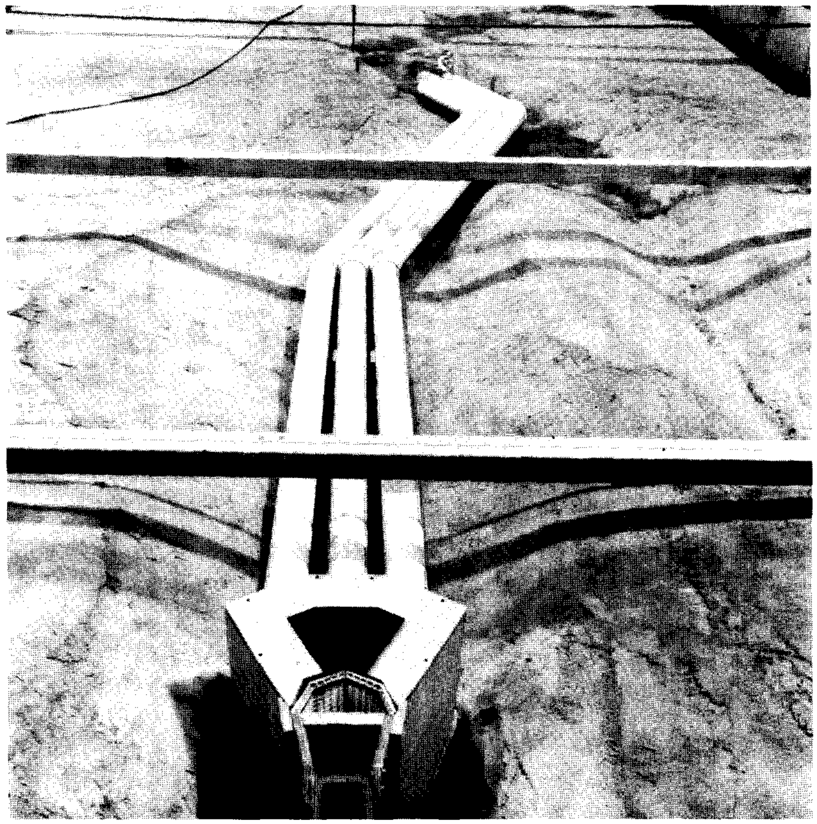


Figure 6. - Photograph of hooded pipe inlet option. A schematic of this option appears in appendix figure A.2.

Flexible Curtain Options

A prototype flexible curtain structure would likely be suspended from the reservoir surface by flotation tanks and would be secured in place with cables and anchors (for more design details see appendix figure A.4.). The curtain bottom would extend to elevation 4454, 40 ft below the maximum reservoir elevation of 4494. At the proposed curtain site, the reservoir bottom is at elevation 4432. The concept behind using a flexible curtain for selective withdrawal is: warmer surface water is blocked, and cooler (denser) water is withdrawn from the reservoir's hypolimnion. During prolonged releases through Prattville, the volume of water stored between the curtain and intake will approach the hypolimnion's water temperature. As a result, the temperature of water released through the Prattville Intake should be cooler than for the existing intake condition.

Hooded Pipe Inlet

The hooded pipe inlet consists of three 12-ft-diameter corrugated-metal pipes extending about 750 ft into Lake Almanor. The pipe inlets will be located beneath a large hood structure (100- by 100-ft) constructed to elevation 4452, or 6 ft above the crown of the pipes. The hood structure allows hypolimnion water to be laterally withdrawn while limiting the vertical velocity component of flow entering the structure. Likewise, the hooded inlet was designed to minimize the flow velocities entering the inlet, which limits the vertical extent of the withdrawal layer.

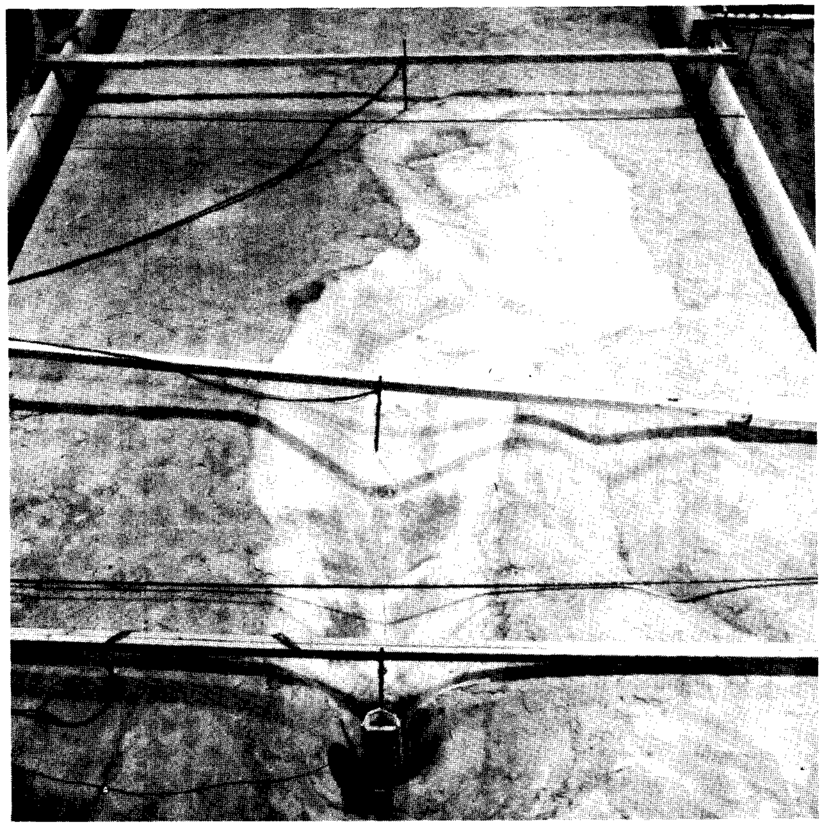


Figure 7. - Photograph of hydraulic model with excavated channel option. A schematic of this option appears in appendix figure A.3.

In addition to measuring withdrawal characteristics, tests were conducted to determine the flow distribution entering the hood perimeter. Velocity vectors were measured at several locations using video techniques. Videotape was recorded using a camera with a known shutter speed (1/30 s). A 1- by 1-in. grid was placed on the plexiglass hood and dye streaks were tracked through the hooded intake. Velocity vectors were developed using video images, time, and distance information. In addition, an electromagnetic velocity meter was used to measure centerline velocities in each of the 12-ft-diameter pipes. Velocities were measured in each pipe 310 ft downstream from the hooded pipe inlet. Velocities were measured with an accuracy of ±0.2 ft/s prototype.

Excavated Approach Channel

The selective withdrawal performance of an approach channel excavated to an invert elevation of 4410 was evaluated. The channel would be about 1000 ft long and would follow the invert of an existing, but smaller, channel. The approach channel alternative would require excavation of about 91,200 yd^3 of material (fig. 7). Enlarging the approach channel would reduce the near-field flow velocities, and consequently, the vertical extent of the withdrawal layer.

DATA ANALYSES

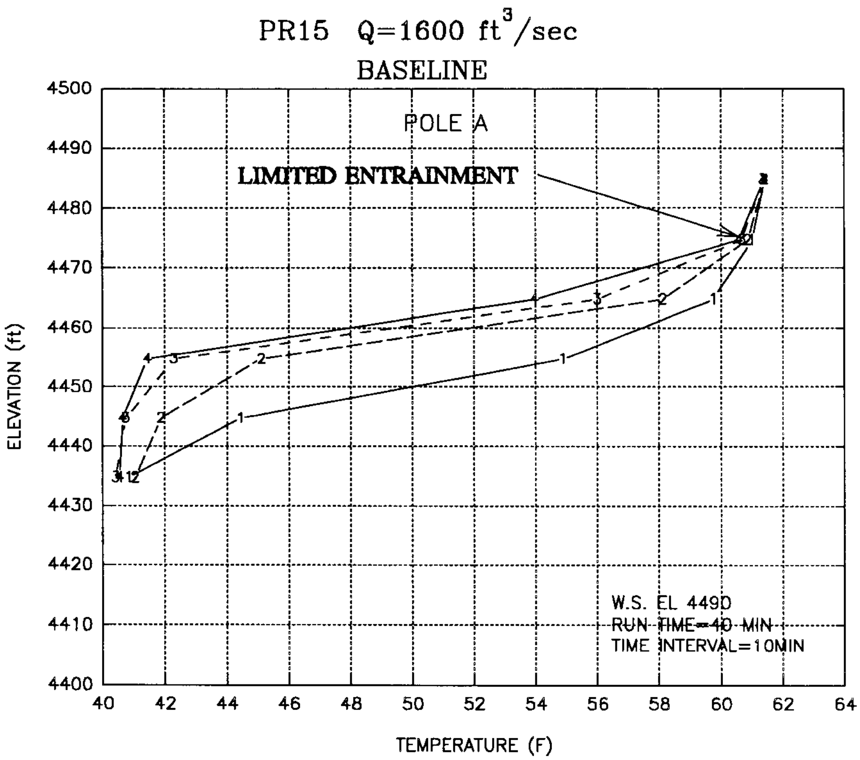
Temperature profiles were the primary source of data used to evaluate the selective withdrawal performance for each option. Figure 8 is a typical example of the temperature profiles which were measured during each model test. Each temperature profile is identified with a number indicating the time step when it was taken. Figure 8 shows how water in the hypolimnion (elevation 4435-4455) was removed rapidly and replaced with colder water from the refrigerated reservoir. Consequently, the temperatures approached a constant value near the reservoir bottom, which represented the hypolimnion. As the test progressed, vertical mixing was responsible for entrainment of water from the metalimnion and epilimnion. Vertical mixing was caused by topographic influences (local flow acceleration) and interfacial shear mixing which occurred at the upper limit of the withdrawal layer. This reservoir cooling does not present a true reservoir response, because in Lake Almanor the warm water supply is very large. Herein lies the difficulty with predicting a true reservoir response for a particular selective withdrawal structure. Therefore, model data were used to obtain a relative selective withdrawal performance for each alternative.

In general, all model tests were similar in filling procedures, test length, and data collection. However, in an effort to directly compare the flexible curtain option with the baseline conditions, the initial curtain tests were different than the others. The concept behind this test procedure was to create a data set which contained withdrawal data for identical temperature profiles. The flexible curtain tests were conducted after an initial 40 to 60 minutes running under baseline conditions. After baseline testing, the curtain was installed and testing continued for another 80 to 120 minutes. This analysis showed that the 400-ft-long curtain was less effective than the baseline conditions. The curtain temperature profiles showed an increased entrainment rate at thermistors in the metalimnion and epilimnion; here entrainment rate is defined as the change in temperature with time. For example, the baseline entrainment rate at elevation 4475 was 0.014 °F/min. After the curtain was installed (test PR15C), the entrainment rate at elevation 4475 increased to 0.023 °F/min (fig. 8). This type of analysis provided a qualitative assessment of the curtain performance, but also made it difficult to apply the same data analysis technique (metalimnion entrainment rate) that was applied to the other structures tested.

Entrainment Rates

Temperature profile data were used to determine the change in temperature with respect to time at each thermistor elevation. In this report, this slope ($\Delta T/\Delta time$) is referred to as the entrainment rate (fig. 9). For model tests, entrainment rate was a measure of warm water being removed from the metalimnion, which was replaced with colder water. Entrainment rates for each thermistor elevation were determined by plotting the cumulative change in temperature versus elapsed time ($\sum\Delta T$ versus Δt). Initially, unsteady entrainment rates existed prior to establishing a quasi-steady-state condition. For a quasi-steady condition, entrainment rate at a thermistor elevation was set equal to the slope of the $\sum\Delta T$ versus Δt curve.

For entrainment rate calculations, the metalimnion and epilimnion were defined as the reservoir volume above elevation 4450. For model tests, temperature data collected at and below prototype elevation 4450 showed a rapid withdrawal of warm water. Consequently, consistent entrainment rates for the thermistors at and below elevation 4450 could not be calculated.



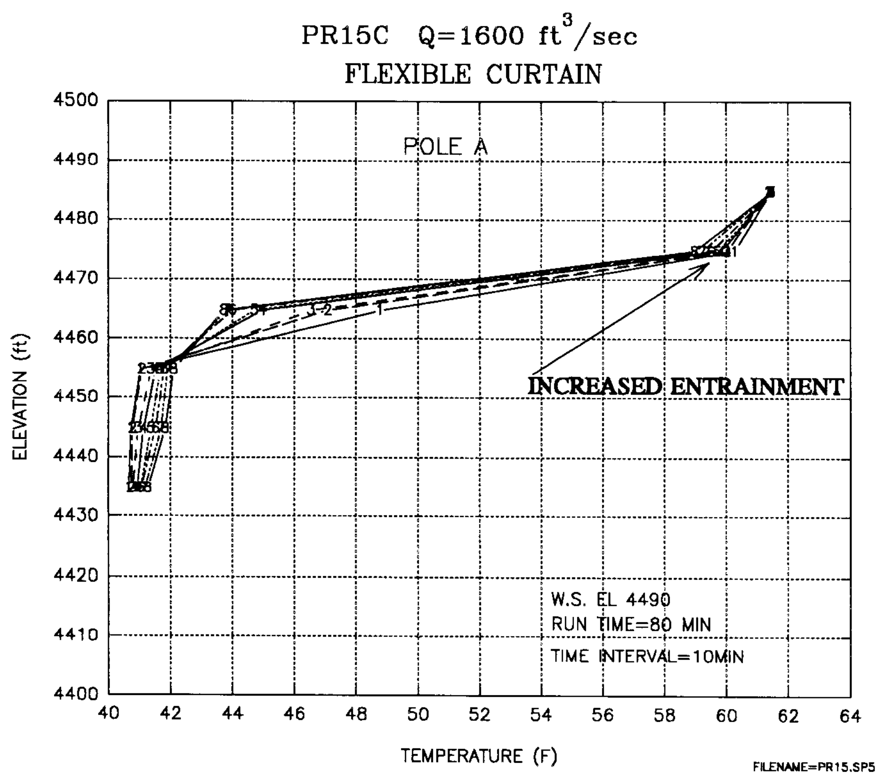


Figure 8. - Temperature profiles measured during test PR15 for baseline and PR15C for flexible curtain options. *Curtain was installed after baseline test ran for 40 min.*

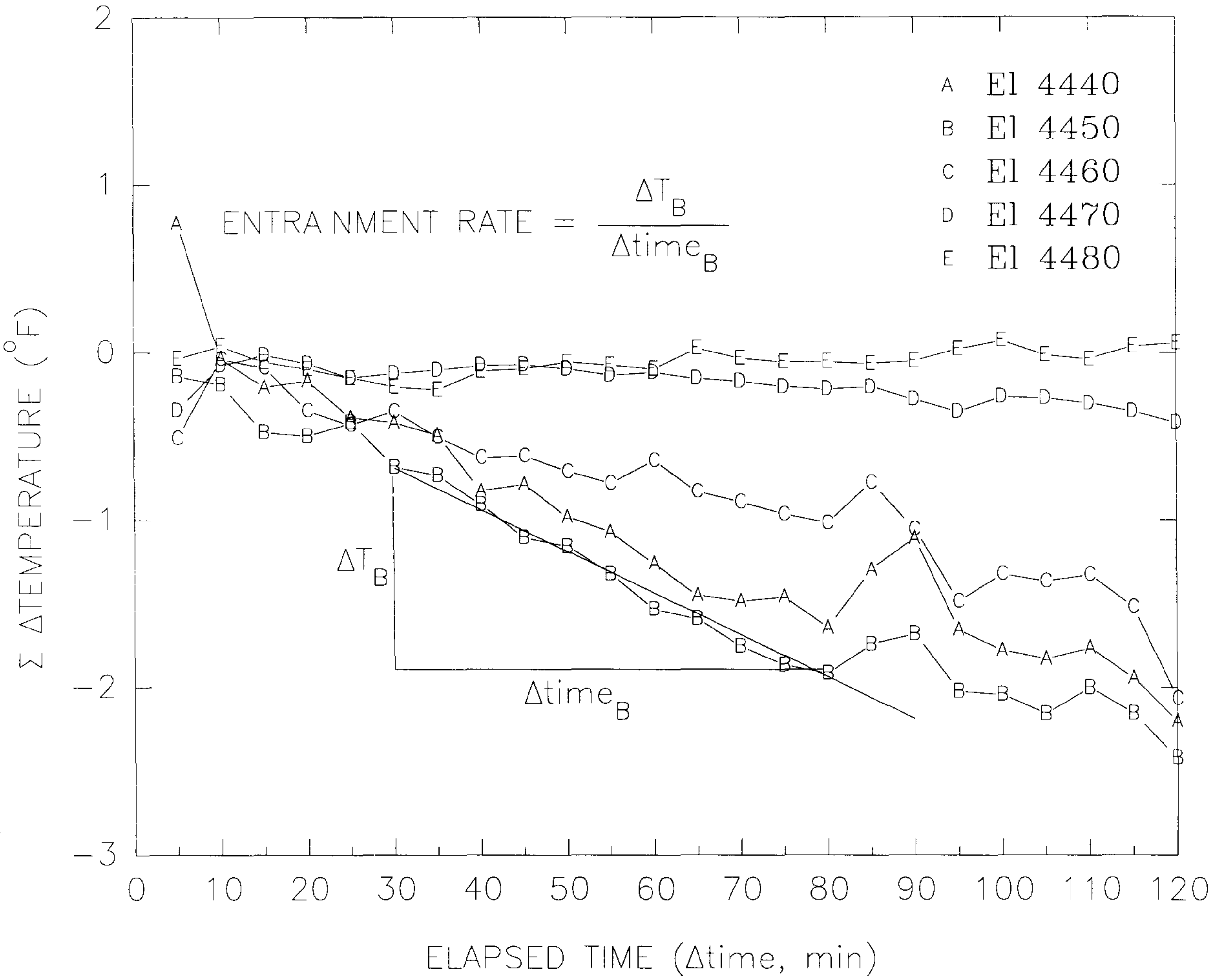


Figure 9. - Typical plot of cumulative change in temperature versus elapsed time. Entrainment rate for each thermistor is the slope, $\Delta T/\Delta time$.

To quantitatively compare selective withdrawal alternatives with variable temperature profiles and their corresponding velocity distributions, the average metalimnion entrainment rates over the entire withdrawal layer had to be determined. This average entrainment rate was found by weighting the metalimnion entrainment rates using the mass flow rate through a reservoir layer (centered about each thermistor elevation). The process involved determining velocity distributions using a dimensionless equation (eqn. 2) developed by Bohan and Grace (1973). Equation 2 was developed for free weir flow which best described the flow field for the temperature profiles measured at pole A. Note that Bohan and Grace developed this equation for a two-dimensional flow field; the Prattville hydraulic model had a three-dimensional flow field.

$$V_i = V_{max}\left[1 - \left(\frac{y_i\,\Delta\rho_i}{Y\,\Delta\rho_{max}}\right)^{1/2}\right] \qquad \textbf{(2)}$$

where: V_{max} is the maximum velocity which was assumed to occur near the reservoir bottom at elevation 4431 in feet per second. *(Measuring V_{max} was not required because it cancels out of the C_i terms in the numerator and denominator in equation 4.)*

y_i is the vertical distance from the elevation of maximum velocity (V_{max}) to that of the corresponding local velocity, V_i, in feet.

Y is the vertical distance from the elevation of maximum velocity (V_{max}) to the upper limit of the withdrawal layer in feet.

$\Delta\rho_i$ is the density difference of fluid between elevations of V_{max} and the corresponding local velocity v_i in grams per milliliter.

$\Delta\rho_{max}$ is the density difference of fluid between elevations of V_{max} and the upper limit of the withdrawal layer in grams per milliliter.

Density profiles were calculated using an equation relating density as a function of temperature (eqn. 3).

$$\rho = (0.993 + 2.4x10^{-4}\ T(°F) - 3.59x10^{-6}\ T^2 + 9.87x10^{-9}\ T^3)\quad (g/ml) \tag{3}$$

The volume for each layer in the model was determined using a three-dimensional terrain model provided by PG&E. The volumes for each layer were centered about each thermistor elevation, which resulted in the volumes in table 2.

Table 2. - Volumes for layers of water used in mass flow rate calculations.

Thermistor elevation (ft)	Volumes for reservoir elevation 4490 (ft^3)	Volumes for reservoir elevation 4485 (ft^3)	Volumes for reservoir elevation 4480 (ft^3)
4430	0.12 X 10^6	0.12 X 10^6	0.12 X 10^6
4440	2.84 X 10^6	2.84 X 10^6	2.84 X 10^6
4450	6.44 X 10^6	6.44 X 10^6	6.44 X 10^6
4460	7.93 X 10^6	7.93 X 10^6	7.93 X 10^6
4470	8.85 X 10^6	8.85 X 10^6	8.85 X 10^6
4480	9.77 X 10^6	9.77 X 10^6	4.64 X 10^6
4490	5.13 X 10^6 (1/2 layer)	N/A	N/A

Equation 4 was used to calculate the average metalimnion entrainment rate using the mass flow rate through each layer as a weighting factor. This term is a volumetric measure of warm water withdrawal from the metalimnion and epilimnion with respect to total flow through the entire withdrawal layer.

$$\overline{\frac{\Delta T}{\Delta t}} = \frac{\sum\left(V_i C_i \left(\frac{\Delta T}{\Delta t}\right)_i\right)}{\sum\left(V_i C_i\right)} \qquad \textbf{(4)}$$

where:

V_i is the reservoir volume for level i in cubic feet

$(\Delta T/\Delta t)_i$ is the entrainment rate determined from the thermistor at level i, °F per minute

$C_i = \frac{V_i}{V_{MAX}} = 1 - \left(\frac{y_i\ \Delta \rho_i}{Y\ \Delta \rho_{\max}}\right)^{1/2}$ *is the velocity distribution factor, dimensionless*

The average metalimnion entrainment rate provides a measure of selective withdrawal performance, which takes into account variability in the density profiles, withdrawal layer thickness, and velocity distribution through the hypolimnion and metalimnion. However, this analysis technique includes several assumptions which were made in applying equations 3 and 4. These assumptions included:

- The upper limit of withdrawal occurs exactly at a thermistor elevation.
- Bohan and Grace's two-dimensional velocity distribution equation for free weir flow equation applies to this model, which had a three-dimensional flow field.
- An exponent of 1/2 in equation 2 was selected because the velocity profiles calculated were representative of the far-field velocity profiles observed in the model.

Limitations

This analysis technique provided a quantitative method to compare the selective withdrawal alternatives under dynamic reservoir conditions, but did not allow for determining the expected cooling for steady-state prototype conditions. During testing, model stratification was continually changing. Thus, it was difficult to estimate a common point in time where the metalimnion entrainment rate would represent steady-state withdrawal in the prototype.

Model metalimnion entrainment rates have little significance in terms of prototype performance. Prattville Intake start-up would initiate a change in temperature with time, but the prototype withdrawal temperature should approach a constant value because of the vast supply of warm replacement water. However, limited warm replacement water was available in the model, so as testing progressed, model temperatures were lowered until they eventually approached the temperature of the cold water supply. This operational condition was similar for all alternatives tested in the model, so they could be directly compared as long as the initial temperature stratification was similar. For this study, much effort was expended to establish similar temperature stratifications. Tests that did not have a representative temperature stratification were rejected.

Model sensitivity to detect the upper limit of the withdrawal zone was limited by the thermistor spacing (10 ft prototype). As a result, it was difficult to compare selective withdrawal performance for tests conducted at different water surface elevations. Changes in water surface elevation result in a different reservoir stratification and will affect the withdrawal zone development. Therefore, selective withdrawal characteristics for each test case (table 1) should be evaluated independently.

Test Rejection

Several tests were rejected on the basis of poor stratification or problems with the data acquisition system. Poor stratification resulted from improper filling procedures and limited cold water supply. Test rejection criteria were based on the buoyancy frequency (*N*), which is a parameter that indicates the stratification strength. For this study, the range of acceptable buoyancy frequencies was $0.013 \leq N \leq 0.027$. Buoyancy frequency is defined as:

$$N = \sqrt{\frac{g}{\rho}\,\frac{\Delta\rho}{\Delta z}}\ , \textit{ units are } 1/\textit{second}$$

where:

g = gravitational constant, ft/s^2
ρ = hypolimnion density, $slugs/ft^3$
$\Delta\rho/\Delta z$ = density gradient within the withdrawal layer, $slugs/ft^4$

The buoyancy frequency for the typical reservoir profile specified by PG&E (July 30, 1986, at station 3) was estimated to be 0.030 for a withdrawal layer extending to elevation 4470 (elevation 4470 was a typical upper limit for withdrawal layers tested in the model). It was not possible to create a model profile with a buoyancy frequency of 0.030 because of cooling limitations and the cool laboratory temperature. However, a lower buoyancy frequency should result in a conservative estimation of prototype selective withdrawal. Laboratory studies by Hino and Furusawa (1969) suggest the densimetric Froude number (eqn. 1) is equal to 1 for bottom withdrawal. These studies were conducted with a linear stratification and bottom withdrawal, which are similar to the Prattville model study. Application of their densimetric Froude number equation with a reduced buoyancy frequency will result in an expanded withdrawal zone and warmer withdrawals. Therefore, prototype performance for each selective withdrawal structure should be better than predicted in the model.

RESULTS

Selective Withdrawal Structure Performance

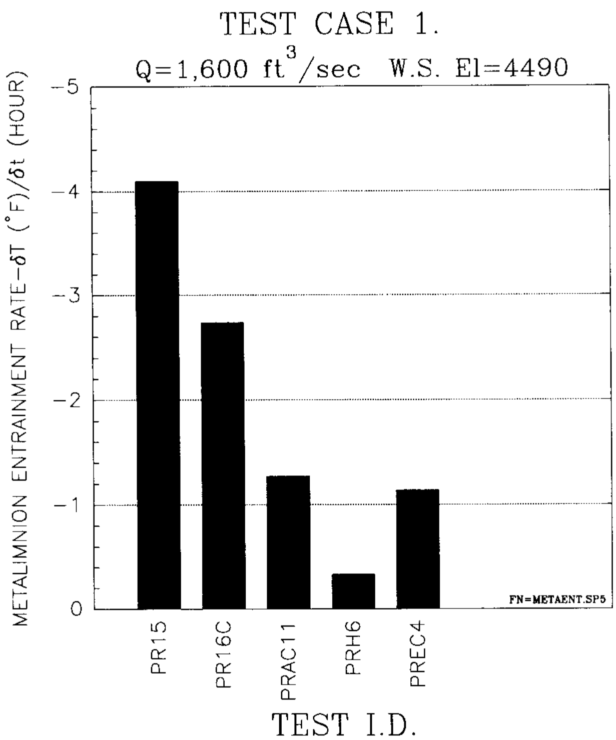
Test cases 1 through 3a were performed on the existing intake, flexible curtains, hooded pipe inlet, and excavated approach channel. Results from each test case were compared to the baseline test to determine which alternative was the most effective selective withdrawal option. Comparisons (for each test) were made based on average metalimnion entrainment rates, calculated using equation 4. In general, for all structures tested, selective withdrawal performance was substantially better for discharges of 800 ft^3/s when compared to 1,600 ft^3/s. Likewise, a small difference in performance existed between selective withdrawal structures for discharges of 800 ft^3/s, including the existing intake. As a result, Prattville release temperatures appear to be nearly independent of withdrawal structure geometry for discharges of 800 ft^3/s. This finding shows that, regardless of withdrawal structure tested, insufficient kinetic energy was available to withdraw water from the metalimnion or epilimnion for the reservoir stratification tested.

Test Cases 1 and 1a. - The results for test cases 1 and 1a, water surface elevation 4490, and flow rates of 1,600 and 800 ft^3/s, respectively, are presented on figure 10. For Test Case 1, the chart of metalimnion entrainment rate at pole A indicated the hooded pipe inlet was the most effective in limiting withdrawal from the metalimnion and the epilimnion. The hooded pipe inlet's entrainment rate (**PRH6**) was 8 pct of the baseline entrainment rate (**PR15**) - 4.10 °F/h. It should be noted that metalimnion entrainment rates are based on model data and are not scaled to prototype values because they are only valid for the model conditions tested. The extended flexible curtain (**PRAC11**) and excavated channel (**PREC4**) options resulted in an entrainment rate that was 30 pct of the baseline value. The original flexible curtain option (**PR16C**) had an entrainment rate that was 67 pct of the baseline value.

For Test Case 1a, the chart (fig. 10) of metalimnion entrainment rates at pole A indicated the hooded pipe inlet was the most effective in limiting withdrawal from the metalimnion and the epilimnion. The hooded pipe inlet's (**PRH4**) entrainment rate was 9 pct of the baseline entrainment rate (**PR20**) - 0.76 °F/h . The flexible curtain (**PR20C**) and excavated channel options (**PREC3**) resulted in entrainment rates that were 72 and 68 pct of the baseline value, respectively. For this test case, no extended curtain tests passed the buoyancy frequency rejection criteria.

Test Case 2. - The results for test case 2, water surface elevation 4485, and flow rate of 800 ft^3/s, are presented on figure 11. The chart of metalimnion entrainment rates at pole A indicated the hooded pipe inlet was the most effective in limiting withdrawal from the metalimnion and the epilimnion. The hooded pipe inlet's (**PRH3**) entrainment rate was 16 pct of the baseline entrainment rate (**PR10**) - 0.37 °F/h. The original flexible curtain (**PR18C**) and extended curtain (**PRAC6**) options resulted in entrainment rates that were 59 and 19 pct of the baseline value, respectively. The excavated channel (**PREC5**) option resulted in an entrainment rate that was 24 pct of the baseline value.

Test Cases 3 and 3a. - The results for test cases 3 and 3a, water surface elevation 4480, and flow rates of 1,600 and 800 ft^3/s, respectively, are presented on figure 12. For Test Case 3, the chart of metalimnion entrainment rates at pole A indicated the hooded pipe inlet was most effective in limiting withdrawal from the metalimnion and the epilimnion. The hooded pipe inlet's (**PRH7**) entrainment rate was 9 pct of the baseline entrainment rate (**PR19**) - 1.90 °F/h. The extended flexible curtain (**PRAC10**) and excavated channel (**PREC2**) options resulted in entrainment rates that were 64 pct and 22 pct of the baseline value, respectively. For these test cases, no flexible curtain tests passed the rejection criteria.



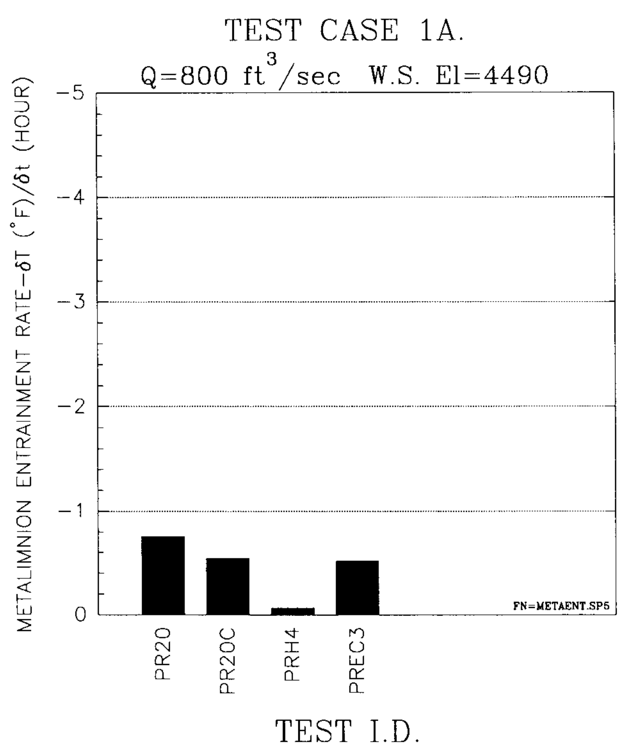


Figure 10. - Comparison of metalimnion entrainment rates for Test Cases 1 and 1a. For Test Case 1, the hooded pipe inlet clearly has the best selective withdrawal characteristics. Test Case 1a showed a similar trend.

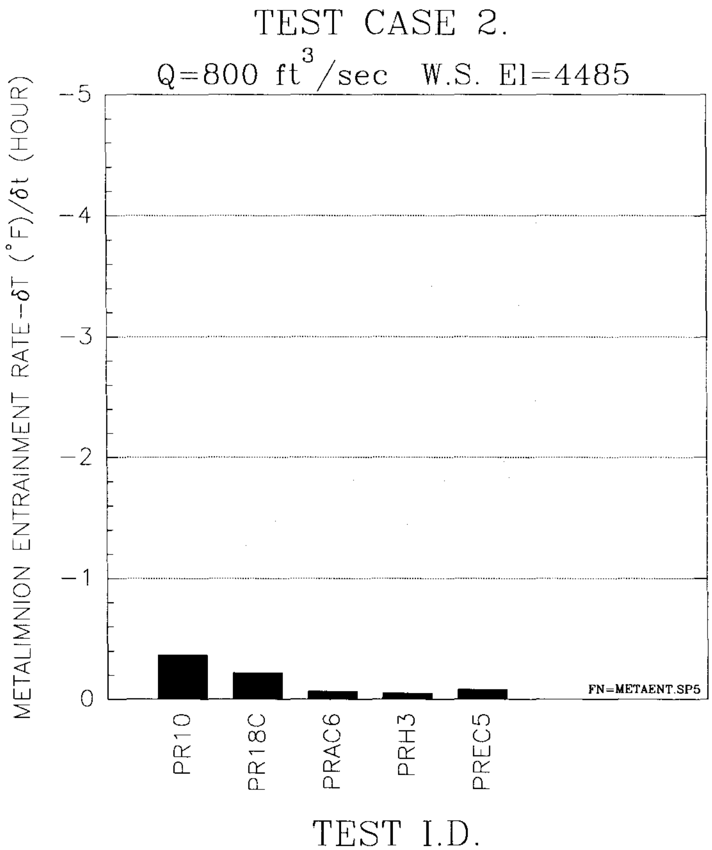


Figure 11. - Comparison of metalimnion entrainment rates for Test Case 2. For this condition, all selective withdrawal alternatives performed favorably. The hooded pipe inlet had the smallest entrainment rate.

For Test Case 3a, the chart (fig. 12) of metalimnion entrainment rates at pole A indicated the excavated channel was the most effective in limiting withdrawal from the metalimnion and the epilimnion. The excavated channel's (**PREC1**) entrainment rate was 22 pct of the baseline entrainment rate (**PR17**) - 0.409 °F/h. The hooded pipe inlet (**PRH1**) produced an entrainment rate that was 32 pct of the baseline value. The original (**PR17C**) and extended flexible curtain (**PRAC7**) option resulted in entrainment rates that were 91 and 76 pct of the baseline value, respectively. This test case was the only one where the hooded pipe inlet was not the most efficient selective withdrawal structure. However, the difference is small, and may be attributed to the variability in stratification. Test **PREC1** had a buoyancy frequency of 0.026, whereas test **PRH1** had a buoyancy frequency equal to 0.016. As a result, withdrawal of metalimnion water for test **PREC1** required more energy than test **PRH1**; therefore, the entrainment rate test for **PREC1** was lower.

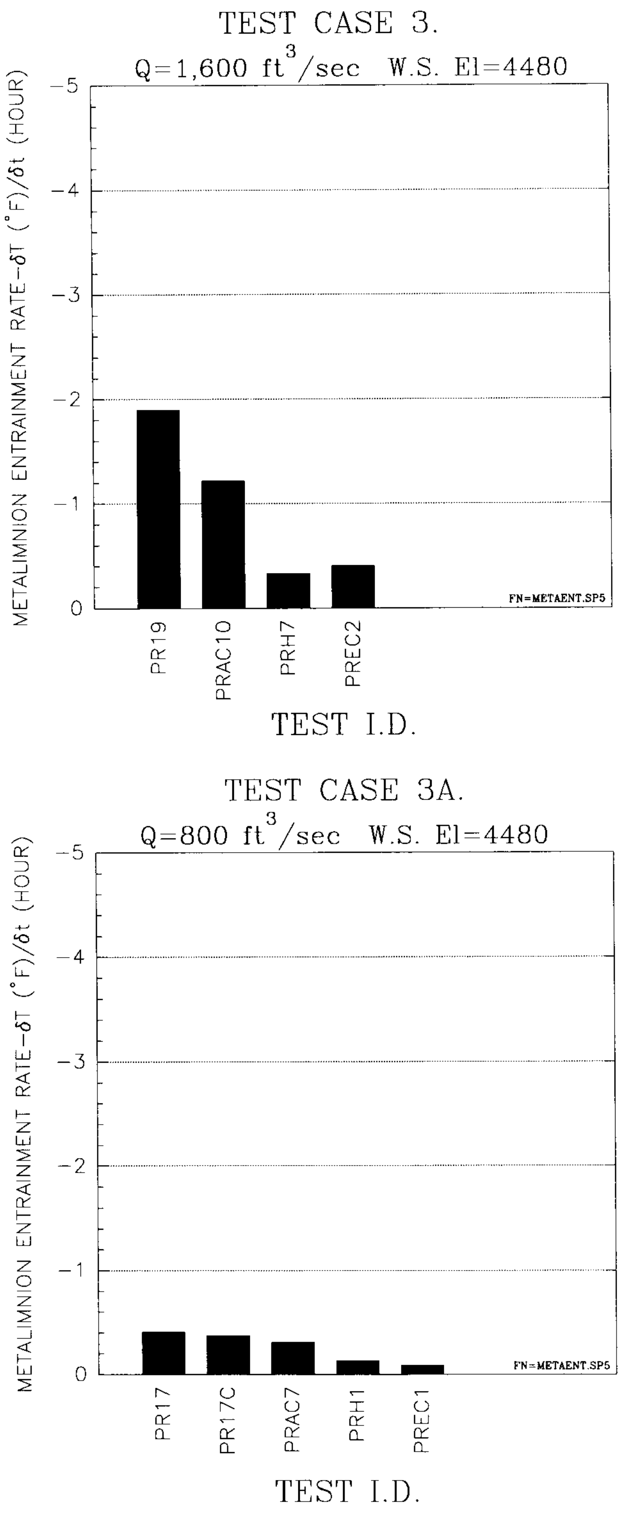


Figure 12. - Comparison of metalimnion entrainment rates for Test Cases 3 and 3a. For Test Case 3 the hooded pipe inlet had the best withdrawal characteristics. For Test Case 3a the excavated channel performed slightly better than the hooded pipe.

Velocity Distributions for the Hooded Pipe Inlet

Velocities were measured in the center of each pipe and around the perimeter of the hood structure. In general, the flow rate in the center pipe was greatest, followed by the flow rate in the right and left pipes (looking downstream). The velocities measured in each pipe for three flow rates are presented in table 3. For flows of 1,200 and 1,600 ft^3/s, the center pipe carried about 6 and 13 pct more flow than the right and left pipes, respectively.

The flow distribution entering the hood, through its perimeter, was reasonably uniform except for slightly higher velocities at the back side of the hood. The flow distributions for Test Cases 3 and 3a are presented in the appendix (figures A.6 and A.7). In an effort to balance the flow distribution along the hood's back edge, the two outside pipes were extended 10 ft, for a total of 30 ft, into the hood structure. The flow distribution for Test Case 3 with the modified pipe geometry is presented in the appendix (figure A.8). The pipe modification did improve the flow distribution by slightly reducing the velocities through the back edge of the hooded structure. If desired, areas with higher velocities could be excavated to lower the entrance velocities. Likewise, flow distribution may be improved by adjusting the location and shape of the hood.

Table 3. - Centerline velocity data for each of the three pipes in the hooded pipe inlet option.

Inlet Pipe (looking downstream)	Flow rate=800 (ft^3/s)	Flow Rate=1,200 (ft^3/s)	Flow Rate=1,600 (ft^3/s)
	$V_{Prototype}$ (ft/s)	$V_{Prototype}$ (ft/s)	$V_{Prototype}$ (ft/s)
Right	2.6	3.6	4.7
Center	2.8	3.8	4.9
Left	2.4	3.3	4.4

NOTE: Velocity data are accurate to ± 0.2 ft/s.

Velocity Profiles Near the Prattville Intake for Excavated Channel Topography

At the request of PG&E, velocity profiles were measured near the Prattville Intake for the excavated channel topography. The velocity meter used to measure velocities could only be used near the intake, where near-field velocities were large enough to be measured. Far-field velocities were too small to be accurately measured. Two sets of velocity data were collected: one set 25 ft upstream from the Prattville Intake trashrack and a second at section A-A (fig. A.3). Representative temperature profiles were measured at pole A (near section L-L, fig. A.3) for each of the velocity profiles.

Velocity profiles, along with their corresponding temperature profiles (at pole A) for Test Case 1 and 1a, are presented in the appendix (figures A.9 through A.12). For convenience, the velocity and temperature data are also given in the appendix (tables A.6 through A.9).

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APPENDIX

Table A.1. - Test Case 1, W.S. El 4490, Prattville Intake discharge is 1,600 ft^3/s.

Test ID	Upper Withdrawal Layer Elevation	Buoyancy Frequency	Densimetric Froude Number	Metalimnion Entrainment Rate (°F/h)
PR15	4480	0.020	0.230	-4.10
PR16C	4485	0.016	0.236	-2.74
PRAC11	4480	0.021	0.225	-1.27
PRH6	4475	0.014	0.419	-0.33
PREC4	4470	0.023	0.322	-1.14

Table A.2. - Test Case 1a, W.S. El 4490, Prattville Intake discharge is 800 ft^3/s.

Test I.D.	Upper Withdrawal Layer Elevation	Buoyancy Frequency	Densimetric Froude Number	Metalimnion Entrainment Rate (°F/h)
PR20	4475	0.017	0.176	-0.76
PR20C	4485	0.017	0.115	-0.55
PRH4	4470	0.013	0.289	-0.07
PREC3	4480	0.024	0.095	-0.52

Table A.3. - Test Case 2, W.S. El 4485, Prattville Intake discharge is 800 ft^3/s.

Test I.D.	Upper Withdrawal Layer Elevation	Buoyancy Frequency	Densimetric Froude Number	Metalimnion Entrainment Rate (°F/h)
PR10	4475	0.017	0.177	-0.37
PR18C	4470	0.018	0.203	-0.22
PRAC6	4470	0.019	0.193	-0.07
PRH3	4465	0.015	0.327	-0.06
PREC5	4470	0.024	0.154	-0.09

Table A.4. - Test Case 3, W.S. El 4480, Prattville Intake discharge is 1,600 ft^3/s.

Test I.D.	Upper Withdrawal Layer Elevation	Buoyancy Frequency	Densimetric Froude Number	Metalimnion Entrainment Rate (°F/h)
PR19	4480	0.016	0.295	-1.90
PRAC10	4470	0.022	0.343	-1.22
PRH7	4470	0.015	0.511	-0.33
PREC2	4470	0.027	0.262	-0.41

Table A.5. - Test Case 3a, W.S. El 4480, Prattville Intake discharge is 800 ft^3/s.

Test I.D.	Upper Withdrawal Layer Elevation	Buoyancy Frequency	Densimetric Froude Number	Metalimnion Entrainment Rate (°F/h)
PR17	4475	0.018	0.163	-0.41
PR17C	4475	0.018	0.163	-0.37
PRAC7	4470	0.026	0.144	-0.31
PRH1	4475	0.016	0.182	-0.13
PREC1	4470	0.026	0.185	-0.09

[1] All elevations are referenced to PG&E's datum (PG&E datum = USGS datum - 10.2 ft).

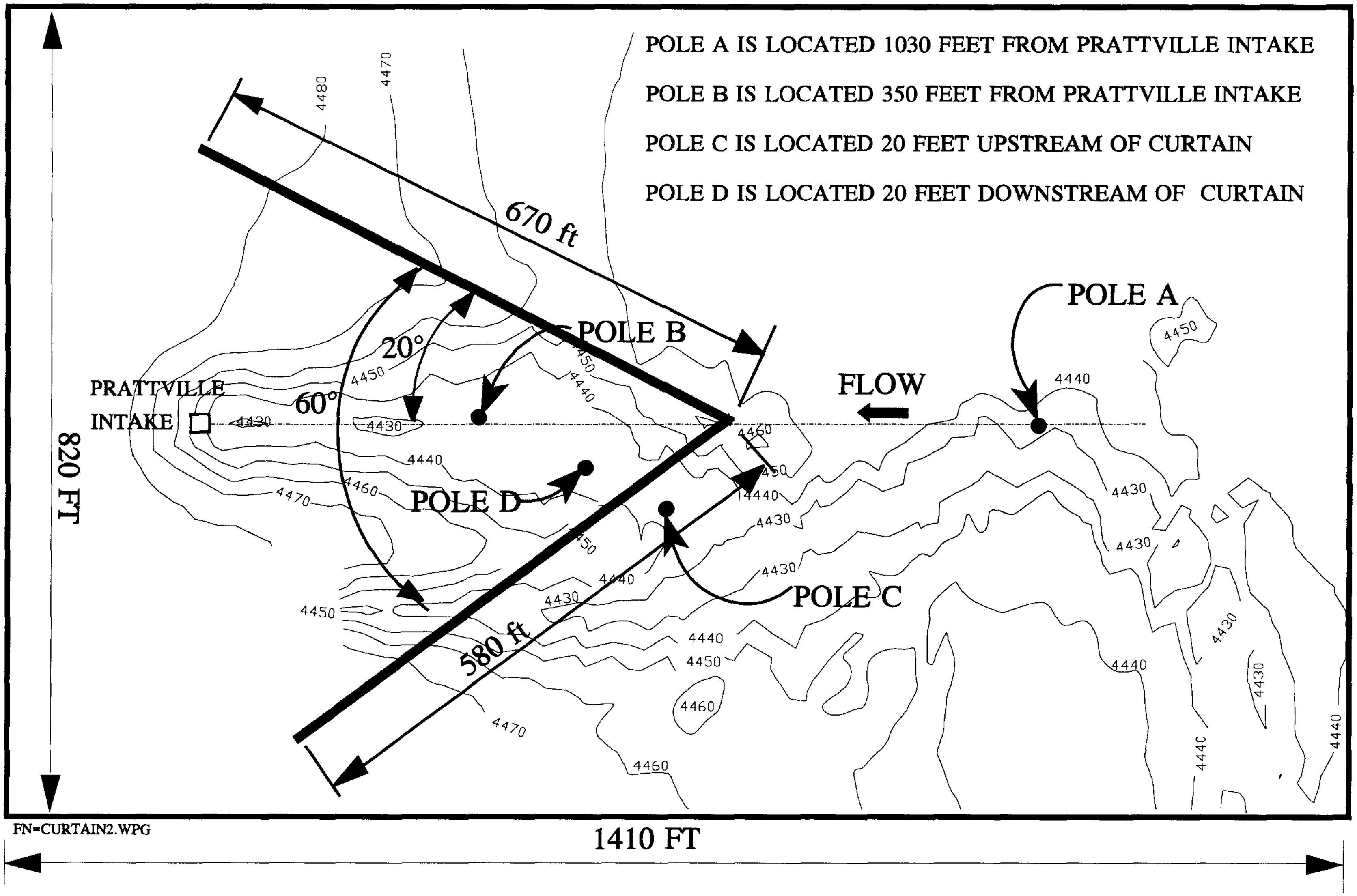


Figure A.1. - Schematic of the modified (extended) flexible curtain option and the model extents (prototype dimensions).

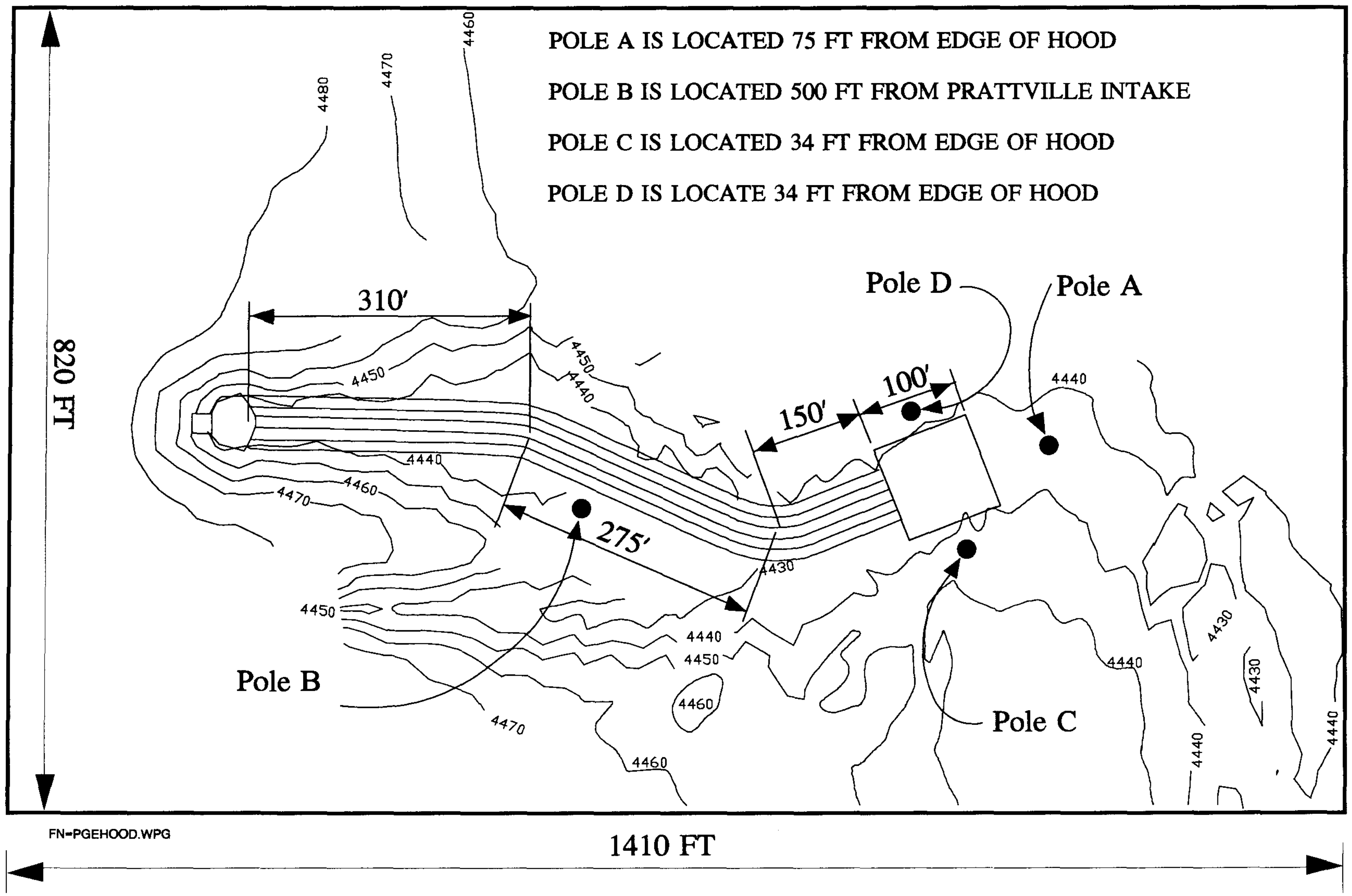


Figure A.2. - Schematic of the PG&E hooded pipe inlet option and the model extents (prototype dimensions).

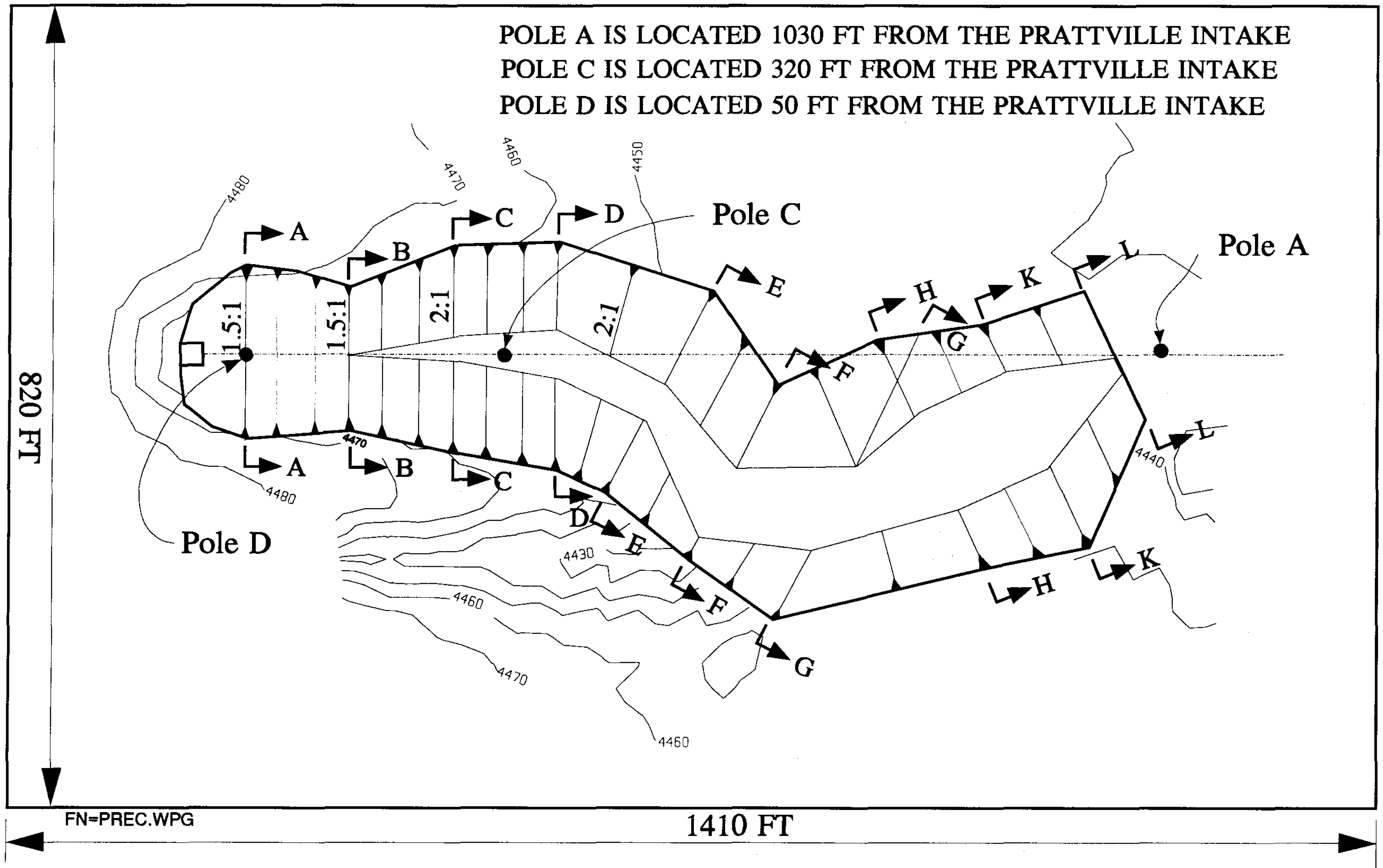
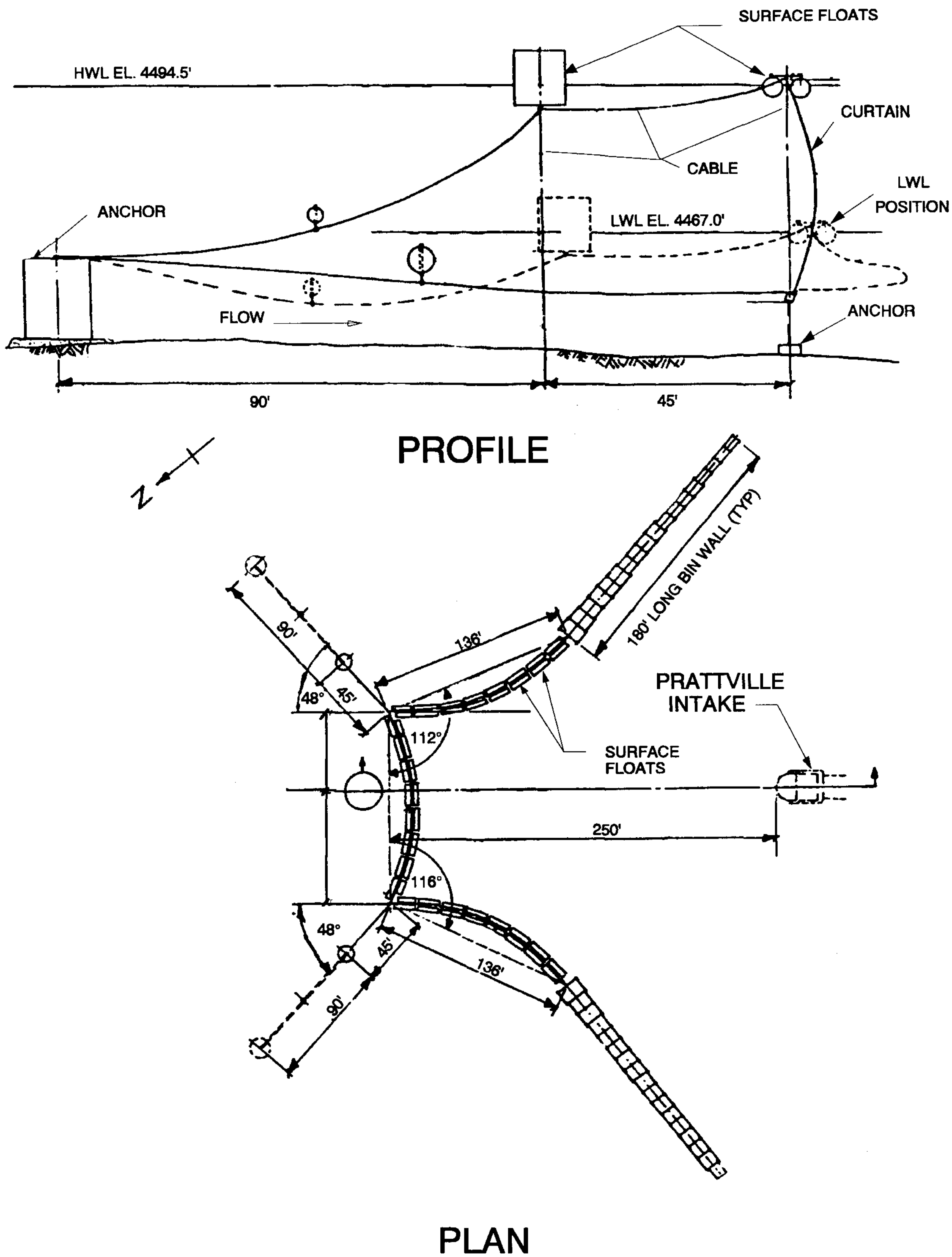


Figure A.3. - Schematic of the excavated channel option and the model extents (prototype dimensions).



FLEXIBLE MEMBRANE CURTAIN WALL

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Figure A.4. - Details of original PG&E flexible curtain design. Reference PG&E drawings PRV-SK-01 and PRV-SK-02.

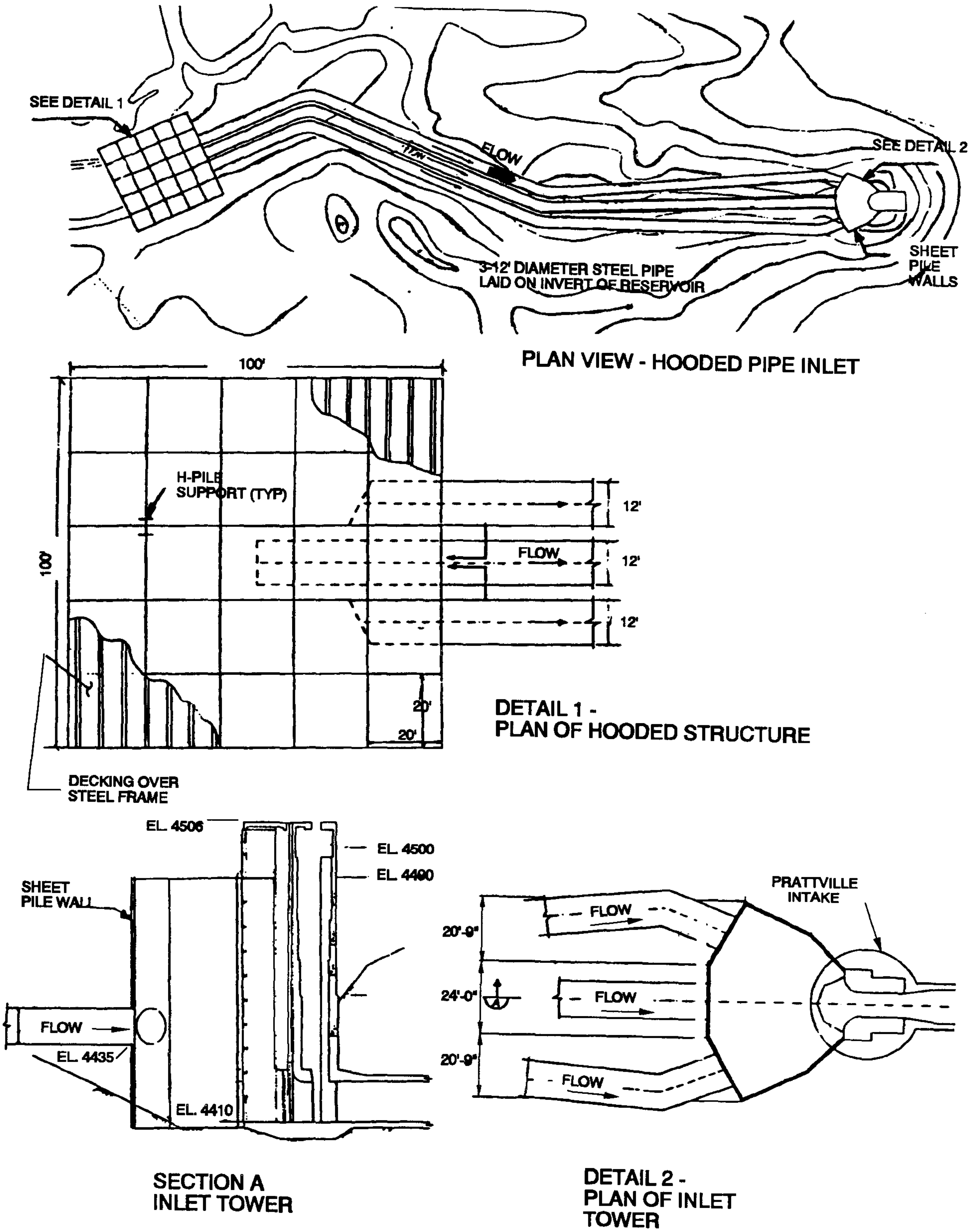

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Figure A.5. - Details of the PG&E hooded pipe inlet design. Reference PG&E drawing PRAT-VCB04, Rev. 1.

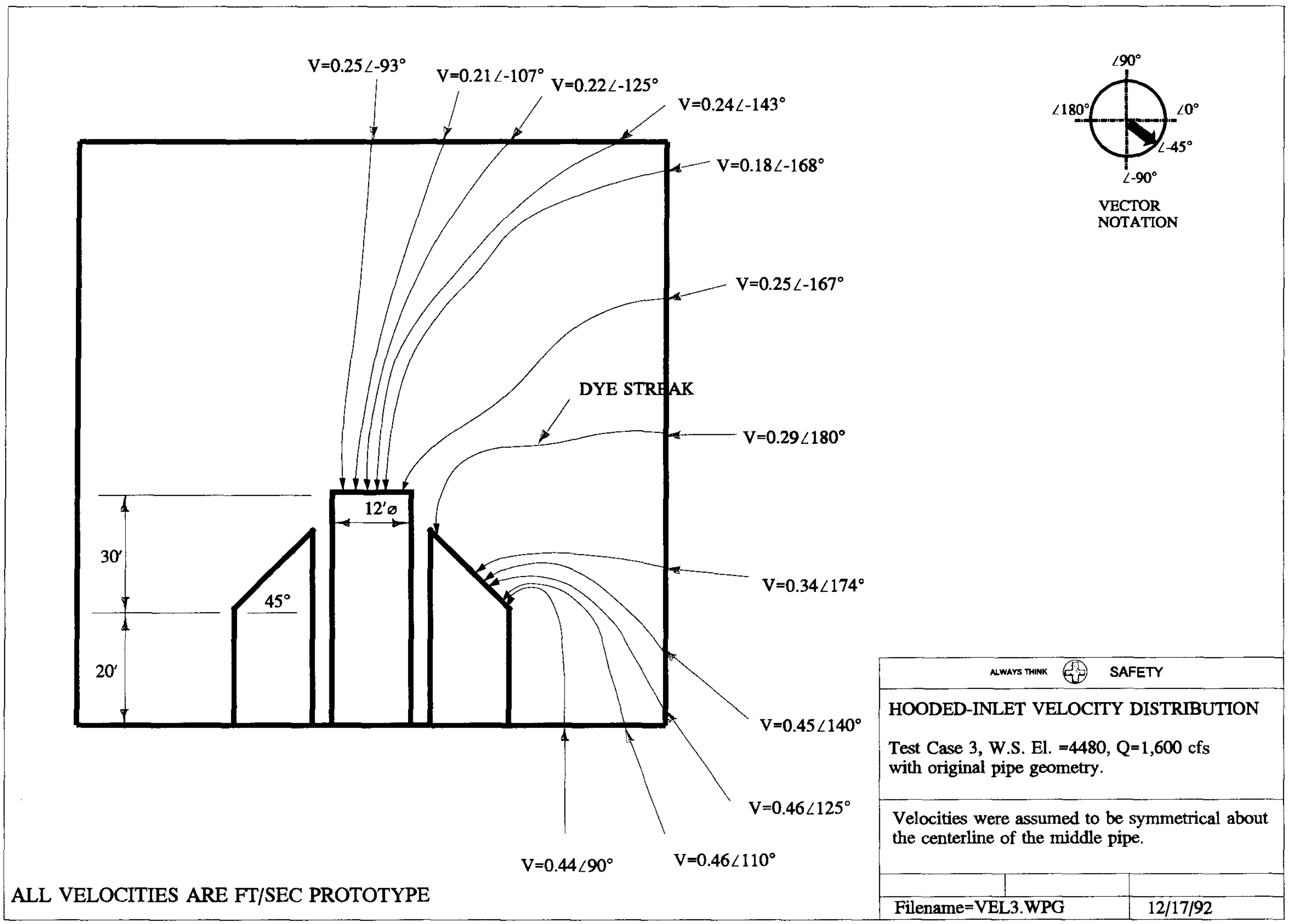

Figure A.6. - Schematic of prototype velocities and streaklines entering the hooded pipe inlet for Test Case 3. Velocities are in feet per second (not to scale).

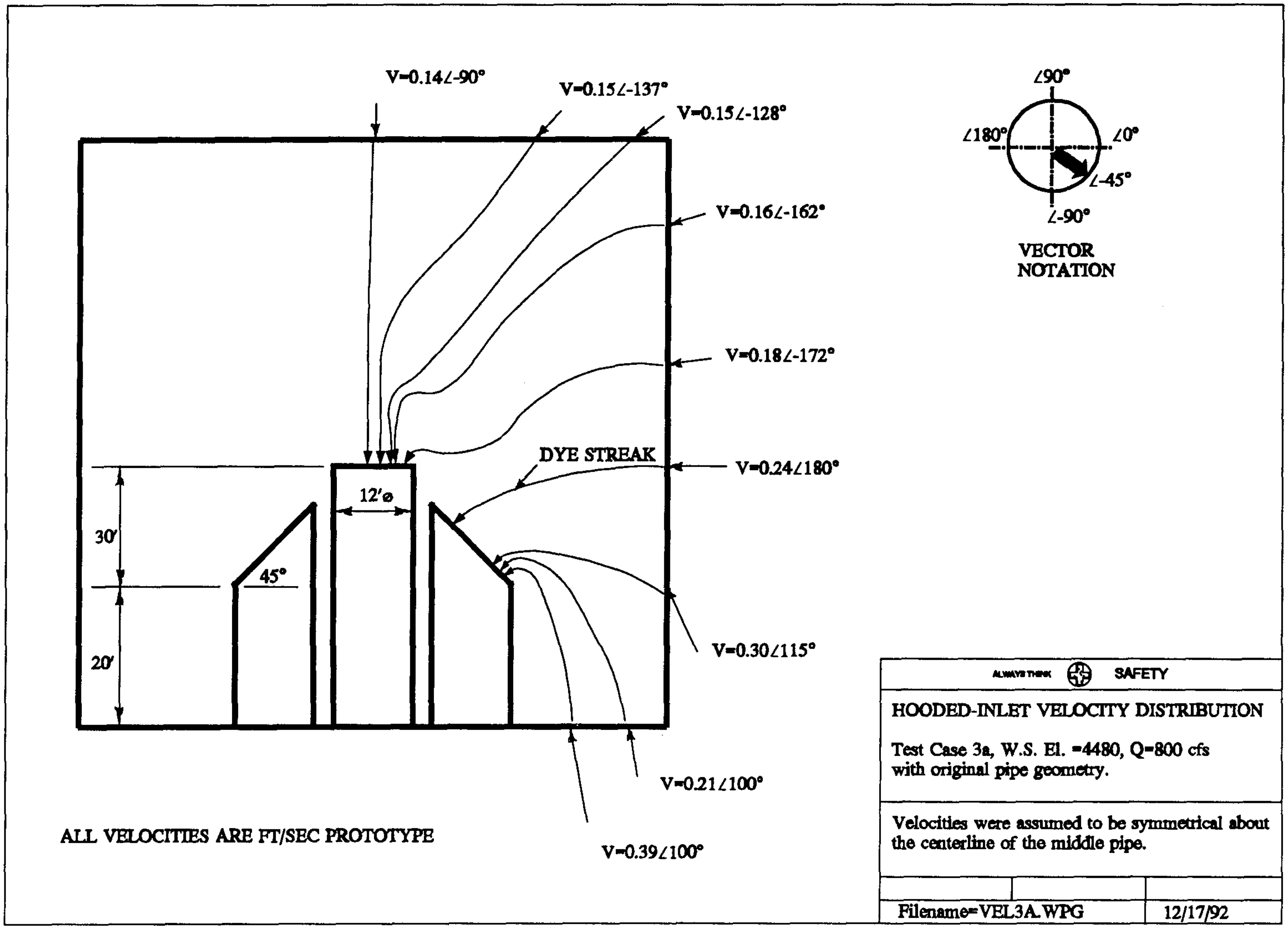

Figure A.7. - Schematic of prototype velocities and streaklines entering the hooded pipe inlet for Test Case 3a. Velocities are in feet per second (not to scale).

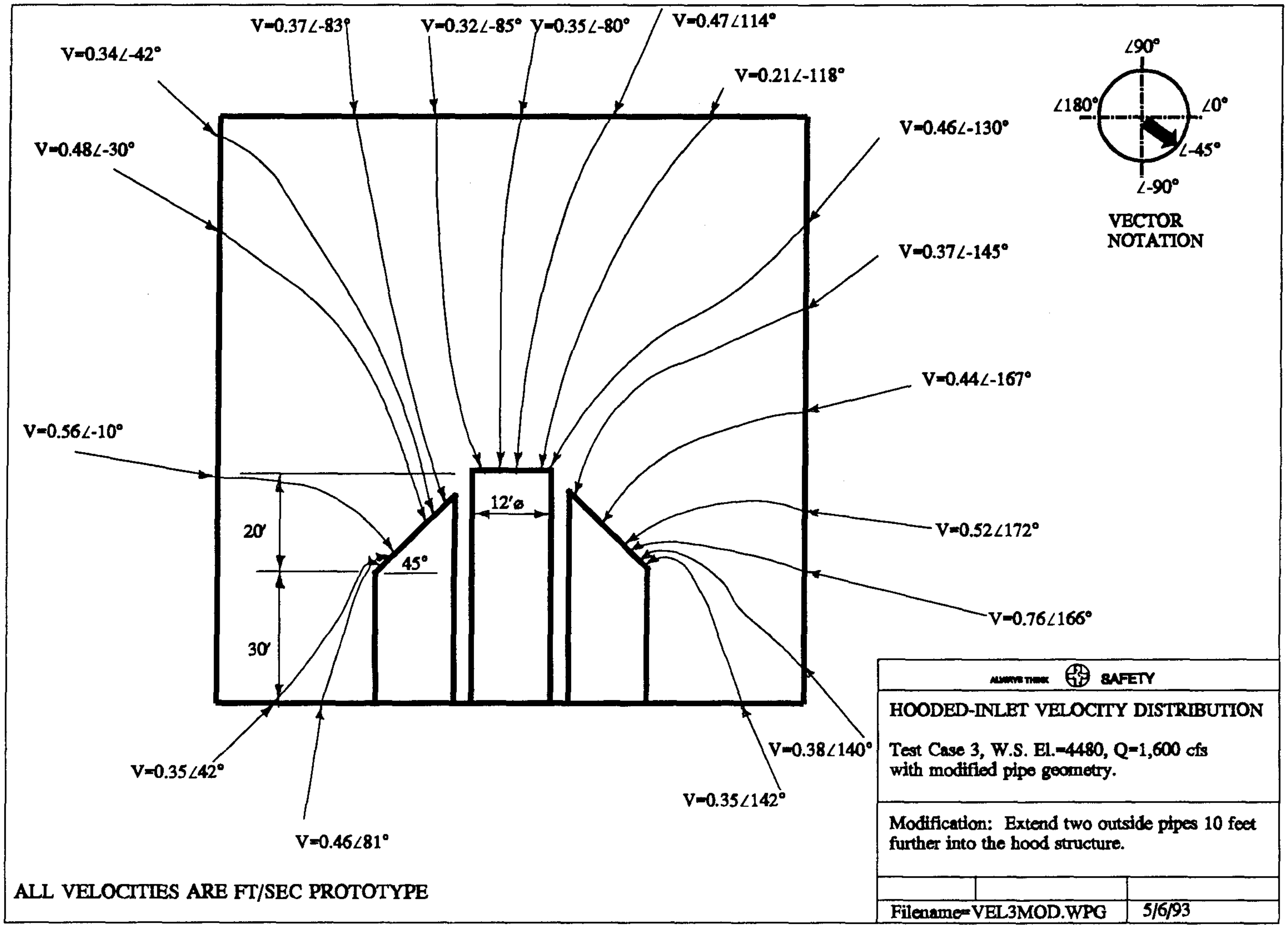

Figure A.8. - Schematic of prototype velocities and streaklines entering the modified hooded pipe inlet for Test Case 3. Velocities are in feet per second (not to scale).

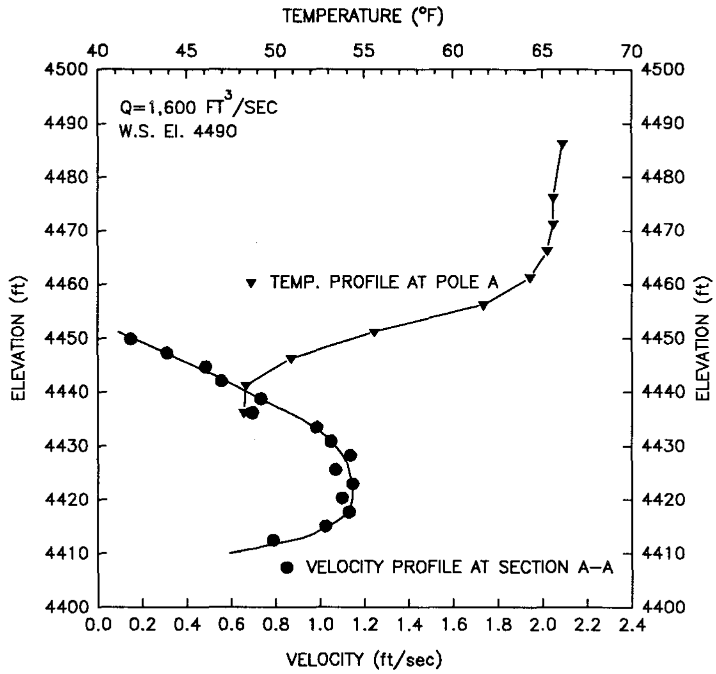

Figure A.9. - Section A-A velocity and pole A temperature profiles for the excavated channel option (Test Case 1, see table A.6. for raw data).

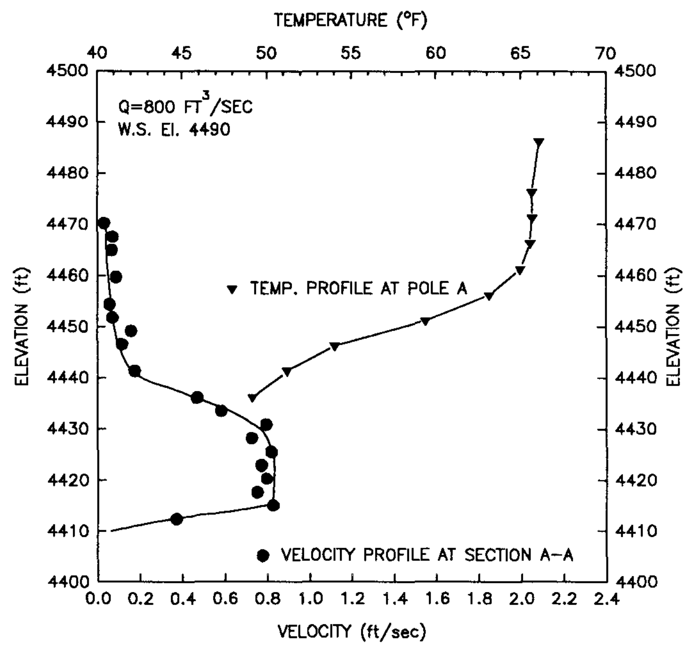

Figure A.10. - Section A-A velocity and pole A temperature profiles for the excavated channel option (Test Case 1a, see table A.7. for raw data).

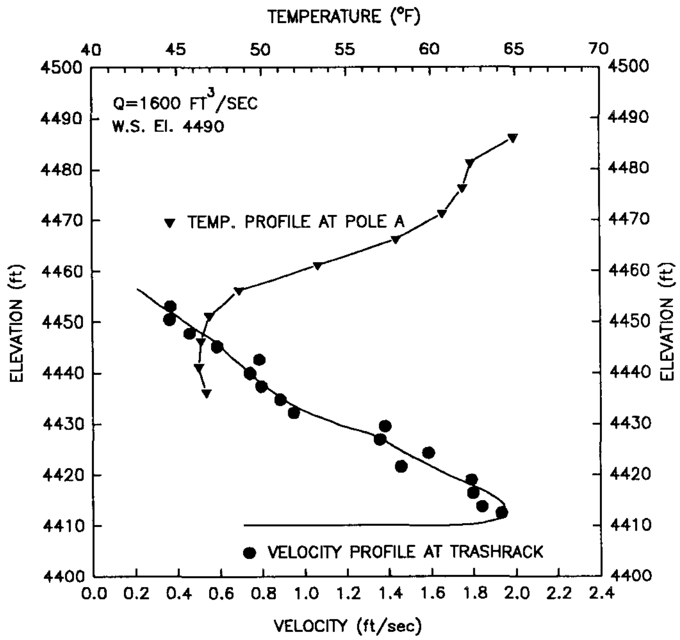

Figure A.11. - Trashrack velocity and pole A temperature profiles for the excavated channel option (Test Case 1, see table A.8. for raw data).

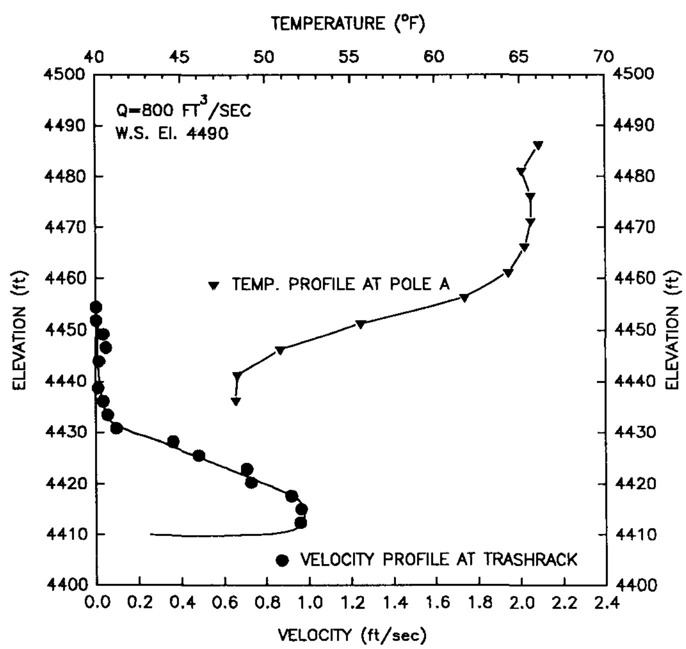

Figure A.12. - Trashrack velocity and pole A temperature profiles for the excavated channel option (Test Case 1a, see table A.9. for raw data).

Table A.6. - Section A-A velocities and Pole A temperature data, Q=1,600 ft^3/s and WSEL=4490.

Elevation (ft)	Velocity (ft/s)	Temperature (°F)
4486.3		66.1
4476.3		65.6
4471.3		65.6
4466.3		65.2
4461.3		64.3
4456.3		61.7
4451.3		55.6
4449.9	0.15	
4447.3	0.31	
4446.3		50.8
4444.7	0.48	
4442.0	0.56	
4441.3		48.3
4438.7	0.73	
4436.3		48.2
4436.1	0.70	
4433.5	0.98	
4430.9	1.05	
4428.2	1.14	
4425.6	1.07	
4423.0	1.15	
4420.4	1.10	
4417.7	1.13	
4415.1	1.02	
4412.5	0.79	

[1] All elevations are referenced to PG&E's datum (PG&E datum = USGS datum - 10.2 ft).

Table A.7. - Section A-A velocities and Pole A temperature data, Q=800 ft^3/s and WSEL=4490.

Elevation (ft)	Velocity (ft/s)	Temperature (°F)
4486.3		66.1
4481.3		65.1
4476.3		65.6
4471.3		65.7
4470.2	0.03	
4467.6	0.07	
4466.3		65.5
4465.0	0.07	
4461.3		64.9
4459.7	0.09	
4456.3		63.1
4454.5	0.06	
4451.9	0.07	
4451.3		59.4
4449.2	0.16	
4446.6	0.11	
4446.3		54.0
4441.4	0.17	
4441.3		51.2
4436.3		49.1
4436.1	0.47	
4433.5	0.58	
4430.9	0.80	
4428.2	0.73	
4425.6	0.82	
4423.0	0.77	
4420.4	0.80	
4417.7	0.75	
4415.1	0.83	
4412.5	0.37	

[1] All elevations are referenced to PG&E's datum (PG&E datum = USGS datum - 10.2 ft).

Table A.8. - Trashrack velocities and Pole A temperature data, Q=1,600 ft^3/s and WSEL=4490.

Elevation (ft)	Velocity (ft/s)	Temperature (°F)
4486.3		64.9
4481.3		62.4
4476.3		61.9
4471.3		60.7
4466.3		58.0
4461.3		53.3
4456.3		48.6
4453.2	0.37	
4451.3		46.9
4450.6	0.36	
4447.9	0.46	
4446.3		46.4
4445.3	0.59	
4442.7	0.78	
4441.3		46.2
4440.1	0.74	
4437.4	0.79	
4436.3		46.7
4434.8	0.88	
4432.2	0.95	
4429.6	1.38	
4426.9	1.36	
4424.3	1.59	
4421.7	1.46	
4419.1	1.79	
4416.4	1.80	
4413.8	1.84	
4412.5	1.93	

[1] All elevations are referenced to PG&E's datum (PG&E datum = USGS datum - 10.2 ft).

Table A.9. - Trashrack velocities and Pole A temperature data, Q=800 ft^3/s and WSEL=4490.

Elevation (ft)	Velocity (ft/s)	Temperature (°F)
4486.3		66.1
4481.3		65.1
4476.3		65.6
4471.3		65.6
4466.3		65.2
4461.3		64.3
4456.3		61.7
4451.3		55.6
4449.2	0.03	
4446.6	0.05	
4446.3		50.9
4444.0	0.02	
4441.3		48.3
4438.7	0.01	
4436.3		48.2
4436.1	0.03	
4433.5	0.05	
4430.9	0.09	
4428.2	0.36	
4425.6	0.48	
4423.0	0.71	
4420.4	0.73	
4417.7	0.92	
4415.1	0.96	
4412.5	0.96	

[1] All elevations are referenced to PG&E's datum (PG&E datum = USGS datum - 10.2 ft).

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.