RECLAMATION

Managing Water in the West

Hydraulic Laboratory Technical Memorandum PAP-1131

Penstock Air Vent Analysis for Helena Valley Pumping Plant

Emergency Gate Closure

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

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Purpose

The purpose of this analysis is to estimate air demand and the existing air vent capacity required to prevent penstock collapse during unbalanced penstock emergency gate closure scenarios. Two scenarios were analyzed including two-unit operation under dead head pumping conditions and two-unit operation under maximum discharge conditions. The first scenario is consistent with the proposed upcoming emergency gate closure test and the second considers the overall performance of the existing air vent under worse case conditions.

Background

Helena Valley Pumping Plant is located on the Missouri River just downstream of Canyon Ferry Dam near Helena, MT. The pumping plant was constructed in the late 1950's and is comprised of two Francis turbines directly connected to two vertical-shaft centrifugal pumps. Each pump was sized to deliver 150 ft^3/s at a total head of 145 ft. The turbines were sized to provide 5,300 HP with an effective head of 120 ft and a discharge of 468 ft^3/s.

The turbine-driven pumps are supplied directly from Canyon Ferry Reservoir via a single 10-ft-diameter penstock which terminates in two 78-in-diameter branches to the pump-turbine units. The section of penstock just downstream of the emergency gate has a diameter of 13-ft and is mostly embedded in the concrete section of the dam. The diameter is reduced to 10-ft after it emerges from the concrete section. The penstock intake is protected by a vertical trash rack structure and is equipped with a 12.78- by 12.78-ft fixed wheel emergency gate. The intake is also equipped with an 18-in-diameter air vent which is embedded in concrete and located just downstream of the emergency gate. The emergency gate closes under unbalanced head in approximately 90 seconds. Reservoir water surface elevations at Canyon Ferry Dam can vary from 3,728-3,800 ft while the tailwater elevation can vary from 3,640-3,665 ft. The normal tailwater elevation is 3,650 ft. The pumping plant is operated during the irrigation season to satisfy irrigation demands.

Reclamation's Hydraulic Investigations and Laboratory Services Group was contacted by Reclamation's Hydraulic Equipment Group and asked to determine the maximum volumetric flowrate or air demand that will pass through the existing 18-in-diameter (~120 ft in length) air vent pipe while evacuating the penstock during a fixed wheel gate emergency closure. The request stems from a planned emergency gate closure test to be conducted in the near future.

Analyses

Penstock Collapse Pressure

The first step in this analysis is to estimate the collapse pressure of the existing penstock. There are various methods for doing so, but a conservative estimate can be obtained using the Stewart formula [1] for uniform external pressure given as

$$P_c = 5.02x10^7(t/d_N)^3 \tag{1}$$

where P_c is the collapse pressure (lbf/in^2 or psi), t is the penstock thickness, and d_N is the penstock diameter (neutral axis). Then with t = 0.5 in and d_N = 120.5 in for the 10-ft-diameter penstock gives

$$P_c = 5.02x10^7(0.5/120.5)^3 = 3.6 \text{ psi} \tag{2}$$

Using the same formula for the 13-ft section of penstock immediately downstream of the emergency gate where d_N = 156.5 in, the collapse pressure is conservatively estimated as

$$P_c = 5.02x10^7(0.5/156.5)^3 = 1.6 \text{ psi} \tag{3}$$

However, it is recognized that the 13-ft section is partially embedded in concrete and has a relatively short length. A more detailed buckling analysis for the 13-ft-diameter section would be required for a less conservative estimate of collapse pressure. These estimates assume the penstock is in good condition and within acceptable tolerances for thickness and roundness.

Next, the required vent capacity can be estimated using the collapse pressure as an allowable pressure drop (i.e., the allowable penstock internal pressure below atmospheric pressure)

$$Q_a = A_v\{2g[(144\Delta P_{all}/\gamma) + \Delta z]/(\sum K_s + fL/d_v)\}^{1/2} \tag{4}$$

where Q_a is the maximum air demand (or vent capacity), A_v is the vent cross sectional area, g is gravitational acceleration, ΔP_{all} is the allowable pressure drop across the vent (in this case P_c), γ is the specific weight of air, Δz is the change in elevation from the vent entrance to the vent exit, $\sum K_s$ is the sum of form losses associated with the vent, f is the friction factor for the vent piping, L is the length of the vent piping, and d_v is the vent diameter. Using the above equation, the vent capacity is estimated to be approximately 340 ft^3/s. This means that the air demand during an emergency closure cannot exceed 340 ft^3/s if the allowable pressure drop across vent is to remain less than 1.6 psi. Additionally, this air flowrate would result in a vent velocity of approximately 190 ft/s. Typically air vents are sized for a maximum vent velocity of 100 ft/s which would further constrain the maximum air demand to less than 175 ft^3/s. Excessive vent velocities are a matter of safety when it is physically possible for personnel to be in close proximity to the vent entrance. Entrainment or impingement of debris may also be problematic depending on vent location. Otherwise, the possibility for choked flow may exist for extremely large vent velocities, but in this case, pipe collapse would likely occur before reaching a choked-flow condition.

The estimated collapse pressures imply that if the actual air demand during an emergency closure is greater than 175 ft^3/s, vent velocities would become excessive and if it exceeds 340 ft^3/s, collapse may be possible. The latter is obviously more critical. Since the penstock collapse pressure is relatively small, a transient analysis was recommended to estimate air demand during the emergency closure.

Estimated Air Demand

Analytical Method

The method of characteristics was used to numerically analyze the transient hydraulic characteristics associated with a relatively rapid emergency gate closure. The basis for this analytical approach is outlined in Wylie & Streeter [2]. The numerical model starts with a specified reservoir elevation and initial steady state discharge under a fully open fixed wheel gate. Although pump-turbine units are located at the downstream end of the system, in this case, the model treats the outflow as a regulating gate set at a fixed opening to provide the initial steady state discharge at a specified reservoir head. The regulating gate setting then remains fixed at that initial position throughout the entire emergency gate closure. This simplification is necessary in the absence of turbine (i.e. head-discharge) characteristics for the proposed emergency gate closure test scenario. The gate closure rate is assumed to be constant based on the specified total closure time of 90 seconds. This closure time is for balanced conditions, but it is assumed to be similar for an unbalanced closure. As the gate closes, the head in the penstock just downstream of the emergency gate decreases until it falls below the top elevation of the penstock and air venting begins. At that point, the method of characteristics algorithm is terminated and a quasi-steady state algorithm is started which computes air demand as a function of time based on Froude number for flow under the emergency gate and an assumed inflow-outflow imbalance in the penstock for the remaining duration of the gate closure.

The physical characteristics of air demand for this particular application generally involve a supercritical high velocity jet discharged underneath the gate. The supercritical flow is then assumed to transition to subcritical as a hydraulic jump which fills the pipe cross section at some point downstream. Air is drawn into the penstock via the existing 18-in air vent due to the large velocity at the air water interface and is entrained into the flow at the hydraulic jump and subsequently transported downstream. The entrainment of air in the case of a hydraulic jump in a closed conduit may be described empirically [1] as

$$Q_a = Q_w[0.0066(Fr - 1)^{1.4}] \tag{5}$$

where Q_a is the volumetric flowrate of air due to entrainment, Q_w is the volumetric flowrate of water in penstock, and Fr is the Froude number upstream of the hydraulic jump defined as

$$Fr = U/(gd_e)^{1/2} \tag{6}$$

where $U = Q_w/A_g$ is the mean jet velocity issuing from the emergency gate and d_e is the effective depth of the flow upstream of the hydraulic jump. As the gate continues to close following the initiation of venting, the hydraulic jump is assumed to advance downstream until the penstock becomes fully evacuated, which typically occurs shortly after the gate has closed completely. Owing to the assumed change in position of hydraulic jump, there is a contribution to the overall air demand from a change in the volume of air the penstock. This effect is accounted for conservatively by assuming that at each time step during venting, the discharge through the fixed regulating gate at the end of the penstock is driven by a fixed head in the penstock (taken at the start of venting) until the entire penstock is evacuated. This artificially creates an inflow-outflow imbalance as the emergency gate continues to close such that the inflow to the penstock decreases while the outflow from the penstock remains constant. The difference between the outflow and inflow represents a volumetric flow rate which is added to the air entrainment to obtain a total air demand. At each time step during venting, the total air demand can then be used to calculate the pressure drop across the existing air vent. Rearranging Eq'n (4), the pressure drop across the vent can be written as

$$\Delta P_v = \gamma[(V^2/2g)(\sum K_s + fL/d_v)/144 \tag{7}$$

where ΔP_v is the vent pressure drop as determined from the air demand using $V = Q_a/A_v$. The simplifying assumptions for this analysis include:

1. The fixed wheel gate discharge coefficient can be described using the polynomial relation for free discharge provided in [3].

2. The pump-turbine hydraulic characteristics can be represented as a fixed regulating gate at the end of the penstock with fixed discharge coefficient and fixed gate setting (i.e., open area) based on the initial head and discharge.

3. The head at the downstream end of the penstock remains constant after the start of venting until the emergency gate is fully closed.

4. The air demand is a function of entrainment in a hydraulic jump filling the conduit plus the change in volumetric flow rate due to an assumed penstock inflow-outflow imbalance during venting.

5. The existing 18-in air vent is in as-designed condition, consistent with DWG 296-D-236 (Section B-B) and free of obstructions.

6. The penstock is in good, as-designed condition and within reasonable tolerances for roundness and wall thickness as they relate to collapse pressure.

Emergency Gate Closure Test Scenario

For the purposes of this analysis, Canyon Ferry Reservoir elevations of 3,800 ft and 3,735 ft were analyzed with the minimum tailwater elevation of 3,640 ft. The initial discharge for the proposed emergency gate closure test of 280 ft^3/s represents the maximum turbine discharge for two-unit operation under the rated head of 120 ft with the pump discharge valve closed (dead head) as provided by Reclamation's Hydraulic Equipment Group.

Emergency Gate Closure at Maximum Discharge Scenario

As with the emergency gate closure test scenario, the same reservoir and tailwater elevations were used to analyze the maximum discharge scenarios. The initial discharges (combined turbine and pump) in this case were taken as 580 ft^3/s for reservoir elevation 3,800 ft, and 1,020 ft^3/s for reservoir elevation 3,735 ft which represent two-unit operation at full pumping capacity under the respective heads. The larger discharge at the lower reservoir elevation is required to provide sufficient turbine horsepower for the pumps to deliver 150 ft^3/s. These values were obtained from the predicted unit speed and discharge quantities as given in the Designers' Operating Criteria for Helena Valley Pumping Plant [4]. While it is not likely that the pumping plant would be operated under these conditions, such operations are considered physically possible and warrant consideration as the upper limits for air demand and air vent performance.

Results & Discussion

Emergency Gate Closure Test Scenario

The emergency gate closure test scenario involves a relatively small discharge. Maximum air demands of 192 ft^3/s and 229 ft^3/s are predicted for emergency gate closures at reservoir elevations of 3,800 ft and 3,735 ft, respectively. In both cases, the maximum air demands occur just before the emergency gate fully closes and produce computed maximum vent pressure drops of less than 0.6 psi and 0.9 psi, respectively. Figures 1 and 2 show predicted air demand and vent pressure drop as functions of percent gate opening. Table 1 provides a summary of the results where Q_i is the initial penstock discharge at the start of the gate closure, Q_g is the emergency gate discharge at start of venting, Q_a is the air demand, and P_v is the vent pressure drop.

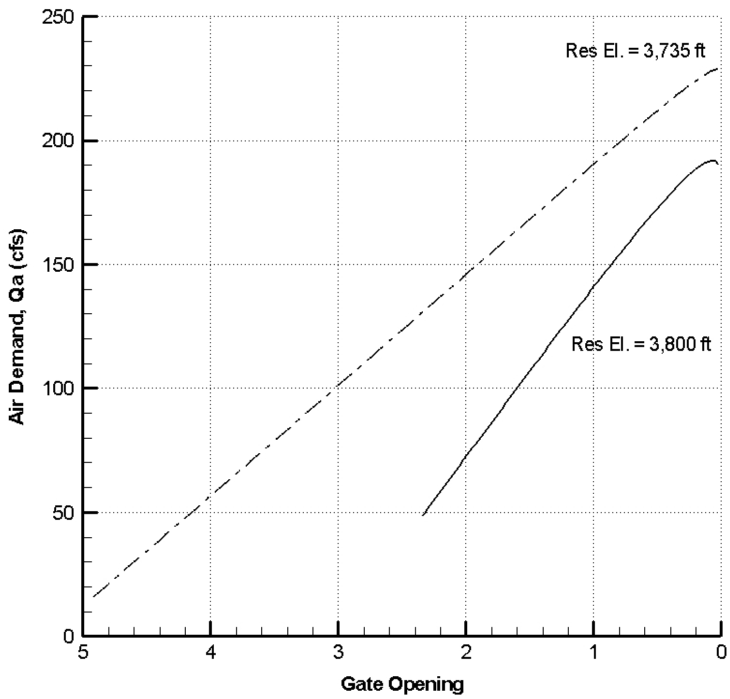


Figure 1. - Air demand versus percent gate opening for emergency gate closure test scenario for Q_i = 280 ft^3/s at minimum and maximum reservoir elevations.

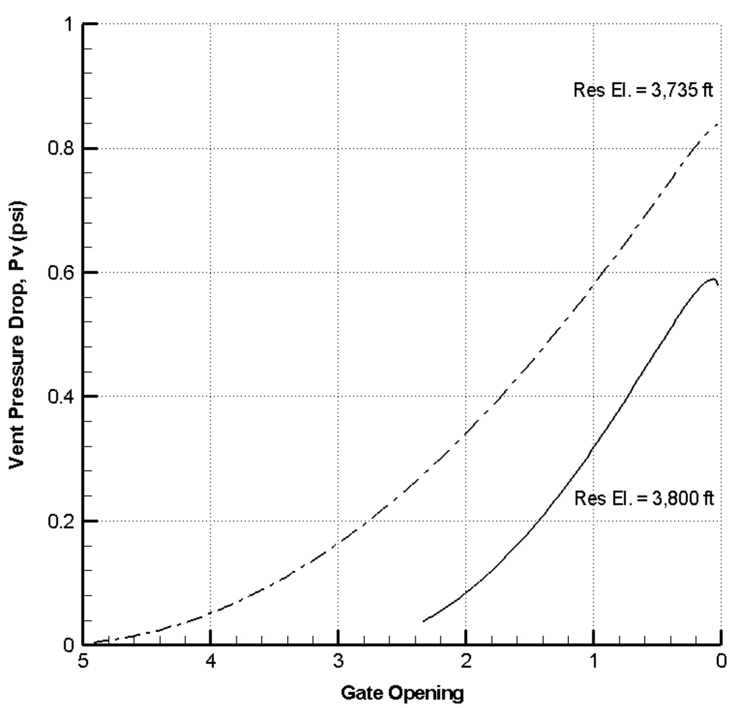


Figure 2. - Pressure drop across the vent versus percent gate opening for emergency gate closure test scenario Q_i = 280 ft^3/s at minimum and maximum reservoir elevations.

Table 1. – Summary of emergency gate closure test scenario results

Res. El. (ft)	Q_i (ft^3/s)	Start of Venting % Gate Opening	Start of Venting Q_g (ft^3/s)	Maximum Q_a (ft^3/s)	Maximum P_v (psi)
3,735	280	4.9	225	229	0.9
3,800	280	2.3	177	192	0.6

Emergency Gate Closure Maximum Discharge Scenario

The maximum discharge scenario as modeled represents the extreme cases during which an emergency gate closure would produce the largest air demands. The results indicate maximum air demands of 417 ft^3/s and 743 ft^3/s for initial penstock discharge conditions of 580 ft^3/s and 1,020 ft^3/s, respectively. These predicted air demands produce computed maximum vent pressure drops of 2.8 psi and 8.8 psi, respectively. The results suggest that larger initial penstock discharges under lower reservoir water surface elevations produce the largest air demand. For the 1,020 ft^3/s initial penstock discharge case, the internal pressure in the penstock is conservatively predicted to well exceed the allowable pressure drop based on penstock collapse pressure. Furthermore, excessive vent velocities would result from such high air demands in both cases. Figures 3 and 4 show predicted air demand and vent pressure drop as functions of percent gate position during the maximum discharge emergency gate closure scenarios. Table 2 provides a summary of the maximum discharge scenario results.

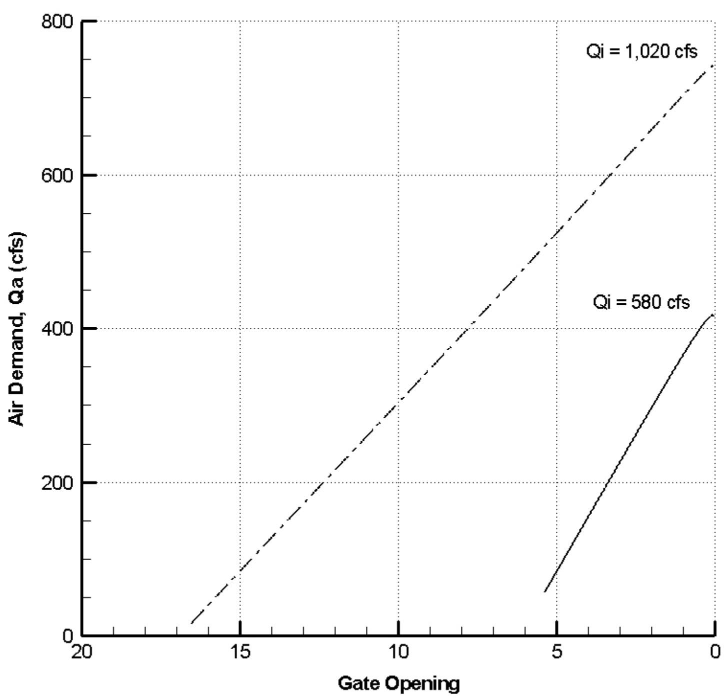


Figure 3. - Air demand versus percent gate opening for minimum reservoir El. 3,735 ft (Q_i = 1,020 ft^3/s) and maximum reservoir El. 3,800 ft (Q_i = 580 ft^3/s).

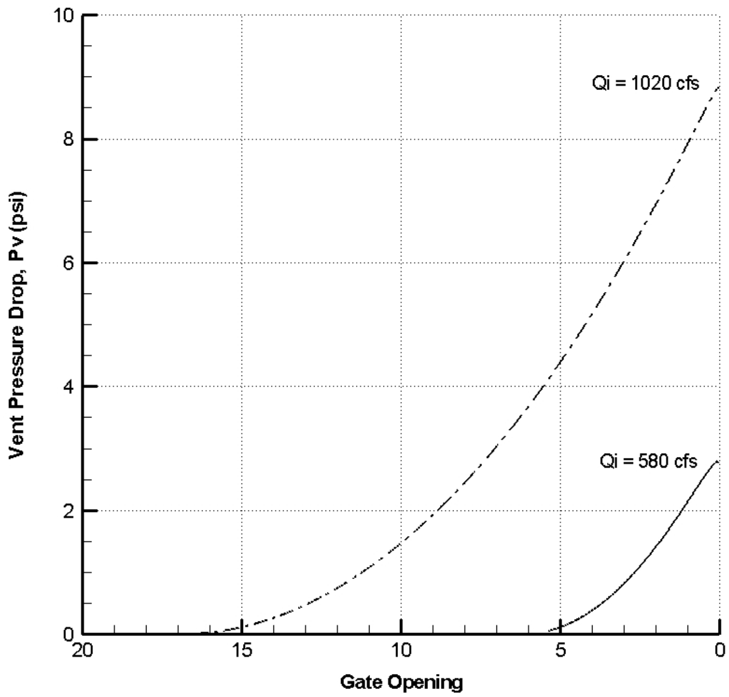


Figure 4. - Vent pressure drop versus percent gate opening minimum reservoir El. 3,735 ft (Q_i = 1,020 ft^3/s) and maximum Reservoirs El. 3,800 ft (Q_i = 580 ft^3/s).

Table 2. – Summary of emergency gate closure maximum discharge scenario results

Res. El. (ft)	Q_i (ft^3/s)	Start of Venting % Gate Opening	Start of Venting Q_g (ft^3/s)	Maximum Q_a (ft^3/s)	Maximum P_v (psi)
3,800	580	5.4	402	417	2.8
3,735	1,020	16.5	738	743	8.8

Conclusions & Recommendations

It should be pointed out that the computational model used for this analysis has not been compared with physical observations from either laboratory or field testing. While it is based on past studies that are similar, there are a number of factors that affect the uncertainty, primarily the hydraulic (head-discharge) characteristics of the pump-turbine units during an emergency gate closure. It was assumed that once the head in the penstock just downstream of the emergency gate falls below atmospheric pressure, venting begins and beyond that point, the head in the penstock at the downstream pump-turbine plant remains constant for the remainder of the gate closure. While this is a conservative means for estimating air demand, it is not a physically accurate representation. Other factors affecting uncertainty include actual losses in the vent system as well as the fixed wheel gate discharge coefficients. The bottom line is that this approach, while thought to be conservative, is approximate. Field data or physical model studies would be needed for comparison to improve the level of confidence in these results.

The results of this analysis indicate the predicted vent pressure drop for the proposed emergency gate closure test discharge of 280 ft^3/s is expected to be well below the allowable vent pressure drop taken as estimated collapse pressure and thus would not pose concerns for collapse. Nevertheless, it is imperative that the vent line be inspected prior to the emergency gate closure test. This is necessary to assure that the vent is in as-designed condition and is free of any obstructions that could increase vent losses and decrease penstock internal pressures to unacceptable levels. An inspection of the penstock is also recommended prior to testing to confirm the penstock is in good condition with emphasis on wall thickness and roundness uniformity, both of which influence buckling pressure.

In contrast to the proposed emergency gate closure test scenario, the maximum discharge scenario is predicted to produce an estimated vent pressure drop on the order of 8.8 psi which is well in excess of the estimated collapse pressure. Thus, the potential for pipe collapse under such conditions remains a concern. While not as large as the 1,020 ft^3/s discharge case, the maximum vent pressure drop for the smaller initial penstock discharge case of 580 ft^3/s still appears to be marginal.

Based on these results, it is recommended that a detailed collapse pressure analysis be completed and, if needed, that penstock stiffening be considered to ensure buckling strength is such that collapse would not be physically possible. Furthermore, the proposed emergency gate testing presents an opportunity to obtain much needed field data to support this analysis. If possible, unbalanced closure tests at three different initial discharges (e.g., 100, 200, and 280 ft^3/s) would be ideal, but a single discharge test case (i.e., the proposed 280 ft^3/s) would still be helpful for comparison with this analysis. It is recommended that the following data are collected during the emergency gate closure test:

- Gate position as a function of time during the closure would be ideal, but total closure time would suffice.
- Penstock discharge at the pump-turbine plant as a function of time during the closure.
- Penstock internal pressures as functions of time downstream of the emergency gate and just upstream of the pump-turbine plant.
- Vent velocity as a function of time at the air vent entrance (or other suitable/accessible location).

At a minimum, total gate closure time, penstock pressures at upstream and downstream ends, and penstock discharge at the pump turbine plant during the closure test would be needed. This information could then be used to refine analytical methods for improving air demand predictions for this project under the worse-case (i.e., maximum discharge) emergency gate closure scenario and other projects in the future.

References

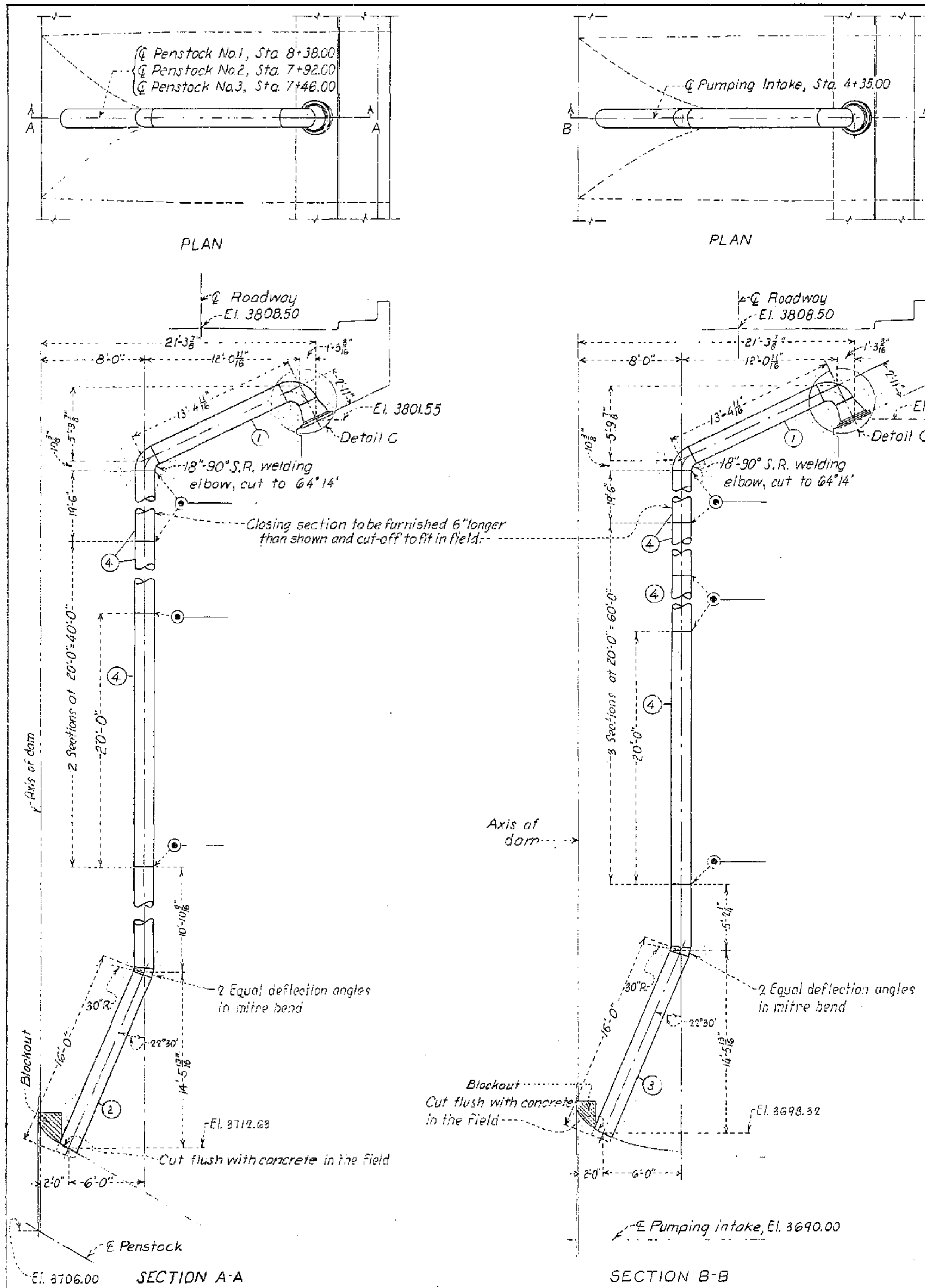
[1] Falvey, H.T., Air-Water Flow in Hydraulic Structures, Engineering Monograph No. 41, Bureau of Reclamation (1980)

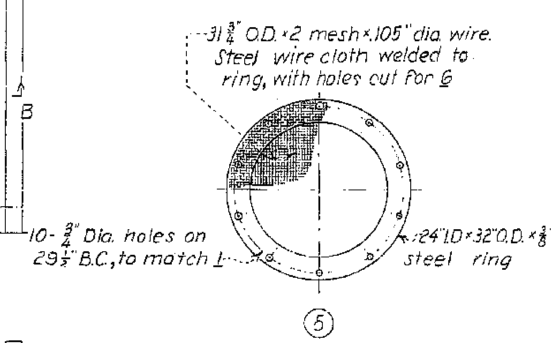
[2] Wylie, E.B. and V.L. Streeter, Fluid Transients, FEB Press (1982)

[3] Falvey, H.T., Air Vent Computations – Morrow Point Dam, HYD-584, Bureau of Reclamation (1968)

[4] Bureau of Reclamation, Designers' Operating Criteria - Helena Valley Pumping Plant, Helena Valley Unit, Montana (1959)

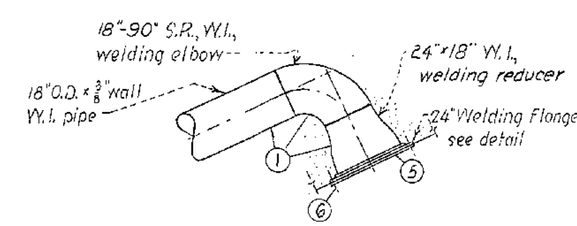
Appendix – Drawings



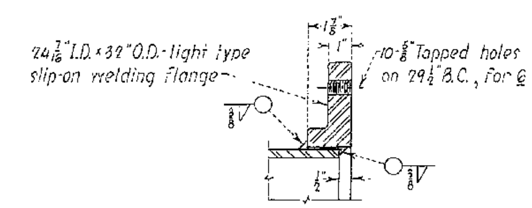


AIR SCREEN

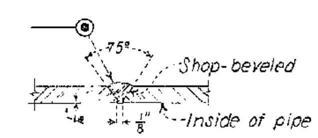
GALV. STEEL - FOUR REQUIRED



DETAIL C



TYPICAL FLANGE DETAIL



TYPICAL FIELD GIRTH JOINT

LIST OF PARTS

PART NO.	DESCRIPTION	MATERIAL	QUANTITY
1	18" O.D. × ⅜" wall pipe bend.	W.I. & steel	4
2	18" O.D. × ⅜" wall pipe bend.	WROUGHT IRON	3
3	18" O.D. × ⅜" wall pipe bend.	WROUGHT IRON	1
4	18" O.D. × ⅜" wall pipe, 20'-0" long	WROUGHT IRON	13
5	Air screen	Steel, galv.	4
6	⅝" × 2¼" Stud with hex. nut	Steel, galv.	40

GENERAL NOTE

Parts 1 to 5 inclusive shall be shop-fabricated complete as shown with flanges refaced after welding. Where field welds are indicated, prepare ends of pipe for welding. Flanges shall be steel, faced to 125# American Standard and tapped as specified.
Part 5 shall be galvanized after fabrication.
All wrought iron fittings shall be standard weight.
Each part or package shall be marked to show the drawing number and part number, thus: 236-1, etc.

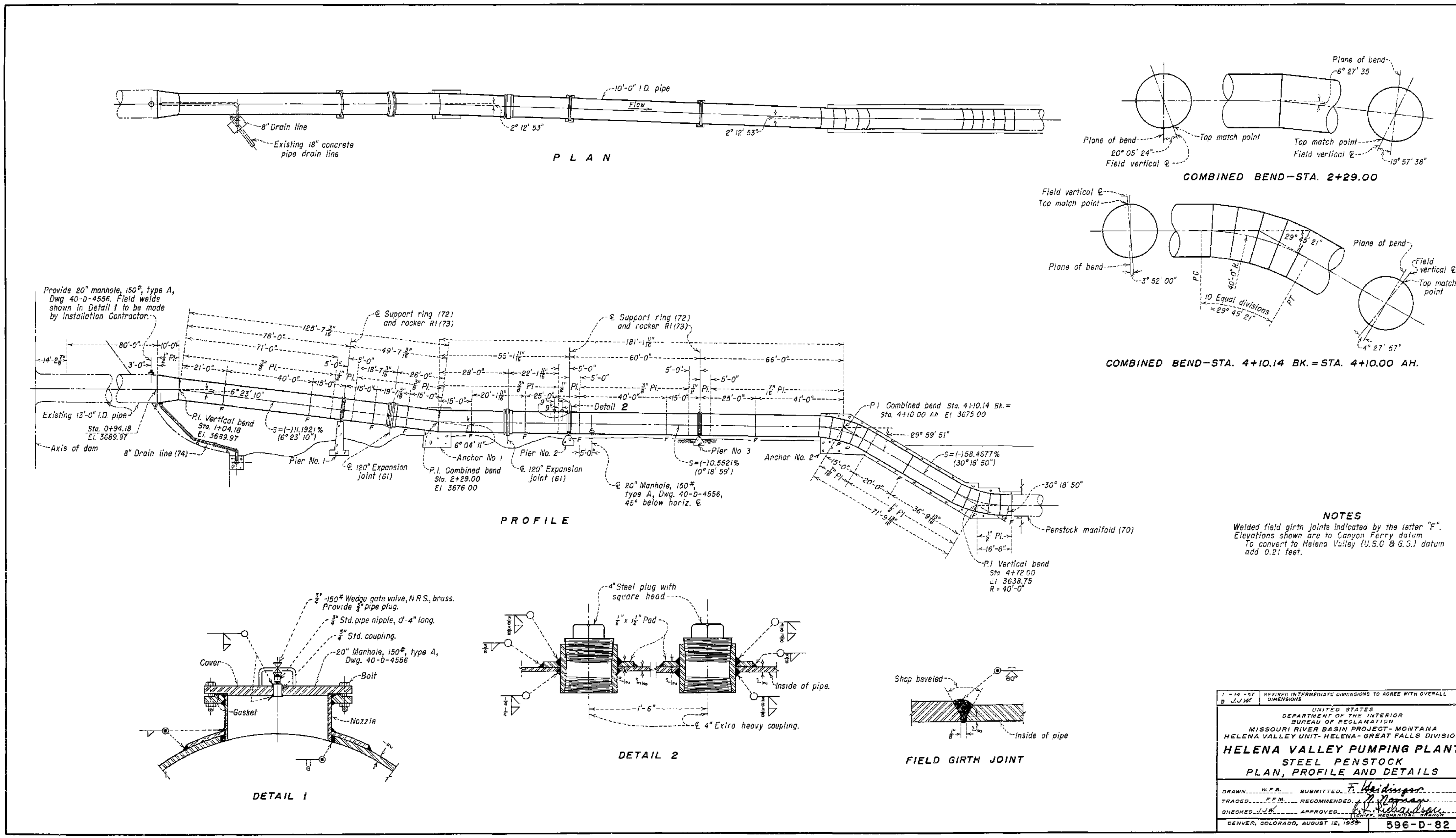
REFERENCE DRAWINGS

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
HELENA - GREAT FALLS DIVISION - CANYON FERRY UNIT - MONTANA

CANYON FERRY DAM
MAIN UNIT PENSTOCKS AND PUMPING INTAKE AIR VENT PIPING

DRAWN... P.G.M. ... SUBMITTED ... [signature]
TRACED ... RECOMMENDED ... [signature]
CHECKED R.Y. ... C.O.S. ... APPROVED ... [signature] CHIEF DESIGNING ENGINEER
DENVER, COLORADO, APRIL 14, 1949 — 296-D-236
REVISED 11-1-49

Job No. 6-296-01-01-3501


PLAN
10'-0" I.D. pipe
Flow
8" Drain line
Existing 18" concrete pipe drain line
2° 12' 53"
COMBINED BEND–STA. 2+29.00
Plane of bend
6° 27' 35
Top match point
Field vertical ℄
20° 05' 24"
19° 57' 38"
COMBINED BEND–STA. 4+10.14 BK. = STA. 4+10.00 AH.
10 Equal divisions = 29° 45' 21"
3° 52' 00"
4° 27' 57"
PROFILE
Provide 20" manhole, 150#, type A, Dwg 40-D-4556. Field welds shown in Detail 1 to be made by Installation Contractor.
Existing 13'-0" I.D. pipe
Sta. 0+94.18
El. 3689.97
Axis of dam
8" Drain line (74)
P.I. Vertical bend
Sta. 1+04.18
El. 3689.97
S=(-)11.1921%
(6° 23' 10")
Pier No. 1
℄ 120" Expansion joint (61)
P.I. Combined bend
Sta. 2+29.00
El 3676.00
Anchor No 1
Pier No. 2
℄ 20" Manhole, 150#, type A, Dwg. 40-D-4556, 45° below horiz. ℄
S=(-)0.5521%
(0° 18' 59")
Pier No 3
℄ Support ring (72) and rocker R1 (73)
Detail 2
Anchor No. 2
P.I Combined bend Sta. 4+10.14 Bk. = Sta. 4+10.00 Ah El 3675.00
29° 59' 51"
S=(-)58.4677%
(30° 18' 50")
30° 18' 50"
Penstock manifold (70)
P.I Vertical bend
Sta 4+72.00
El 3638.75
R = 40'-0"
NOTES
Welded field girth joints indicated by the letter "F".
Elevations shown are to Canyon Ferry datum
To convert to Helena Valley (U.S.C & G.S.) datum add 0.21 feet.
DETAIL 1
3/4" -150# Wedge gate valve, N.R.S. brass. Provide 3/4" pipe plug.
3/4" Std. pipe nipple, 0'-4" long.
3/4" Std. coupling.
20" Manhole, 150#, type A, Dwg. 40-D-4556
Cover
Bolt
Gasket
Nozzle
DETAIL 2
4" Steel plug with square head
1/2" x 1 1/2" Pad
Inside of pipe.
1'-6"
℄ 4" Extra heavy coupling.
FIELD GIRTH JOINT
Shop beveled
60°
Inside of pipe
1-14-57 D J.J.W. REVISED INTERMEDIATE DIMENSIONS TO AGREE WITH OVERALL DIMENSIONS
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT–MONTANA
HELENA VALLEY UNIT–HELENA–GREAT FALLS DIVISION
HELENA VALLEY PUMPING PLANT
STEEL PENSTOCK
PLAN, PROFILE AND DETAILS
DRAWN W.F.B. SUBMITTED F. Heidinger
TRACED F.F.M. RECOMMENDED
CHECKED J.J.W. APPROVED
DENVER, COLORADO, AUGUST 12, 1955
596-D-82