R-93-6

NACHES/COWICHE DIVERSION DAM SPILLWAY MODIFICATION PROJECT – FISH BARRIER STUDY

SUMMARY OF INVESTIGATIONS

April 1993

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Denver Office
Research and Laboratory Services Division
Hydraulics Branch

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16. ABSTRACT

A physical model having a scale of 2.5:1, Denver Office Hydraulic Laboratory, Bureau of Reclamation, was used to analyze the use of rubber dams and pneumatic crest gates as possible methods for preventing fish passage over the spillway at Naches/Cowiche Diversion Dam, Washington. Velocity and depth of flow data were collected and analyzed for several placements and orientations of both types of designs for a range of discharges and tailwater elevations. These data were then compared to available biological data for the fish species present at the site to determine the effectiveness of these types of designs as fish barriers. Analyses found that the Naches/Cowiche site does not allow development of sufficient head to achieve velocities in excess of the maximum fish darting velocities for steelhead; therefore, a 100-percent effective barrier cannot be ensured. Fish barrier efficiency cannot be closely estimated based on the laboratory model tests. However, the best overshot gate option for increasing barrier effectiveness is clearly the addition of a properly located crest gate. This conclusion was based on an evaluation of the combined effects of increased velocity and resulting work required to swim upstream, reduced flow depths, and abrupt changes in flow direction.

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by

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Denver Office
Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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INTRODUCTION

The PN (Pacific Northwest) Region requested the Denver Office Hydraulics Branch to conduct a study for spillway modification to the Naches/Cowiche diversion dam, located near Yakima, Washington (fig. 1). The purpose of the spillway modification is to prevent anadromous fish from bypassing an existing fish ladder and catchment facility. Currently, migrating fish are able to pass up and over the ogee crest spillway.

The two options for fish barriers studied, using a sectional model of the dam, were a water-filled rubber dam and a pneumatic crest gate, each attached to the top of the existing spillway crest.

CONCLUSIONS

- The Naches/Cowiche site does not allow the development of sufficient head to achieve velocities in excess of the maximum fish darting velocities for steelhead; therefore, a 100-percent effective barrier cannot be ensured.

- Fish barrier efficiency cannot be closely estimated based on the laboratory model tests. However, the best overshot gate option for increasing barrier effectiveness is clearly the addition of a properly located crest gate. This conclusion was based on an evaluation of the combined affects of increased velocity and the resulting work required to swim upstream, reduced flow depths, and abrupt changes in flow direction.

BACKGROUND INFORMATION

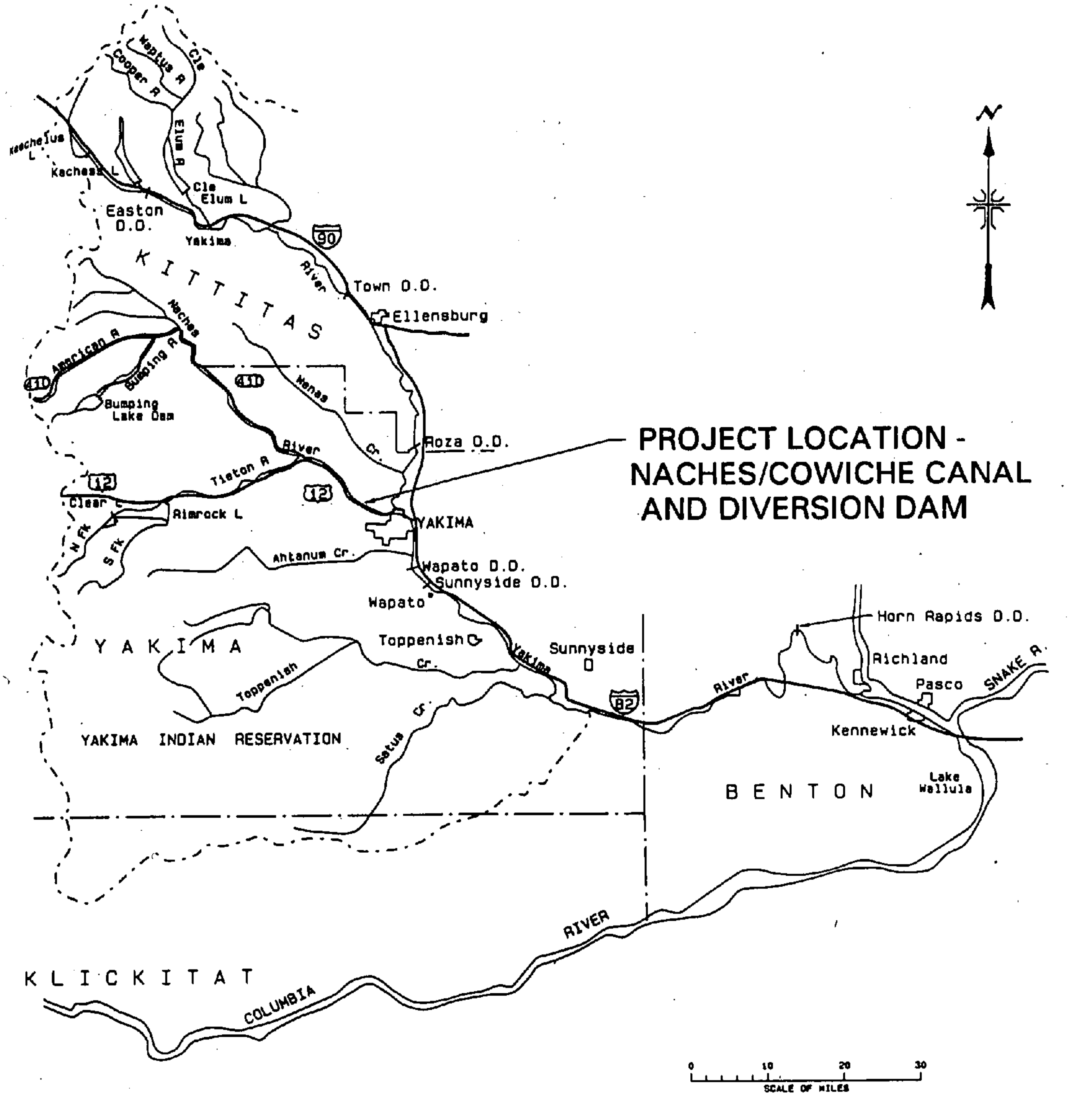
Naches/Cowiche diversion dam is located on the Naches River, about 2 mi west of Yakima, Washington. The diversion dam is a concrete ogee spillway structure, about 212.5 ft wide by 15 ft high, consisting of a 5-ft-long crest, a 21-ft-long ogee spillway, and a 21-ft-long apron.

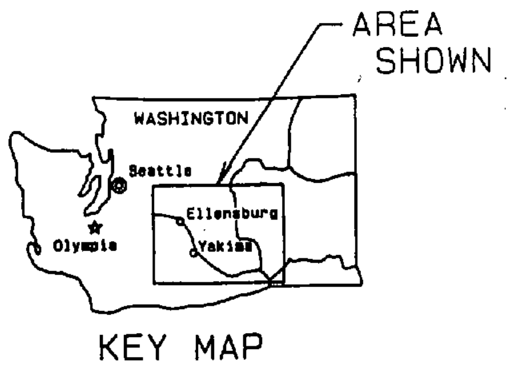
Radio tagging of spring chinook salmon and steelhead trout at the site confirmed the need to create a stronger barrier to adult fish passage. The project requires a more positive fish barrier during key periods of the year while retaining the ability to pass flood flows under conditions similar to the existing conditions. An evaluation of the operations and fish barrier needs indicated that an overshot-type structure that could be raised and lowered would best meet the requirements.

Fish Barrier Criteria

Two basic designs for fish barrier dams have been developed:

- One design is based on creating a barrier by maintaining, at all streamflows, a drop of sufficient height to prevent fish migration upstream. To be effective for salmon and trout species, this type of barrier requires at least 10 ft of free overfall. This design was not feasible for Naches/Cowiche diversion dam.





UNITED STATES
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BUREAU OF RECLAMATION
YAKIMA PROJECT - WASHINGTON
FISH PASSAGE AND PROTECTIVE FACILITIES

GENERAL
LOCATION MAP

DESIGNED ______ SUBMITTED
DRAWN Ed Nordhorst/DAS RECOMMENDED
CHECKED APPROVED
REGIONAL ENGINEER
BOISE, IDAHO JUNE 1991 33-100-1669

Figure 1. - Location map - Naches/Cowiche Canal.

- The second design will minimize flow depth; maximize velocity; and include, where possible, sharp changes in the flow direction. For the Naches/Cowiche site, these fish barrier criteria were incorporated by testing the addition of overshot-type gates on the spillway crest. When necessary, an overshot-type gate can be raised to increase the net head drop across the structure. Increasing the head decreases the flow depth and increases the velocity on the spillway. In addition, downstream from the gate, a sudden change in flow direction can be created where the flow nappe impinges on the spillway.

  The principles of this type of barrier are as follows: For a fish to swim along the spillway, it must negotiate the high velocities and low depths created on the spillway. The fish must then ascend the dam or gate structure, which would require a sudden change in vertical direction.

Flow Velocity Barrier. — Bell (1991) lists the sustained swimming speeds of Chinook salmon and steelhead as 11 and 15 ft/s, respectively. In addition, darting speeds of steelhead trout are estimated to reach about 26 ft/s for a short duration. Darting speeds can be maintained for about 5 to 10 s under optimum conditions.

To achieve a 100-percent effective fish barrier at Naches/Cowiche diversion dam, based solely on maximum velocity, the structure must create flows with maximum velocities of at least 26 ft/s (maximum darting speed for steelhead). The head drop required to achieve barrier velocities (assuming no losses) can be estimated as:

$$H_d = V^2/(2g) \tag{1}$$

where:

H_d = difference in elevation between the upstream reservoir surface and the tailwater (ft)
V = maximum darting velocity (ft/s)
g = acceleration of gravity (ft/s^2)

Substituting a velocity of 26 ft/s velocity into equation 1 gives a required head drop across the structure of at least 10.5 ft. The maximum desirable reservoir elevation at Naches/Cowiche dam is elevation 1171 ft. Given tailwater elevations listed in table 1, insufficient head is available to create a total fish barrier based solely on maximum velocity.

Table 1. — Discharges and corresponding tailwater elevations for Naches/Cowiche diversion dam.

Discharge (ft^3/s)	Tailwater elevation (ft)
1,000	1161.26
2,000	1162.18
3,000	1163.03
4,000	1164.24

A barrier can also be established by creating flow velocities greater than the sustained swimming speed of the fish species (velocities greater than 15 ft/s for steelhead) for a sufficient distance. Assuming an average darting duration of 7.5 seconds as given by Bell, the average darting distance of a steelhead can be estimated as:

$$D_m = 7.5 * (26 - V_a) \tag{2}$$

where:

D_m = maximum darting distance (ft)
V_a = average flow velocity over the distance traveled (ft/s)

For a known structure length, equation 2 can also be used to determine the average velocity required on the spillway face to prevent passage. The length of high velocity flow at Naches/Cowiche is roughly between the spillway crest and the tailwater, or about 12 ft. Substituting a distance of 12 ft into equation 2 gives a required average velocity of 24.5 ft/s along the entire 12-ft length. With the limited available head at Naches/Cowiche, these criteria are also unattainable.

Flow Depth Barrier. — When combined with flow velocities in the darting range, it is generally excepted that depths less than about 0.5 to 0.67 ft are effective barriers (Wagner, 1967).

Flow Direction Barrier. — The most difficult aspect of a barrier to evaluate is the effect of abrupt changes in the flow direction or turbulence levels encountered by migrating fish. Wagner cites other fish barriers which have shown that free jets impinging in shallow flow where maneuvering is limited are highly effective.

Therefore, in the model study, the combination of fish barrier parameters (high velocities, shallow depths, and rapid changes in the flow direction) of each overshot-type structure were evaluated in comparison to the performance of the as-built structure.

Rubber Dam Studies

Rubber dams can be attached to an existing hydraulic structure to increase hydraulic head, thereby increasing velocities downstream. Rubber dams consist of a tube, normally constructed of rubber laminated with nylon reinforcing plies, anchored to a foundation in a watercourse or to an existing hydraulic structure. There are two main types of rubber dams: air-filled and water-filled. Piping and a compressor or pump permit the flow of air or water into and out of the rubber body, thereby raising and lowering it.

The air-filled dam, because of its supply and discharge systems, is relatively simple and economical and has operating advantages. However, air-filled rubber dams tend to V-notch in the center of the tube when partially inflated. This V-notch action can diminish the barrier effectiveness because fish could likely pass through the notch area. Therefore, an air-filled rubber dam requires full inflation to perform as an effective fish barrier.

Manufacturers claim water-filled rubber dams are less subject to V-notching than the air-filled, although no manufactures were able to provide test data on V-notching of water-filled dams. The placement of water-filled dams is restricted, because they must be mounted on a horizontal surface large enough to support the deflated size of the dam. A horizontal surface is necessary to ensure the dam deflates completely.

Pneumatic Crest Gate Studies

The second type of overshot gate tested was a pneumatic activated crest gate. The crest gate system consists of a row of steel panels hinged and anchored to the spillway along the gate's upstream edge. The steel panels are raised by an inflatable air bladder located downstream from the gate hinge point. The gates can be operated between 0° and about 60° referenced to the plane of the hinge point. Thus, the upstream pool elevation is controlled by the angle at which the steel panels are inclined in the direction of flow.

Some of the advantages of pneumatic crest gates as given by the manufacturers are:

(1) They provide accurate automatic pool elevation control even under power failure conditions;

(2) Unlike steel crest gates, pneumatic crest gate panels are supported for their entire width by an inflatable bladder, resulting in simple foundation requirements and a cost-effective and efficient structure;

(3) The thin profile of the gate efficiently passes flood flows, ice, and debris;

(4) Unlike rubber dams, the steel panels overhang the rubber bladder in all positions, thereby protecting the bladder from floating logs, debris, ice, etc.; and

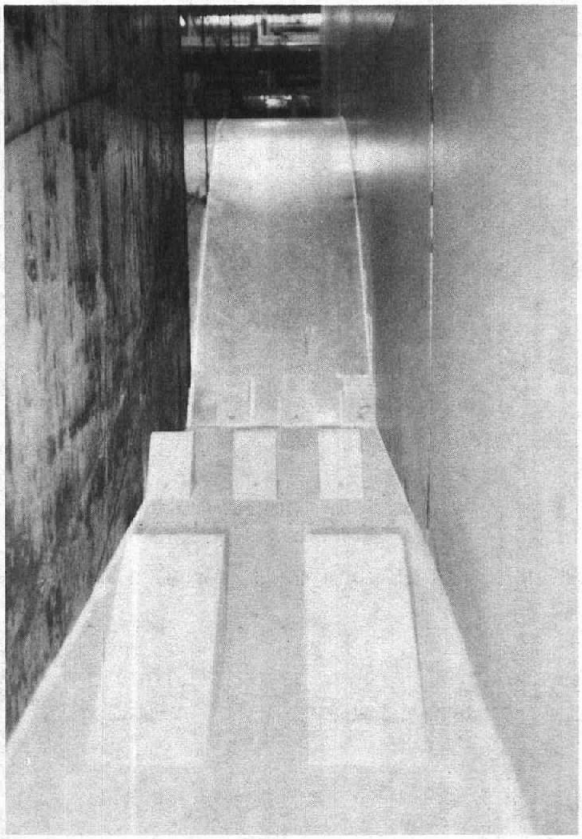
(5) The gates have low maintenance and installation costs.

MODEL TESTS

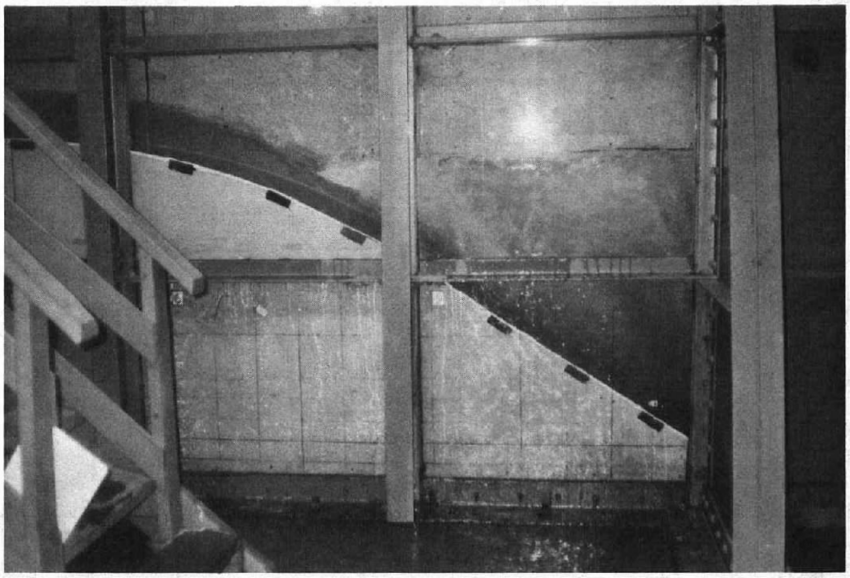
A 4-ft-wide by 8-ft-high by 90-ft-long glass-walled laboratory flume was used for the study. The flume was modified to a 2-ft width for the Naches/Cowiche model. A 2.5:1 Froude scale sectional model including the dam crest, ogee spillway, and stilling basin were constructed in the flume (fig. 2). The model scale was chosen based on modeling a maximum prototype unit discharge of 23.9 $ft^3/s/ft$.

Dimensions of the spillway and stilling basin were taken from drawings provided by the PN Region. Tests were conducted at discharges and tailwater conditions as given in table 1. The maximum permissible upstream pool elevation was given as 1171 ft.

Depth measurements along the spillway were taken at stations every 0.8 ft in the model (2.0 ft prototype), beginning at the crest PC (point of crest curvature). These points are referred to in the data as $X = 0$ ft, $X = 2.0$ ft, etc. Six points along the spillway were evaluated. Where possible, depths were measured vertically and then converted to normal depths perpendicular



(a) Upstream view of the 2-ft-wide sectional model of Naches/Cowiche diversion dam.



(b) Side view of water passing over the as-built spillway.

Figure 2. — Views of sectional model.

to the spillway surface. Table 2 summarizes these values for several tests performed. The flow downstream from the ogee crest was typically fast-shallow-aerated flow in the model. In many instances, the combination of small depths, large velocities, and air entrainment prevented measuring the depth or velocity. Therefore, depth and velocity estimates were calculated using the upstream total head measured in the model for locations downstream from $X = 6$ ft. Table 3 summarizes these calculated values. Velocities were calculated from total head assuming no losses. Depths were then calculated based on flow continuity. This procedure results in maximum possible velocities and minimum possible depths at each station. For the flow conditions witnessed in the model, this procedure of calculating spillway chute flow data should closely model prototype conditions.

Discharge coefficients for all structures were calculated using the general equation for a sharp-crested weir under free flow conditions:

$$C = \frac{Q}{L * H^{1.5}} \tag{3}$$

where:

C = coefficient of discharge
Q = discharge (ft^3/s)
L = length (ft)
H = total head above weir (ft)

As-built Structure Test Results

Initially, flow depths and average velocities over the as-built structure (fig. 3) were measured for flows up to 4,500 ft^3/s. These data were used as a basis for evaluating flow changes achieved by installing each fish barrier option.

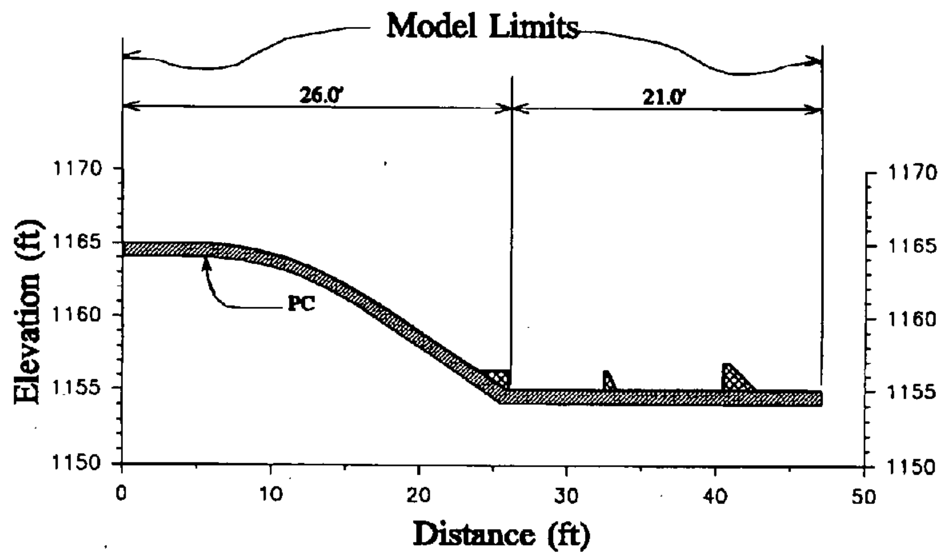


Figure 3. — Elevation view of section through center of Naches/Cowiche diversion dam.

Table 2. — Measured flow velocities and depths within the first 4 ft (horizontal) downstream from the crest PC.

Discharge (ft^3/s)	Structure type	Location downstream from ogee crest PC						Reservoir elevation (ft)
		$X = 0$ ft		$X = 2$ ft		$X = 4$ ft		
		V_m	Depth	V_m	Depth	V_m	Depth	
2,000	As-built	11.2	0.94	11.6	0.91	13.3	0.79	1167.00
	Rubber dam	9.1	1.16	14.1	0.75	17.4	0.61	1170.32
	Crest gate, $P_p = 4.17$ ft	No data		No data		No data		
	Crest gate, $P_p = 1.67$ ft	No data		No data		No data		
	Crest gate, $P_p = 1.25$ ft	6.8	1.61	No data		18.7	0.57	1170.00
3,000	As-built	12.1	1.31	13.0	1.22	14.8	1.07	1167.85
	Rubber dam	10.7	1.48	15.7	1.01	19.1	0.83	1170.37
	Crest gate, $P_p = 4.17$ ft	5.9	2.71	14.1	1.13	19.5	0.82	1170.20
	Crest gate, $P_p = 1.67$ ft	No data		No data		No data		1170.65
	Crest gate, $P_p = 1.25$ ft	7.62	2.10	No data		19.8	0.80	1170.65
4,500	As-built	13.6	1.75	14.8	1.61	15.7	1.52	1168.92
	Rubber dam	10.6	2.25	16.0	1.49	18.7	1.28	1171.20
	Crest gate, $P_p = 4.17$ ft	5.9	4.06	11.0	2.17	18.9	1.26	1171.05
	Crest gate, $P_p = 1.67$ ft	No data		No data		No data		1171.47
	Crest gate, $P_p = 1.25$ ft	8.8	2.70	No data		20.9	1.14	1171.45

[1] P_p = crest gate pivot point.

Table 3. — Flow velocities and depths between 6 and 12 ft (horizontal) downstream from the crest PC. Values were calculated using head drop across the dam and gate structures.

Discharge (ft^3/s)	Structure type	Location downstream from ogee crest PC								Discharge coefficient	Reservoir elevation (ft)
		X = 6 ft		X = 8 ft		X = 10 ft		X = 12 ft			
		V_m	Depth	V_m	Depth	V_m	Depth	V_m	Depth		
1,000	As-built	11.2	0.47	13.3	0.40	14.6	0.36	17.8	0.30	5.70	1165.95
2,000	As-built	13.9	0.76	15.6	0.68	17.5	0.60	19.7	0.53	3.75	1167.00
	Rubber dam	20.2	0.52	21.4	0.50	22.8	0.46	24.5	0.43	2.99	1170.32
	Crest gate, P_p = 4.17 ft	No data		No data		No data		No data			No data
	Crest gate, P_p = 1.67 ft	No data		No data		No data		No data			No data
	Crest gate, P_p = 1.25 ft	19.6	0.54	20.9	0.51	22.3	0.47	24.1	0.44	3.74	1170.00
3,000	As-built	15.7	1.01	17.2	0.92	19.0	0.78	Below tailwater		3.30	1167.85
	Rubber dam	20.3	0.78	21.5	0.74	22.9	0.69	Below tailwater		4.34	1170.37
	Crest gate, P_p = 4.17 ft	20.0	0.79	21.2	0.75	22.7	0.70	Below tailwater		4.86	1170.20
	Crest gate, P_p = 1.67 ft	20.7	0.77	21.9	0.73	23.3	0.68	Below tailwater		3.68	1170.65
	Crest gate, P_p = 1.25 ft	20.7	0.77	21.9	0.73	23.3	0.68	Below tailwater		3.68	1170.65
4,500	As-built	17.8	1.34	19.2	1.25	20.8	1.15	Below tailwater		3.07	1168.92
	Rubber dam	21.5	1.11	22.7	1.05	24.0	0.99			4.17	1171.20
	Crest gate, P_p = 4.17 ft	21.3	1.12	22.5	1.06	23.9	1.00			4.48	1171.05
	Crest gate, P_p = 1.67 ft	21.9	1.09	23.0	1.04	24.4	0.98			3.68	1171.47
	Crest gate, P_p = 1.25 ft	21.9	1.09	23.0	1.04	24.4	0.98			3.69	1171.45

[1] P_p = crest gate pivot point.

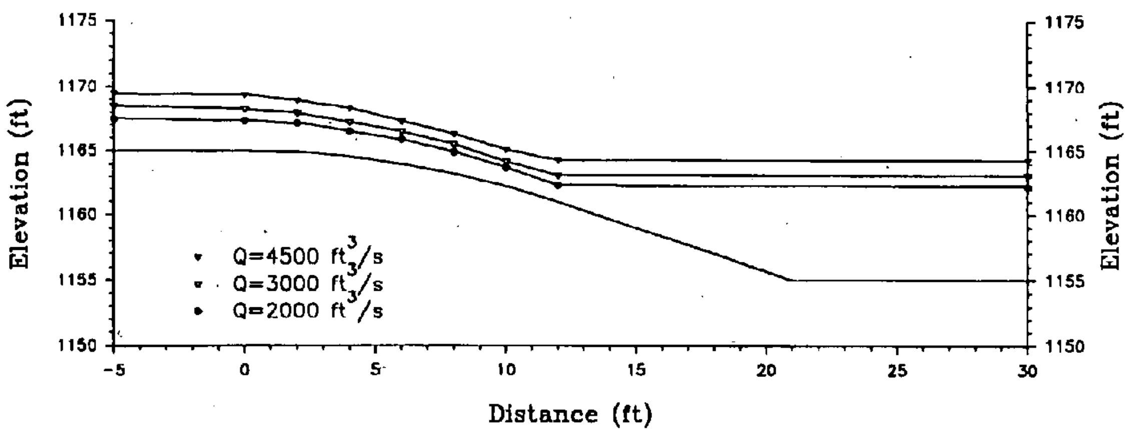
The following summarizes data for the as-built structure. The complete data are given in tables 2 and 3. Water surface profiles are plotted on figure 4.

- ***Discharge at 1,000 ft³/s.*** — The maximum velocity attained was about 18 ft/s near the tailwater contact. Depths less than 0.5 ft were attained near X = 6 ft and beyond. The upstream pool elevation was 1166.0 ft.

- ***Discharge at 2,000 ft³/s.*** — The maximum velocity attained was about 20 ft/s near the tailwater contact. A depth of 0.5 ft was attained at the tailwater contact. The upstream pool elevation was 1167.0 ft. The discharge coefficient was 3.8.

- ***Discharge at 3,000 ft³/s.*** — The maximum velocity attained was about 19.0 ft/s near the tailwater contact. Depths less than 0.5 ft were not attained. The minimum depth attained was 0.8 ft at X = 10 ft. The upstream pool elevation was 1167.8 ft. The discharge coefficient was 3.3.

- ***Discharge at 4,500 ft³/s.*** — The maximum velocity attained was about 21 ft/s near the tailwater contact. Depths less than 0.5 ft were not attained. The minimum depth attained was 1.1 ft at the tailwater contact. The upstream pool elevation was 1168.9 ft. The discharge coefficient was 3.1.



Note: Zero = PC.

Figure 4. — Water surface profiles for as-built conditions.

Rubber Dam Tests

The test section geometry and discharge characteristics of the water-filled rubber dam were based on information provided by Bridgestone Engineered Products Company. The rubber dam section was constructed of plywood ribs and a sheet metal skin. The implications of modeling a water-filled dam with a rigid model were discussed with the Bridgestone engineers. It was concluded that a water-filled rubber dam is essentially incompressible, and therefore, a rigid model would be satisfactory. A 2-in-diameter model air vent was placed on the side wall just downstream from and below the nappe breaker to provide aeration to the lower flow nappe. The rubber dam was not tested for partially inflated conditions, because no information could be obtained on the rubber dam shape.

Tests were conducted for a 3-ft-high rubber dam located 8.5 ft upstream from the crest PC (the minimum foundation width, including the clamping mechanism, required to accommodate deflating the rubber dam) (fig. 5). Discharge flows of 2,000, 3,000, and 4,500 ft^3/s were tested at this location. In evaluating the rubber dam performance, the laboratory study considered factors such as upstream pool elevation, depth of water on the spillway crest, water velocity, and flow nappe profile. Videos were taken of all tests.

Rubber Dam Test Results

Flow over the rubber dam separated off the nappe breaker fin located near the dam crest. Within the separation zone a backflow eddy occurred for flows above 2,000 ft^3/s. To estimate the eddy strength, dye was injected into the recirculation zone. The dye revealed the separation zone to be relatively tranquil with a weak circulating eddy.

The following summarizes data for the rubber dam structure. The complete data are given in tables 2 and 3. Water surface profiles are plotted on figure 6.

- ***Discharge at 1,000 ft^3/s.*** — No data were taken for this flow because as-built flow depths were less than 0.5 ft down much of the spillway face.

- ***Discharge at 2,000 ft^3/s.*** — A maximum velocity of 24.5 ft/s occurred on the spillway near the tailwater contact. Depths less than 0.5 ft were attained at $X = 8$ ft and beyond. The upstream pool elevation was 1170.3 ft. The discharge coefficient was 3.0.

- ***Discharge at 3,000 ft^3/s.*** — The velocity and depth at the tailwater contact were about 23 ft/s and 0.7 ft, respectively. The upstream pool elevation was 1170.4 ft. The discharge coefficient was 4.3. Velocities exceed the sustained swimming speed for steelhead between $X = 4$ and $X = 10$.

- ***Discharge at 4,500 ft^3/s.*** — The velocity and depth at the tailwater contact were about 24 ft/s and 1.0 ft, respectively. The upstream pool elevation was 1171.2 ft, which exceeds the maximum allowable upstream pool elevation by 0.2 ft. The discharge coefficient was 4.2. Velocities exceeded the sustained swimming speed for steelhead between $X = 2$ and $X = 10$.

Pneumatic Crest Gate Model Tests

The test section geometry for the pneumatic crest gate consisted of a 2-ft-wide by 1.4-ft-long by 3/4-in-thick plywood plank braced underneath by 2- by 4-in boards. The length of the gate was determined based on a crest gate set at an angle of 60° (from horizontal), with a height of 1.2 ft (3.0 ft prototype), to duplicate the rubber dam conditions. A 2-in-diameter model air vent was placed on the side wall just downstream from and below the top of the gate to aerate the flow nappe.

The barrier effectiveness of the crest gate option was also optimized by investigating the best location for placement on the crest, taking into consideration: velocity and flow depths downstream from the barrier, nappe impingement location and attachment to the spillway crest, depths of ponded water beneath the barrier, and performance under maximum and intermediate discharges.

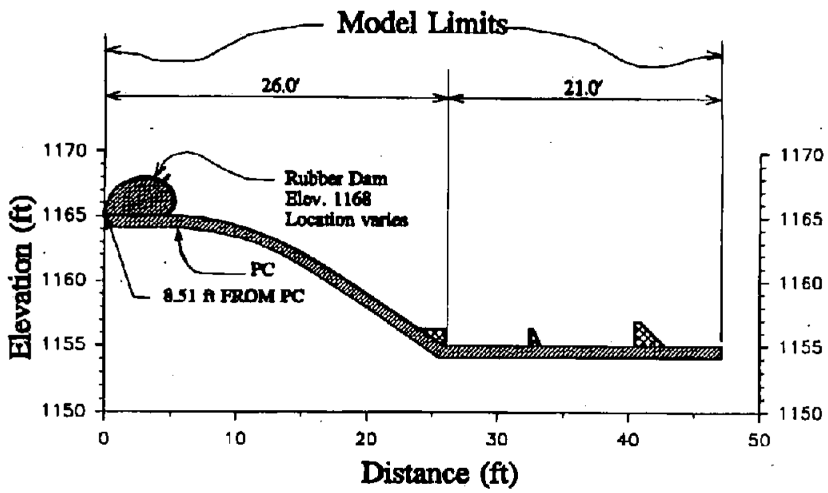
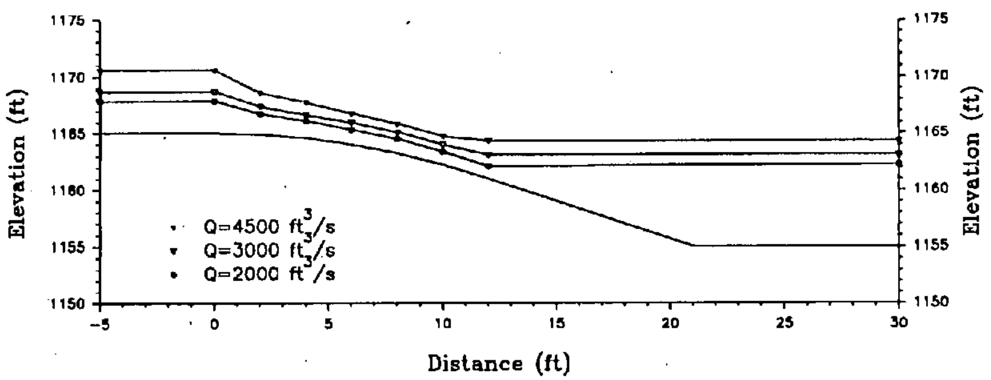


Figure 5. — Elevation view of water-filled rubber dam mounted on the spillway crest.



Note: Zero = PC.

Figure 6. — Water surface profiles for rubber dam.

Initially, the crest gate was set at a 60° angle and tested at three different pivot point positions on the spillway crest—4.17, 1.67, and 1.25 ft upstream from the crest PC (fig. 7). At the 4.17-ft location the nappe was suppressed for all flow conditions tested. To obtain an aerated condition in the separation zone, the gate was moved downstream until the flow passing over the gate impinged downstream from the crest PC. By impinging the flow on the downward sloping surface of the spillway face, the strength of the backflow component was reduced. Mounting the gate 1.67 ft upstream from the crest PC created an aerated condition for flows up to about 3,000-ft^3/s. To maintain an aerated nappe at 4,500-ft^3/s required the gate be moved to 1.25 ft upstream from the crest PC. Although aerated, the impinging jet forces a backflow pool between the gate and the jet impingement point. Small depths of pooling were felt to be desirable should fish reach the gate and attempt to jump the structure. Obviously, large pool depths behind the gate are not desirable if they provide a resting zone for fish and adequate room for the fish to negotiate jumping over the crest gate.

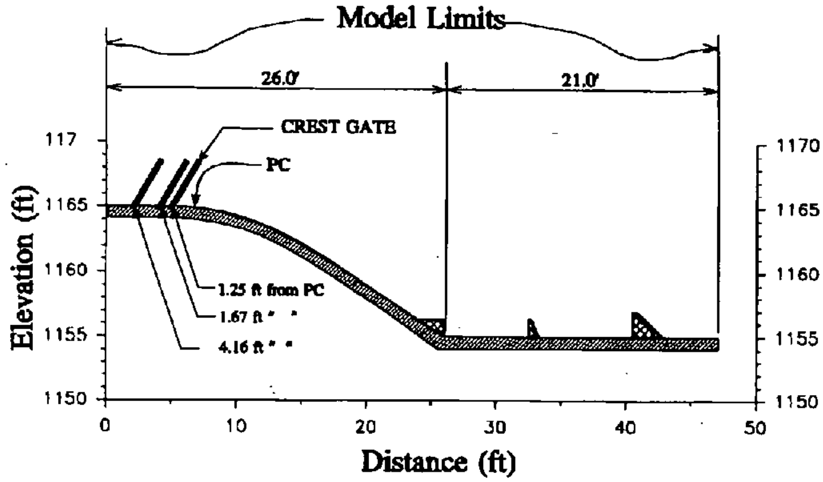


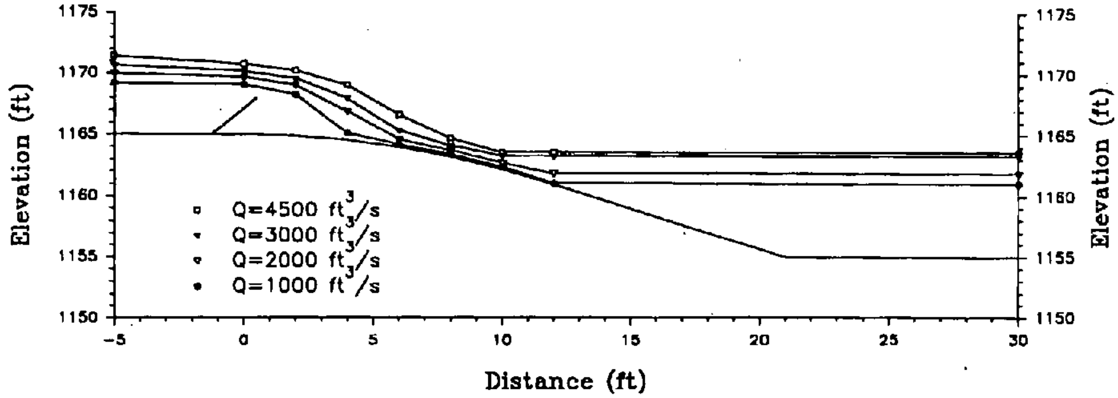
Figure 7. — Elevation view of crest gate test locations.

Operating under suppressed conditions, the crest gate, set at 60°, develops flow depths and velocities on the spillway face that are similar to those measured for the rubber dam. The reduced pressures that develop along the lower flow nappe under suppressed conditions increase the gate discharge coefficient and the average flow velocity downstream from the gate. However, a suppressed nappe eliminates a free impinging jet downstream from the gate, creates a relatively calm area of water immediately downstream from the gate in which fish could rest, and the fluctuating pressures under the gate may contribute to gate vibration.

Pneumatic Crest Gate Test Results

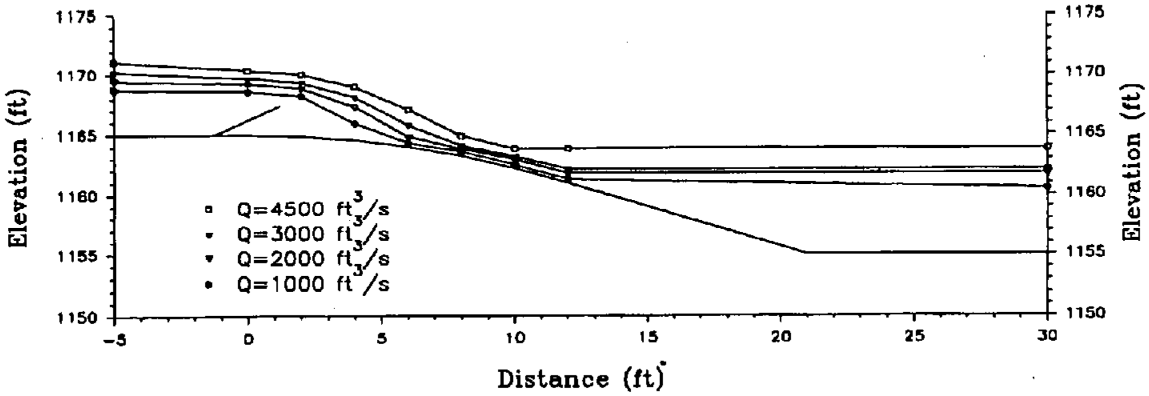
Flow data for a 60° gate angle, including all gate locations on the spillway crest, are given in tables 2 and 3. For the final configuration, the gate was moved forward to 1.25 ft upstream from the PC to sustain an aerated nappe. The following summarizes flow conditions with the pneumatic crest gate structure set at 60° and located 1.25 ft upstream from the PC.

Crest gate located 1.25 ft upstream from the ogee PC. — At the 1.25-ft location the gate was tested at gate angles of 60°, 45°, and 15°. Water surface profiles for each gate angle are plotted on figures 8, 9, and 10, respectively. Free flow was obtained for all tests except for higher flows with the crest gate angle at 15°. For aerated conditions, the backflow from the jet impingement on the spillway surface sustains a pool behind the flow nappe. Both the depth of the back-flow pool and the centerline location of the jet impingement are given in table 4.



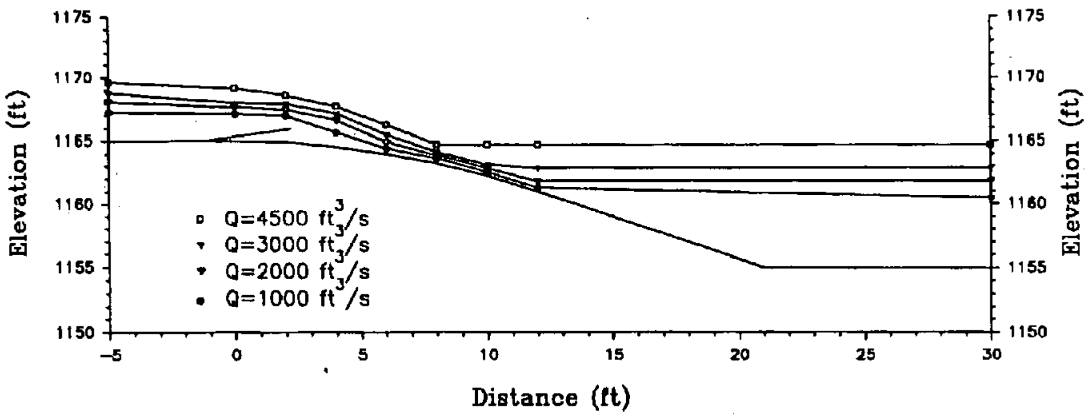
Note: Zero = PC.

Figure 8. — Water surface profiles for crest gate at 60°, located 1.25 ft upstream from PC.



Note: Zero = PC.

Figure 9. — Water surface profiles for crest gate at 45°, located 1.25 ft upstream from PC.



Note: Zero = PC.

Figure 10. — Water surface profiles for crest gate at 15°, located 1.25 ft upstream from PC.

Table 4. — Hydraulic data with the crest gate located 1.25 ft upstream from the crest PC and at a 60°angle. The 60° angle corresponds to a vertical gate height of 3.00 ft.

Summary of results				
Discharge (ft^3/s)	1,000	2,000	3,000	4,500
Reservoir elevation (ft)	1169.20	1169.98	1170.65	1171.45
Pool depth behind gate (ft)	0.95	1.25	1.40	1.48
Nappe impingement point (ft) (horizontal from crest PC)	3.90	4.95	5.60	5.95
Total head on gate (ft) $\leftarrow H_t$	15.08	15.85	16.52	17.32
Discharge head (ft) $\leftarrow H_c$	1.20	1.98	2.65	3.45
Discharge coefficient $\leftarrow C$	4.03	3.82	3.68	3.73

Depth and velocity data along spillway

Discharge — PC dist	1,000		2,000		3,000		4,500	
	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)
$X = 0.0$ ft	4.06	1.30	4.69	2.26	5.18	3.07	5.77	4.14
$X = 2.0$ ft	3.36	1.58	4.10	2.59	4.63	3.43	5.31	4.50
$X = 4.0$ ft	0.56	9.48	2.34	4.54	3.34	4.76	4.35	5.49
$X = 6.0$ ft	0.20	26.93	0.59	17.90	1.31	12.16	2.53	9.43
$X = 8.0$ ft	0.19	27.95	0.48	22.32	0.83	19.13	1.38	17.31
$X = 10.0$ ft	0.18	29.19	0.45	23.32	TW[1]	NA[2]	1.20	19.95
$X = 12.0$ ft	TW[1]	NA[2]	TW[1]	NA[2]	TW[1]	NA[2]	TW[1]	NA[2]

[1] = tailwater.
[2] = not applicable.

Crest Gate at 60°. —

- ***Discharge at 2,000 ft³/s.*** — A maximum velocity of 24.1 ft/s occurred on the spillway near the tailwater contact. Depths less than 0.5 ft were attained at X = 8 ft and beyond. The upstream pool elevation was 1170.0 ft. The discharge coefficient was 3.8.

- ***Discharge at 3,000 ft³/s.*** — The velocity and depth at the tailwater contact were about 23.3 ft/s and 0.7 ft, respectively. The upstream pool elevation was 1170.6 ft. The discharge coefficient was 3.7. Velocities exceeded the sustained swimming speed for steelhead between $X = 6$ and $X = 10$.

- ***Discharge at 4,500 ft³/s.*** — The velocity and depth at the tailwater contact were about 24.4 ft/s and 1.0 ft, respectively. The upstream pool elevation was 1171.45 ft, which exceeds the maximum pool elevation by 0.45 ft. The discharge coefficient was 3.7. Velocities exceeded the sustained swimming speed for steelhead between $X = 6$ and $X = 10$.

Additional tests of the crest gate were made with the gate angle set at 45° and 15° above horizontal. These tests were conducted to evaluate flow characteristics over the structure at partial openings. The hydraulic data from these partial gate opening tests are given in tables 5 and 6.

The gate must be lowered to an angle of about 45° (height of 2.45 ft) to pass 4,500 ft³/s at the maximum reservoir elevation, 1171.0 ft. At this gate position, the velocity and depth at the tailwater contact were about 22.4 ft/s and 0.94 ft, respectively. The discharge coefficient was 3.5.

Table 5. — Hydraulic data with the crest gate located 1.25 ft upstream from the crest PC and lowered to a 45° angle. The 45° angle corresponds to a vertical gate height of 2.45 ft.

Summary of results

Discharge (ft³/s)		1,000	2,000	3,000	4,500
Reservoir elevation (ft)		1168.75	1169.50	1170.20	1171.02
Pool depth behind gate (ft)		0.78	1.05	1.20	1.30
Nappe impingement point (ft) (horizontal from crest PC)		4.18	5.18	5.90	6.42
Total head on gate (ft)	$\leftarrow H_t$	14.62	15.38	16.08	16.90
Discharge head (ft)	$\leftarrow H_c$	1.30	2.05	2.75	3.58
Discharge coefficient	$\leftarrow C$	3.57	3.61	3.48	3.53

Depth and velocity data along spillway

Discharge	1,000		2,000		3,000		4,500	
PC dist	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)
$X = 0.0$ ft	3.63	1.46	4.25	2.50	4.71	3.38	5.36	4.46
$X = 2.0$ ft	3.32	1.60	3.97	2.68	4.43	3.59	5.06	4.72
$X = 4.0$ ft	1.35	3.93	2.72	3.90	3.49	4.56	4.33	5.52
$X = 6.0$ ft	0.29	18.32	0.79	13.36	1.67	9.50	2.94	8.12
$X = 8.0$ ft	0.32	16.45	0.53	19.84	0.80	20.01	1.52	15.71
$X = 10.0$ ft	0.23	23.30	0.63	16.96	0.83	19.14	TW[1]	NA[2]
$X = 12.0$ ft	0.23	23.49	0.67	15.82	TW[1]	NA[2]	TW[1]	NA[2]

[1] = tailwater.
[2] = not applicable.

Table 6. — Hydraulic data with the crest gate located 1.25 ft upstream from the crest PC and lowered to a 15° angle. The 15° angle corresponds to a vertical gate height of 0.92 ft.

Summary of results

Discharge (ft^3/s)	1,000	2,000	3,000	4,500
Reservoir elevation (ft)	1167.27	1168.10	1168.75	1169.65
Pool depth behind gate (ft)	0.52	Full	Full	Full
Nappe impingement point (ft) (horizontal from crest PC)	4.48	None	None	None
Total head on gate (ft) ←H_t	13.15	13.98	14.62	15.52
Discharge head (ft) ←H_c	1.35	2.18	2.83	3.73
Discharge coefficient ←C	3.38	3.30	3.35	3.32

Depth and velocity data along spillway

Discharge — PC dist	1,000 Depth (ft)	1,000 Velocity (ft/s)	2,000 Depth (ft)	2,000 Velocity (ft/s)	3,000 Depth (ft)	3,000 Velocity (ft/s)	4,500 Depth (ft)	4,500 Velocity (ft/s)
X = 0.0 ft	2.14	2.48	2.68	3.96	3.01	5.28	4.14	5.77
X = 2.0 ft	2.08	2.54	2.55	4.17	3.02	5.26	3.68	6.49
X = 4.0 ft	1.05	5.03	2.02	5.26	2.53	6.29	3.07	7.77
X = 6.0 ft	0.39	13.71	0.84	12.64	1.37	11.59	2.12	11.24
X = 8.0 ft	0.35	14.96	0.58	18.14	0.85	18.67	1.36	17.59
X = 10.0 ft	0.24	22.44	0.51	20.73	0.77	20.67	TW[1]	NA[2]
X = 12.0 ft	0.24	21.67	TW[1]	NA[2]	TW[1]	NA[2]	TW[1]	NA[2]

[1] = tailwater.
[2] = not applicable.

DISCUSSION

- The Naches/Cowiche site does not allow the development of sufficient head to achieve velocities in excess of the maximum fish darting velocities for steelhead; therefore, a 100-percent effective barrier cannot be ensured.

- Fish barrier efficiency cannot be closely estimated based on the laboratory model tests. However, the best overshot gate option for increasing barrier effectiveness is clearly the addition of a properly located crest gate. This conclusion was based on an evaluation of the combined effects of increased velocity and the resulting work required to swim upstream, reduced flow depths, and abrupt changes in flow direction. A discussion of each of these effects follows.

Barrier Effectiveness of Flow Depth

The flow depth on the as-built spillway exceeds the 0.5-ft maximum desired depth criterion at about 2,000 ft^3/s. The addition of a 3-ft-high overshot gate structure extends the discharge range for which depth is less than the 0.5-ft criterion, but only by a few hundred ft^3/s. Therefore, the decreased spillway depths achieved by adding a 3-ft-high overshot gate provide only marginal improvement to the fish barrier effectiveness.

Barrier Effectiveness of Velocity and Energy Requirements

The maximum flow velocity over the as-built spillway structure is less than the maximum darting speed of salmon and steelhead (about 22 and 26 ft/s, respectively). Adding either of the overshot gate structures tested will increase the maximum spillway velocities to greater than 22 ft/s for flows from 2,000 to 4,500 ft^3/s. The velocities never exceed 26 ft/s. Therefore, adding either gate structure will increase velocity sufficiently to provide an effective barrier for salmon. However, under low stress conditions for fish (optimum oxygen and water temperature), the swimming speeds and stamina of steelhead are sufficient to move against the maximum spillway velocities.

To gain additional perspective of the likely increase in steelhead barrier effectiveness, the work required for fish to move against the flow for each barrier option can be calculated. The work required to move upstream is proportional to the square of flow velocity. Work can be expressed as:

$$\text{Work} = \text{Force} * \text{Distance} \tag{4}$$

or

$$\text{Work} = (C_d A \rho V^2/2) * D \tag{5}$$

where:

C_d = coefficient of drag (0.2 for salmon, Bell, 1991)
A = area projected normal to the flow direction (ft^2)
ρ = mass density of water (lb/ft^3)
V = velocity of flow (ft/s)
D = distance traveled (ft)

Using equation 5, the work per unit area is plotted for each barrier option and flow on figures 11, 12, and 13. As shown, adding the gate structures increases the work required for fish to move upstream along the initial 6 to 8 ft of spillway by about 60 percent. For the crest gate option, values of work are not shown upstream from the jet impingement zone. The work plotted in figures 11 to 13 does not reflect additional work required to move over the gate structures.

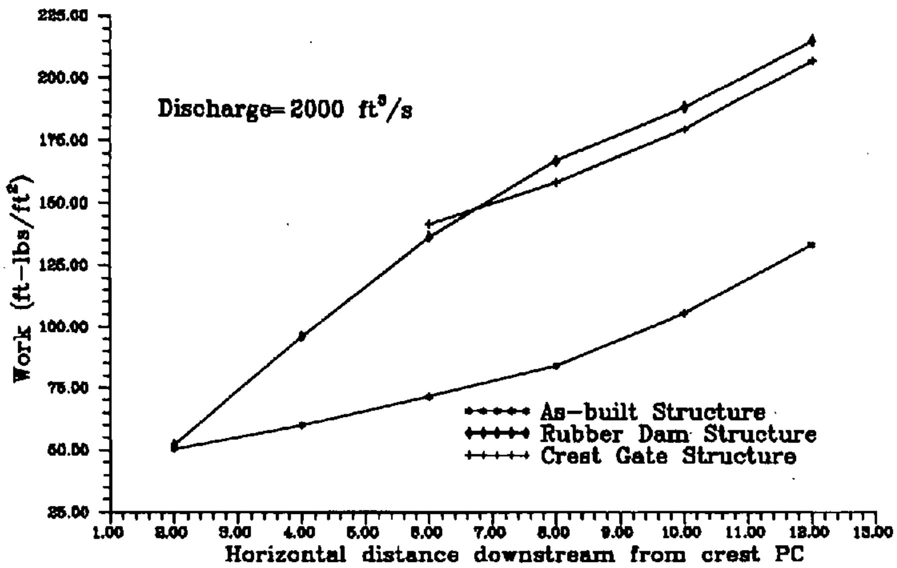


Figure 11. — A comparison of the additional work required for fish to negotiate the fish barrier gate structures at 2,000-ft^3/s discharge.

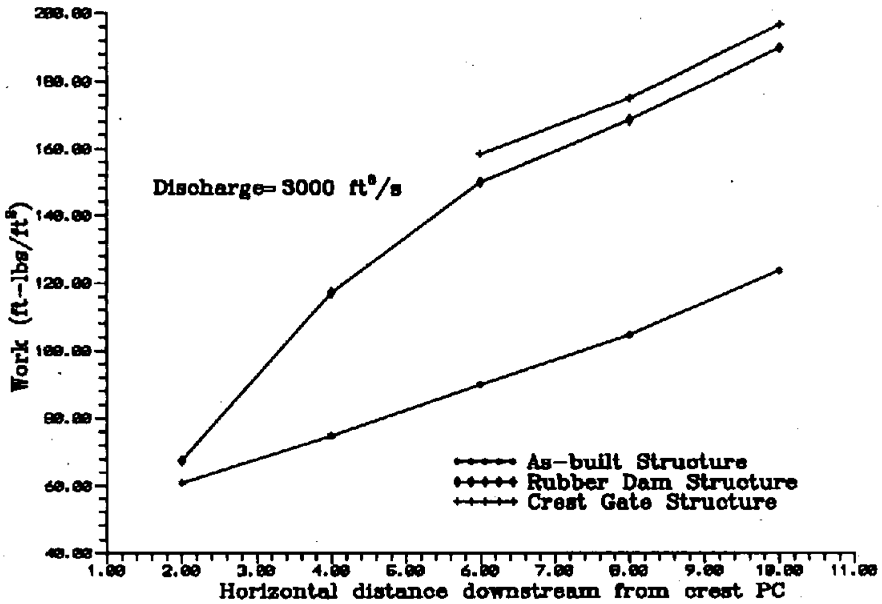


Figure 12. — A comparison of the additional work required for fish to negotiate the fish barrier gate structures at 3,000-ft^3/s discharge.

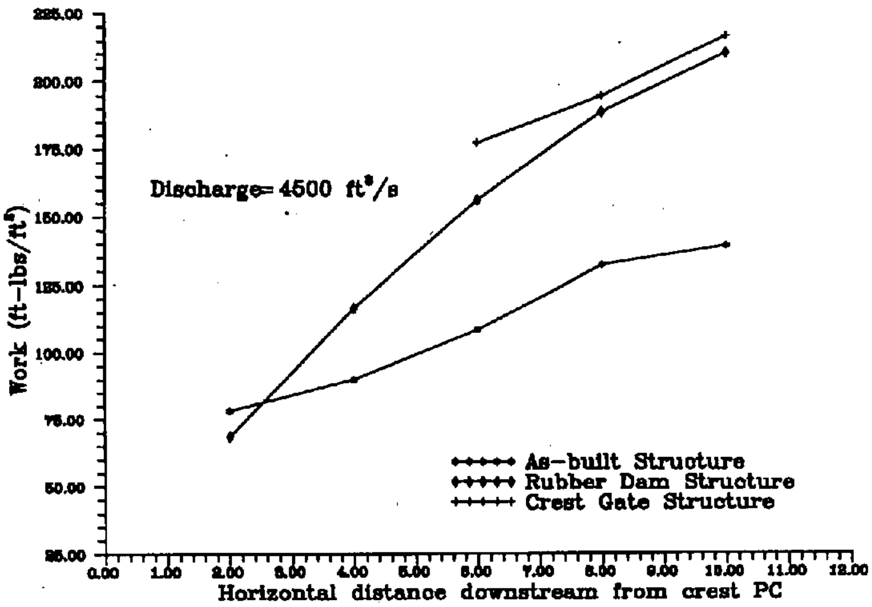


Figure 13. — A comparison of the additional work required for fish to negotiate the fish barrier gate structures at 4,500-ft^3/s discharge.

Barrier Effectiveness of the Flow Over the Gates

Visual observations of the flow field in the separation zone downstream from the rubber gate (or crest gate when suppressed) indicated the zone is relatively tranquil. The separation zone could likely be used as a resting area for fish that have moved up the spillway. Providing a resting area about half way up the structure will greatly increase the likelihood that fish can negotiate the structure.

The resting zone was eliminated for the crest gate option by moving the gate downstream closer to the spillway ogee section. With the gate pivot point located 1.25 ft upstream from the PC, the jet freely aerated at the gate brink. Although not tested because of uncertainties about creating an overhang between the lowered gate and the crest, the gate could be moved farther forward to reduce the pool depths behind the gate. The option of mounting the gate as close as 1 ft to the upstream edge of the ogee crest should be discussed with gate manufacturers. The same strategy for creating an aerated nappe is not possible for the water-filled rubber dam because of drainage requirements previously discussed.

Creating a free impinging jet on the downward sloping portion of the spillway face provides several characteristics that increase fish barrier effectiveness. Fish encounter the free impinging jet while amid a darting spurt. Flow conditions and direction vary rapidly at the jet impingement point. Fish must reorient to the new flow direction and conditions in a relatively shallow, swiftly flowing, highly turbulent zone.

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Bell, M. C., *Fisheries Handbook of Engineering Requirements and Biological Criteria*, U.S. Army Corps of Engineers, North Pacific Division, 1991.

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