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HYDRAULIC MODEL STUDY RESULTS FOR BLACK ROCK DAM

STRUCTURAL ANALYSIS
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As a client service to the Bureau of Indian Affairs, the Bureau of Reclamation is designing the spillway rehabilitation and dam overtopping protection required for Black Rock Dam during the PMF (Probable Maximum Flood. The hydraulic model study investigated the consequences of passing large flows through the existing spillway and dam overtopping. Two separate models were used to investigate the right abutment treatment and the required modifications to the existing spillway and downstream channel area. The right abutment model was used to locate a training wall, determine the wall height, and determine the extent of roller-compacted concrete protection needed. The existing spillway model was used to determine spillway wall heights, downstream flow deflector geometry, and the extent of the downstream apron.

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by

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Water Resources Research Laboratory
Water Resources Group
Technical Service Center
Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ **BUREAU OF RECLAMATION**

ACKNOWLEDGMENTS

The hydraulic model study was conducted at the request of the Waterways and Concrete Dams Group, Civil Engineering Services, Technical Service Center, to aid in the design of the dam overtopping protection and spillway rehabilitation. Assistance and guidance were provided throughout the study by Bruce Feinberg, Timothy P. Dolen, and William R. Fiedler of that group, and John A. Wilson of the Geotechnical Engineering Group. Our clients, the Bureau of Indian Affairs, provided key decision-making during the studies.

Laboratory shop personnel, Manuel Flores and Warren R. King, provided expert and timely model construction. Peer review was performed by Tony Wahl of the Water Resources Research Laboratory.

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INTRODUCTION

Black Rock Dam, located in eastern Arizona, is owned and operated by the Zuni Indian Tribe. The dam is about 60 ft high and is named after the distinctive blocks of black rock that cover the downstream slope of the dam. The PMF (probable maximum flood) will surpass the capacity of the existing spillway and overtop the dam, creating a dam safety concern. The dam, abutments, and a portion of the river channel will be protected with stepped RCC (roller-compacted concrete) to prevent failure caused by overtopping under the PMF. The existing spillway walls will be modified and the downstream area protected with RCC, also to prevent failure during the PMF. The dam also has an existing seepage problem that will be remedied during the rehabilitation work.

INVESTIGATIONS

Two separate models were used to investigate the proposed modifications to Black Rock Dam:

- 275 ft of the dam and right abutment area with a proposed training wall
- The existing spillway, adjacent dam section, and downstream area with a proposed training wall (fig. 1).

Figure 1a shows the original topography at the dam and the extent of the area modeled. Figure 1b shows the proposed final overtopping protection determined as a result of the model studies.

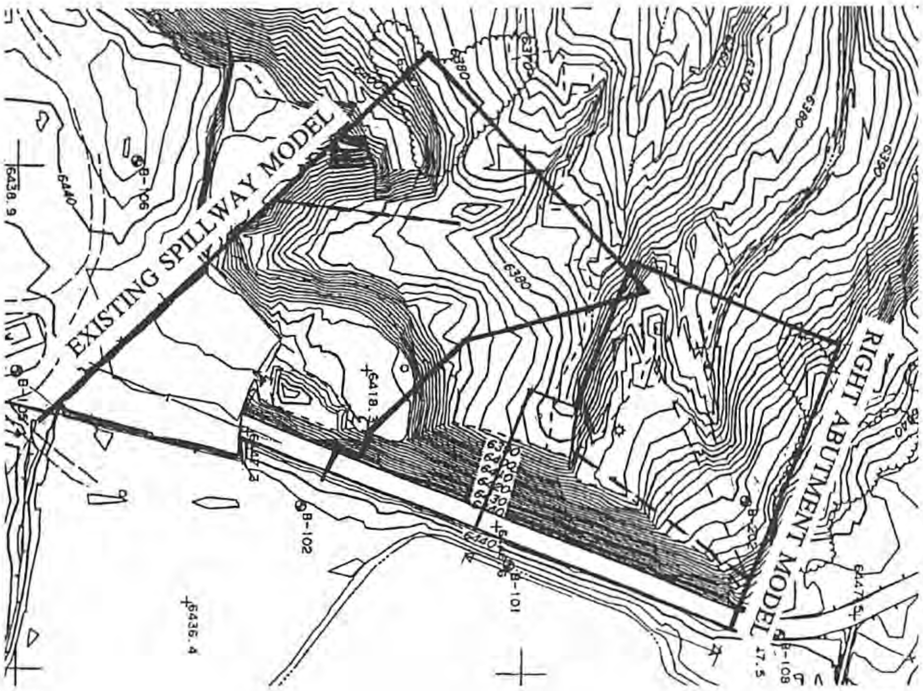

Figure 1a. - Map of the existing topography at Black Rock Dam locating the boundaries of the 1:36 scale models of the dam and right abutment area, and the existing spillway and adjacent area.

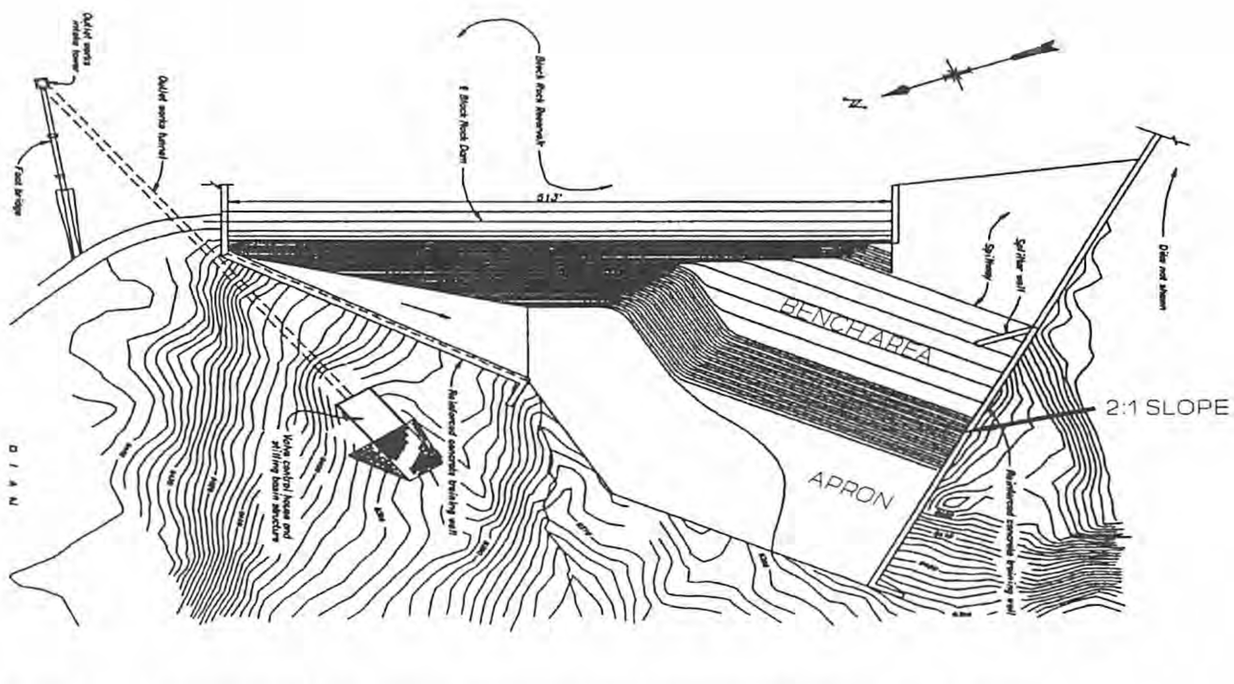

Figure 1b. - General plan of the final overtopping protection determined from the model studies.

The PMF will produce a flow of 46,978 ft^3/s through the spillway and 65,086 ft^3/s over the dam for a total PMF discharge of 112,064 ft^3/s. A total dam length of 513 ft produces a unit discharge over the dam during the PMF of 126.9 $ft^3/s/ft$. The right abutment model included 275 ft of the dam crest. The existing spillway model included 86 ft of the dam crest adjacent to the spillway.

Test discharges investigated for dam overtopping were determined based upon the length of dam crest modeled and the total or percent of the PMF. The spillway model combined the spillway discharges with the appropriate dam unit discharge. Table 1 shows the discharges investigated during the model studies.

Table 1. - Discharges investigated during each of the model studies.

%PMF	Total Dam Overtopping Discharge (ft^3/s)	Unit Discharge ($ft^3/s/ft$) for Total Dam Length (513 ft)	Total Discharge (ft^3/s) Right Abutment Model (dam length=275 ft)	Dam Discharge (ft^3/s) Spillway Model	Existing Spillway Discharge (ft^3/s)	Total Discharge (ft^3/s) Spillway and Dam Model
50	32,543	63.44	17,445	5,457	23,489	28,946
75	48,815	95.15	26,194	not tested	not tested	not tested
100	65,086	126.9	34,898	10,913	46,978	57,891

The discussion and results from both model studies are presented in the following sections.

DAM RIGHT ABUTMENT MODEL

Purpose

The purpose of this hydraulic model is to investigate the wall height and location necessary to protect the right abutment area of the dam while attempting to minimize the amount of RCC abutment protection required during dam overtopping. The wall should contain and redirect the flow away from the right abutment area and outlet works stilling basin structure toward the river channel.

Model

A tabletop size model, 1:36 scale, was constructed of 275 ft of the dam; the 1.25:1 downstream sloping stepped face and various walls were angled over the right abutment toward the river channel. The dam steps were modeled assuming the existing blocks on the dam averaged 1.5 ft in height. The model extent included the dam from about the center of the dam to the right abutment wall normal to the dam axis. The right abutment wall normal to the dam axis extended from the upstream face of the dam downstream to the end of the model. The walls investigated to contain and direct the dam overtopping flow across the abutment were attached to this right abutment wall at various angles. The first angled abutment wall tested was angled 105° to the right abutment wall normal to the dam axis. The 15-ft-high wall formed a 5-ft-wide trough parallel to the contact line between the dam and the abutment contact. The abutment slope was approximated at 5:1 from the top of the abutment to the basalt face above the river channel. The overall area modeled is shown on figure 1; the 1:36 scale model with maximum wall angle tested across the right abutment appears on figure 2.

Figure 2. - The 1:36 scale right abutment model with the maximum wall angle tested.

Results of the Right Abutment Protection

The decision was made to protect against erosion during the PMF. A trade-off exists between wall position (location and angle) and height and the extent of the RCC protection provided on the abutment and at the toe of the dam. Both the wall height and length and the RCC protection have costs associated with their construction. The higher wall, located close to the toe of the dam, will reduce the amount of RCC protection required by reducing the extent of the coverage, but has some aesthetic disadvantages. After viewing the wall options in the model, tribal representatives and Reclamation agreed upon a wall geometry and location. The final wall configuration is a 20-ft-high wall, angled 117° across the right abutment with a fillet in the upstream corner. The end of the wall will be located about 60 ft downstream from the El. 6390.0 contour on the downstream face of the dam. The water surface will slightly overtop this wall during the PMF without a cap along the wall. This wall location and geometry adequately contains the flow depth while maintaining aesthetics and minimizing the RCC abutment and downstream apron coverage at the dam toe.

Right Abutment Wall Investigations

The initial wall geometry was based upon photographs of a Japanese model study that showed a tightly converging wall down the face of a high dam with a smooth spillway surface. Unfortunately, the lower flow velocities parallel to the wall and higher unit discharges required at Black Rock did not allow the wall convergence angle to be as great as predicted by the Japanese work. Tests showed that the wall would not contain the amount of flow needed as the wall angled across the dam abutment toward the center of the dam and the river channel. Flow impinged upon the wall with a roller forming in the narrow, 5-ft-wide trough. Flow accumulated in the trough and overtopped the 15-ft-high wall along almost the entire length. As a result, testing of several alternative wall locations and heights began.

For the first modification (mod. No. 1), the wall was moved downstream at the same 105° angle across the abutment to form an 18-ft-wide trough parallel to the dam and abutment contact. The wall was raised to 40.5 ft to ensure containment of all the flow during the PMF. The PMF discharge is shown on figure 3 where the flow is contained by the wall, and the dam overtopping looks like a side channel spillway operating. The measured water surface profile indicated that a minimum wall height of 34 ft, plus freeboard, would be needed to contain the flow (fig. 4).

The next modification (mod. No. 2) repositioned the same wall to flare from 5 ft wide at the intersection with the dam abutment wall (normal to the dam centerline) to about 60 ft wide at the downstream end, producing a wall angle of 117°. In addition, a fillet is needed at the intersection of the angled wall with the dam abutment wall to reduce the height of the roller in this area. The fillet begins 23 ft downstream from the existing dam centerline and angles about 42.75° from the dam abutment wall intersecting with the 117° flared wall about 37.5 ft from the beginning of the wall (fig. 5a). The fillet provides a transition of the flow over the dam to the 117° angled abutment training wall. By providing a transition, the loading on the wall and the height of the wall are reduced; however, the amount of flow being contained and turned by the wall in this area still requires a high wall. A roller forms along the wall as the flow over the dam impinges on the angled wall. The height of the roller increases as the flow accumulates between the wall and the dam contact with the abutment. Figures 5a, 5b, and 5c show this wall geometry at PMF flow, 75% of PMF flow, and 50% of the PMF flow, respectively.

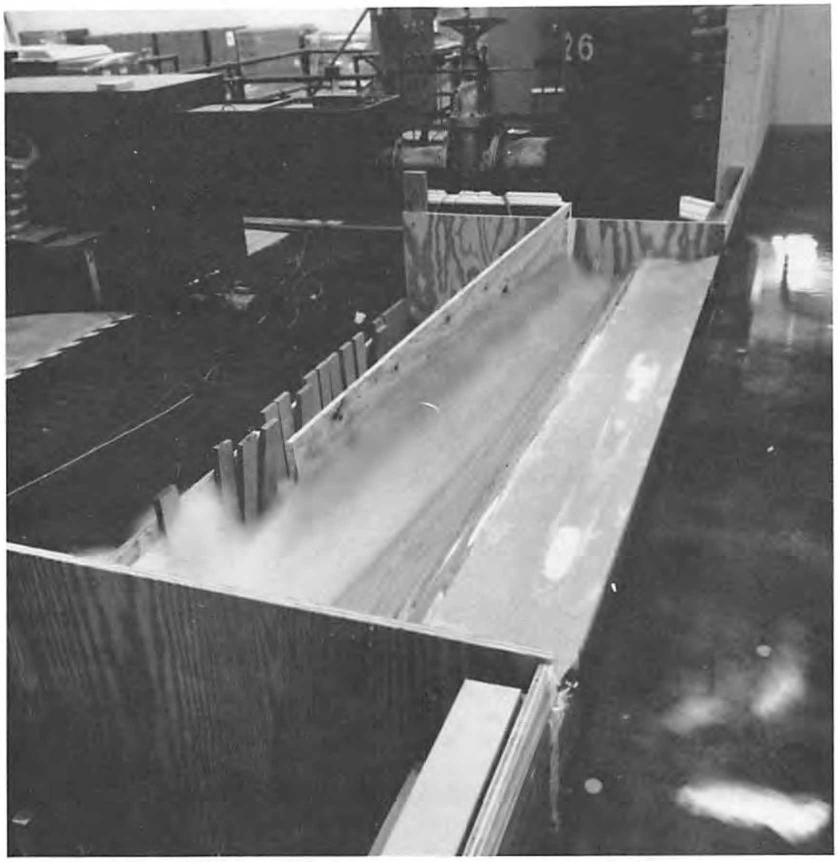

Figure 3. - The PMF discharge contained by an excessively high wall with an 18-ft-wide trough (mod. No. 1).

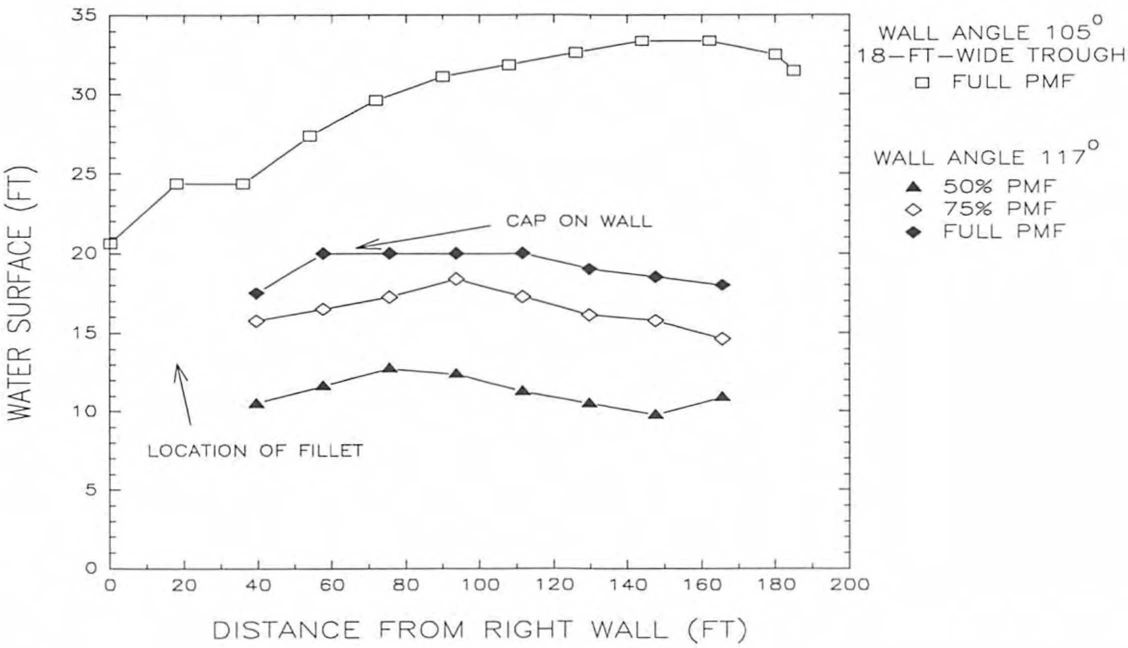

Figure 4. - Water surface profiles for the constant 18-ft-wide trough (mod. No. 1) and the wall flaring at 117° to 60 ft wide to the end (mod. No. 2).

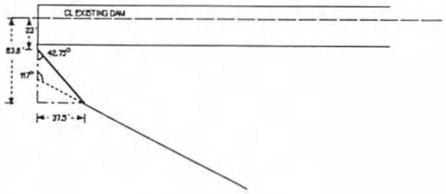

Figure 5a. - The 117° angled wall, with fillet, ending 60 ft downstream from the dam at El. 6390.0, showing the PMF flow rate contained by a 20-ft-high wall.

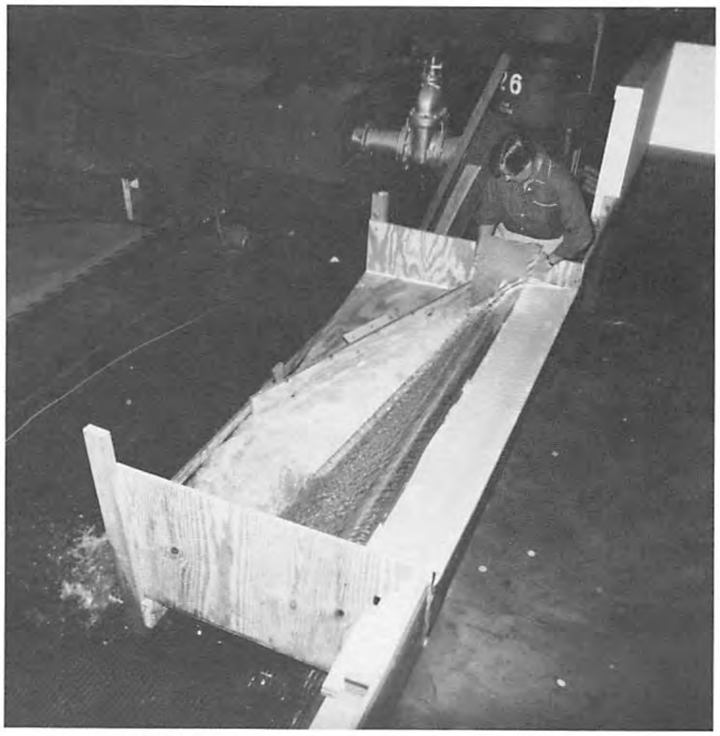

Figure 5b. - The 117° angled wall, ending 60 ft downstream from the dam at El. 6390.0—flow rate = 75% of the PMF.

Figure 5c. - The 117° angled wall, ending 60 ft downstream from the dam at El. 6390.0—flow rate = 50% of the PMF.

The water surface profiles for the flow rates tested are shown on figure 4. The flow depths were measured normal to the abutment slope and are given in table 2 in the appendix. At 50% of the PMF, the maximum flow depth along the wall is 12.75 ft; at 75% of the PMF, the maximum depth is 18.38 ft; and at the full PMF, the 20-ft-high wall is slightly overtopped without a cap. The wall overtopping is essentially a splashing of the flow that begins about 50 ft downstream from the intersection with the dam abutment wall and continues for about 70 ft. If used, the cap should extend over the 20-ft-high wall about 2.25 ft. These flow depths do not include flow bulking or freeboard.

The force on the wall was measured in two locations, 93.0 and 156.75 ft downstream from the beginning of the angled abutment wall, 2.8 ft above the floor for 50%, 75%, and the full PMF. The dynamic loading on the wall is less than the hydrostatic load for a given flow depth because of the sweeping action of the flow along the wall (fig. 6).

With aesthetics a major concern for the project, attempts were made to reduce the height of the wall by increasing the wall angle, thus increasing the RCC coverage on the abutment. Two more wall angles were investigated:

- 127°, ending about 100 ft downstream from El. 6390.0 on the dam face (mod. No. 3)
- 135°, ending about 150 ft downstream from the dam (mod. No. 4).

The 127° angled wall follows a small ridge on the abutment topography. The angle of about 135° is the maximum possible angle that may extend across the abutment without encroaching upon the outlet works structure. Flow conditions and depths were recorded for both additional options to determine the benefit of extending the wall farther away from the toe of the dam.

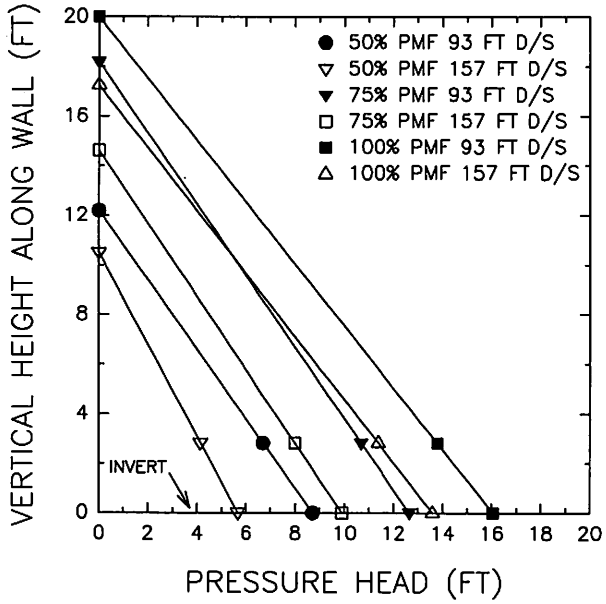

Figure 6. - Loading measured on the wall angled at 117° from the right abutment wall.

Increasing the wall angle to 127° (mod. No. 3) requires a wall height of 18 ft, with no freeboard, to contain the PMF. The flow conditions under the PMF are shown on figure 7, and the flow depths along the wall for 50%, 75%, and 100% of the PMF are shown on figure 8 and in table 3 in the appendix.

The wall angle was then increased to 135° (mod. No. 4) and extended across the abutment farther downstream from the toe of the dam. This wall angle reduces the wall height to about 15 ft, with no freeboard, but the RCC coverage on the abutment would be extensive (fig. 9). The flow depths along the wall are shown on figure 10 and in table 4 in the appendix. The minimal wall height reduction does not justify either the extensive wall length or the abutment protection required. While increasing the flare angle of the abutment wall, an upward step was added to decrease the flow velocity of the jet prior to it impinging upon the various wall locations. This step, positioned parallel to the toe of the dam, does not significantly reduce the energy impacting on the wall. The amount of flow being diverted by the wall is unchanged; therefore, the wall height is not significantly reduced. The fin created as the jet impinges on the step under low conditions produces undesirable flow conditions in the area between the dam contact with the abutment and the wall.

Flow Over the Dam

The right abutment wall normal to the dam axis is being constructed to support the reservoir berm being raised to contain the maximum reservoir water surface and to confine the dam overtopping section. The wall must be high enough to contain dam overtopping flows under the PMF. The flat surface on the top of the dam acts as a broad-crested weir. Flow goes through critical near the upstream edge of the dam crest and accelerates downstream. The water surface across the width of the dam crest decreases from the reservoir water surface at the upstream edge of the crest to about 8 ft at the dam brink during the PMF. The water surface remains at 8 ft down the face of the 1.25:1 sloping stepped face until it increases to just under 20 ft after impinging on the wall fillet.

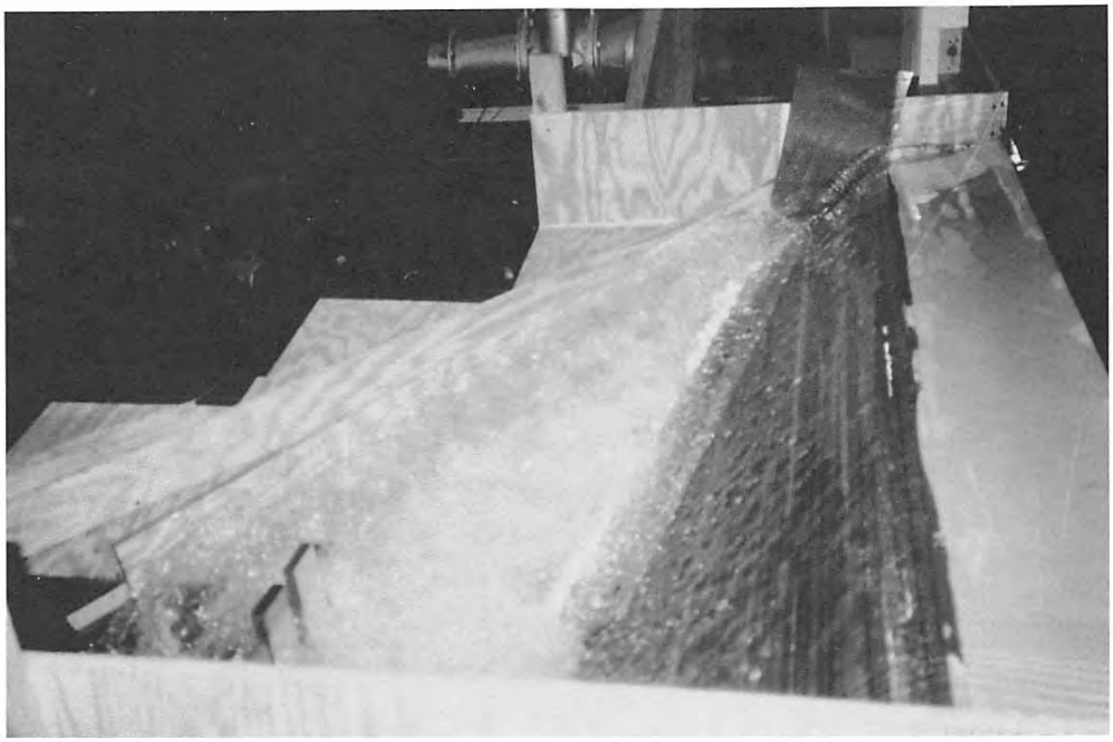

Figure 7. - The 127° angled wall option ending about 100 ft downstream from the dam at El. 6390.0, showing the PMF (mod. No. 3).

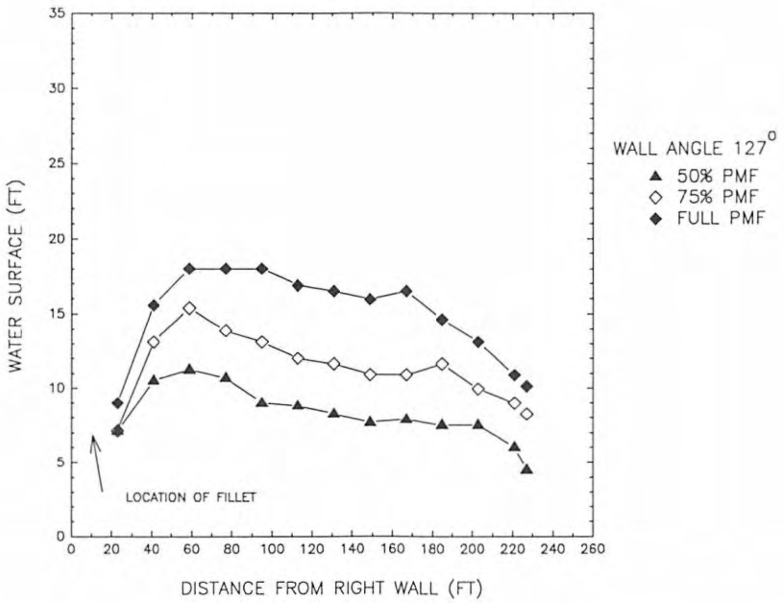

Figure 8. - Flow depths measured normal to the abutment slope for the 127° angled wall ending about 100 ft downstream from the dam (mod. No. 3).

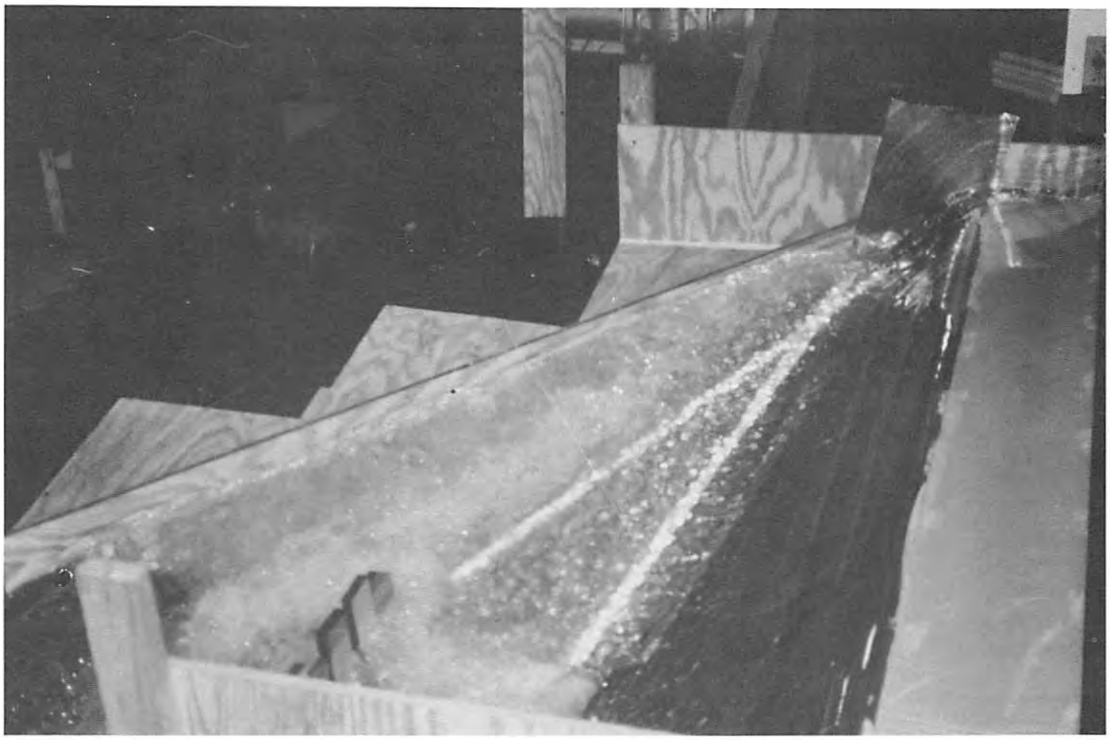

Figure 9. - The 135° angled wall option ending about 150 ft downstream from the dam at El. 6390.0, showing the PMF (mod. No. 4).

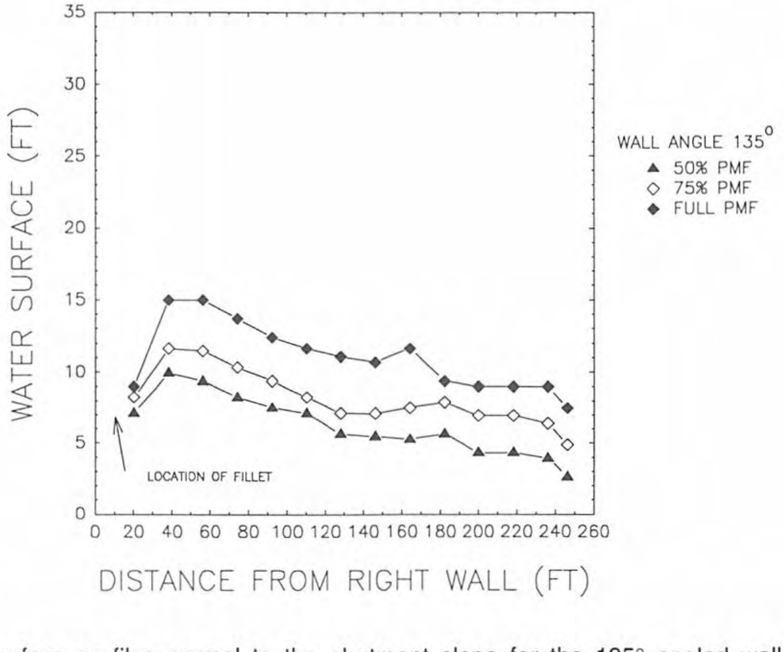

Figure 10. - Water surface profiles normal to the abutment slope for the 135° angled wall ending about 150 ft downstream from the dam (mod. No. 4).

Flow over the dam brink, formed by the intersection of the 1.25:1 downstream slope of the dam with the flat crest, will produce a low pressure zone. The RCC thickness at the dam brink should be adequate to prevent instability at the dam brink. A transition from the flat crest to the 1.25:1 slope should be provided. A transition will prevent the nappe from springing free from the downstream face of the dam and skipping over several rows of steps before adhering to the downstream dam face.

Summary

The required wall height and the extent of RCC abutment protection were determined for protecting against erosion during the PMF. The final wall configuration is a 20-ft-high wall, angled 117° across the right abutment with a fillet in the upstream corner. The end of the wall will be located about 60 ft downstream from the El. 6390.0 contour on the downstream face of the dam. The water surface will slightly overtop this wall during the PMF without a cap along the wall. This wall location and geometry adequately contain the flow depth while maintaining aesthetics and minimizing the RCC abutment and downstream apron coverage at the dam toe.

EXISTING SPILLWAY AND DAM SECTION MODIFICATIONS

Purpose

The purpose of this hydraulic model is to investigate the flow conditions in the existing spillway, and the flow conditions between the dam and the existing spillway, while determining the necessary downstream protection.

Model

The model, also a 1:36 scale, included the existing spillway, a section of the dam, and the downstream area below the spillway and dam. A plan view of the extent of the model is shown on figure 1a, on the topographic map for Black Rock Dam. The existing spillway crest geometry was simplified and the piers and walkway were not modeled. High left and right walls were modeled to ensure containment of PMF flows. The existing spillway crest, at El. 6436.9, is aligned at about a 98° angle from the proposed right wall aligned normal to the dam centerline. The left wall of the spillway is angled in toward the centerline of the spillway by about 56°. The spillway converges from a total length at the crest of 191 ft to 107 ft at the downstream end of the spillway. The area downstream from the existing spillway will be excavated and/or filled and covered with RCC stepped protection. The area downstream from the spillway includes the bench area (S=0.08), leading to a 2:1 sloping stepped section ending on an apron to be formed over the existing spillway plunge pool area and dam toe (fig. 1b). In the initial design, a proposed wall on the left side, angled across the 2:1 slope and apron, contains spillway flow upstream from a large rock outcropping and turns it toward the river channel (fig. 1a).

The model also included 86 ft of the top of the dam, at El. 6442.1, 5.2 ft above the spillway crest. Flow over this section of the dam was used to evaluate the flow conditions between the spillway and dam section. An apron was modeled at the toe of the dam down to El. 6484.0. The entire flow condition at the toe of the dam will have to be assumed because the entire dam was not modeled. Figure 11 shows an overall view of the initial design tested by the 1:36 scale model of the existing spillway, adjacent dam section, and downstream area.

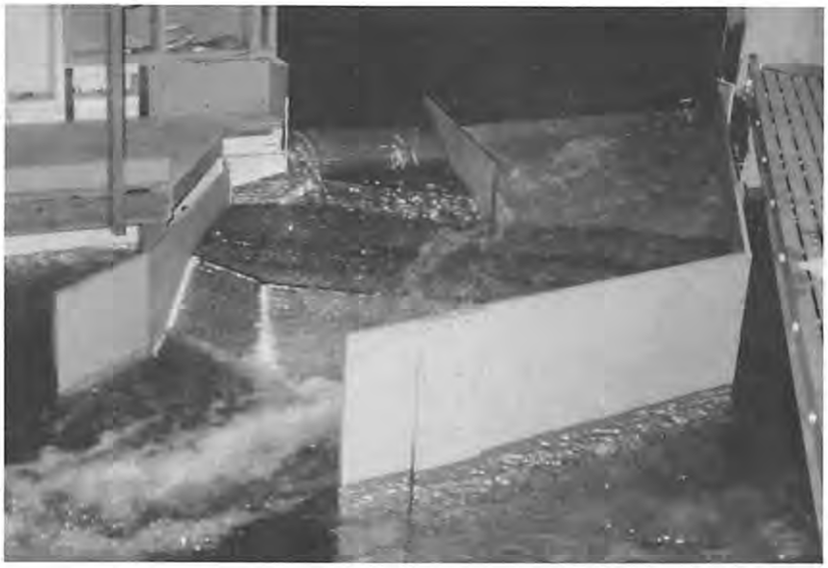

Figure 11. - Overall view of the 1:36 scale model of the initial geometry for the existing spillway, downstream wall, and dam section.

Results from the Existing Spillway Study

The left wall of the existing spillway should be raised to contain a flow depth of 27.75 ft, normal to the invert. This additional height will contain the flow depth created by the hydraulic jump in the chute and the deflector vane located downstream on the bench area. The left wall should extend straight downstream from the existing spillway wall through the bench area and the 2:1 slope. The wall will end near the end of the apron, as determined by the topography.

The right wall, separating the dam and spillway, should extend to the height of the maximum reservoir elevation upstream from the dam. This height should be maintained through the end of the transition steps downstream from the crest. The wall height should then match the stepped profile created during construction of the RCC protection adjacent to the spillway.

An 18-ft-high flow deflector vane should be constructed immediately downstream from the existing spillway on the bench area. The vane should be oriented at 45° to the left spillway wall and should extend 46.68 ft away from the wall along the angled vertical face.

The RCC protection should extend 300 ft downstream from the end of the existing spillway over the full width of the spillway. The apron length from the toe of the 2:1 slope is 159 ft. The apron downstream from the spillway will meet with the apron designed to protect for flows from the right abutment and over the center of the dam. The left wall, extending straight downstream from the end of the left spillway wall, should continue along the side of the apron, ending where the topography dictates. A wing wall should extend back into the topography at the end of the wall. Thickness of the RCC protection will be based upon PMF flow depth.

Initial Flow Conditions

Existing spillway flow conditions.-The existing spillway capacity under the PMF is 46,978 ft^3/s, or 246 $ft^3/s/ft$ at the crest and 439 $ft^3/s/ft$ at the downstream end of the spillway. The spillway passes low flows before the dam overtops. A hydraulic jump forms diagonally across the chute, caused by impingement of the flow on the left wall and convergence of the spillway walls. As the flow increases, the toe of the jump moves upstream and the flow depth increases in the chute (fig. 12). At the PMF, the toe of the jump moves up to about the toe of the crest by the left wall and to about 62 ft downstream from the toe of the crest along the right wall. The left wall orientation will not be changed to improve flow conditions; it will only be raised to contain flows. A left spillway wall height of 22.7 ft, plus freeboard, will be required to contain the PMF spillway discharge (fig. 13a). The right wall height must be 19.9 ft, plus freeboard, to fully contain the flow (fig. 13b).

Figure 12. - The hydraulic jump in the existing spillway chute under PMF flow conditions.

Flow conditions downstream from the existing spillway.-Flow from the spillway accelerates across the downstream bench section to the 2:1 slope. The horizontal acceleration of the flow prevents impingement of the jet on the 2:1 stepped section until jumping over several rows of steps. The high unit discharge from the spillway also prevents noticeable energy dissipation over the steps.

The downstream training wall, beginning just downstream from the bench on the 2:1 slope, is directed toward the river channel at an angle of 130° to the left spillway wall. The wall is angled across the existing spillway plunge pool area to prevent excavation of a large rock outcropping just downstream. However, flow impinges on and accumulates along the wall, forming a highly concentrated jet. The jet does not dive to the apron surface, but stays on the surface of the tailwater (fig. 14). The jet will impinge on the right bank of the river channel near the location of the new outlet works structure.

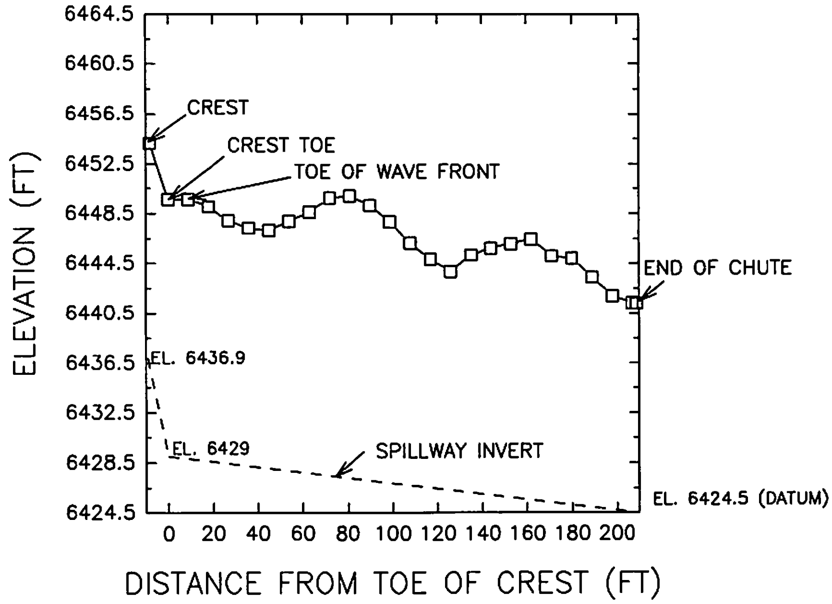

Figure 13a. - Initial flow depths along the left spillway wall normal to the invert for the PMF.

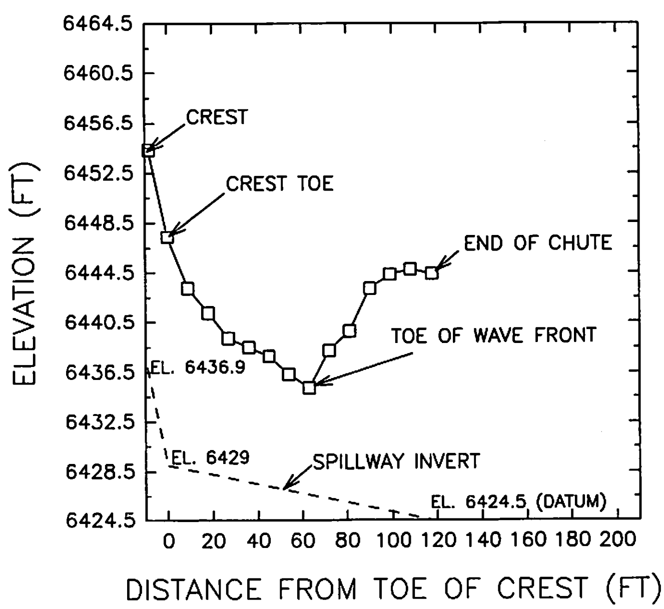

Figure 13b. - Initial flow depths along the right spillway wall normal to the invert for the PMF.

Figure 14. - PMF flow conditions downstream from the existing spillway with the wall angled across the apron toward the river channel.

Flow conditions over the dam section.-The dam section, with the crest at El. 6442.1, is 5.2 ft higher than the spillway crest. The dam unit discharge, during the PMF, is 126.9 $ft^3/s/ft$, compared to 439 $ft^3/s/ft$ at the end of the spillway channel. Flow over the dam follows the right spillway wall down to the exit of the spillway. At the intersection with the spillway flows, the flow from the dam overtopping is diverted to the right by the significantly larger spillway flow. Flow from the dam overtopping forms a hydraulic jump on the face of the 2:1 sloping section at the tailwater level (fig. 14).

Spillway Wall and Downstream Modifications

Initial operation of the model showed that the existing spillway was carrying a significantly larger amount of flow than the overtopped dam and that minimal energy dissipation occurred. Also, the angled wall across the area downstream from the 2:1 slope produced undesirable flow conditions in the river channel.

The first modification was to remove the angled wall and extend the left spillway wall straight downstream until it extended 227 ft downstream from the end of the spillway. The 84-ft-long apron slopes from El. 6390.0 to El. 6384.0, where the flow returns across the topography to the river channel. This modification to the downstream area prevented the flow from concentrating, but did not dissipate energy from the spillway flow. The tailwater (El. 6404.0 at the PMF) is not high enough to keep the jump on the apron near the toe of the 2:1 slope. This first modification to the area downstream from the spillway allowed later evaluation of several different alternatives.

Right spillway wall modifications.-The right spillway wall was initially designed to contain all flow from the spillway. The entire dam and downstream area will be protected with RCC; therefore, containing the spillway flow is no longer necessary. To minimize wall height and allow spillway flow to spread over the adjacent dam area, the entire length of the right spillway wall was lowered to the dam crest level. This modification did not perform well because additional flow from the reservoir went over the dam crest and into the spillway. Also, the spillway flow depth is less than the depth over the dam, so the resulting flow over the wall creates an instability on the spillway side of the wall. As a result, the portion of the wall from the spillway crest through the transition steps downstream from the dam crest was raised to the reservoir water surface of the PMF. The downstream portion of the right wall will follow the topography and the tips of the RCC steps until intersecting with the spillway invert. Minimizing the wall height downstream from the dam crest allows spillway flows to spread over the adjacent area of the dam, decreasing the intensity of the spillway flows.

Downstream modifications.-With the right spillway wall height decreased downstream from the dam crest to allow maximum spread of existing spillway flows, the next effort was to determine the appropriate protection downstream from the existing spillway. Several alternatives were discussed and/or investigated to help dissipate, deflect, or spread the spillway flow while minimizing the protection required downstream.

The following alternatives were discussed:

1. Extend the RCC apron, with a cutoff wall at the end, to protect underneath the entire length of the hydraulic jump.

2. Force more tailwater by constructing a berm in the river channel downstream, which would move the jump upstream toward the toe of the 2:1 slope.

3. Use an end sill at the end of the apron to force a jump with normal tailwater.

4. Form a large hump with RCC in the benched area downstream from the spillway. The hump would be stepped up from the end of the spillway downstream and toward the left wall. The extent and height would need to be determined in the model.

5. Use vanes in the spillway or on the benched area below the spillway to redirect the flow to the adjacent dam area on the right.

6. Decrease the spillway capacity and notch out a section near the center of the dam to stage spillway releases. This notch would redistribute the flow more evenly over the entire structure, decreasing the flow concentration in the spillway. The spillway capacity could be decreased by blocking off the spillway crest between several of the pier sections.

7. Use a baffled apron drop on the 2:1 sloping section below the spillway to dissipate energy.

8. Use an SAF (Saint Anthony Falls) stilling basin at the toe of the 2:1 sloping section to dissipate energy and reduce the extent of RCC coverage.

All alternatives listed above include the right spillway wall modification. Of these alternatives, numbers 1 through 5 were investigated in the model; numbers 2, 6, 7, and 8 were determined infeasible because of downstream topography (2), the upstream seepage blanket design (6), and hydraulic calculations (7, 8). The results of investigations with increased tailwater and extended RCC apron, the end sill, the RCC "hump," and the flow deflector vane will be discussed.

Model observations indicated that the RCC apron (1) would have to be extended too far downstream to protect against erosion caused by the hydraulic jump. A substantial cutoff wall at the end of the apron and a wing wall to prevent eddy currents eroding behind the wall would also be required. The apron could be shortened if additional tailwater could be forced by constructing a downstream berm in the river channel (2). The height of the berm was determined by increasing the tailwater until a satisfactory hydraulic jump occurred up on the present 84-ft-long apron. At the PMF, an additional 5.7 ft of tailwater, consequently berm height, would be required. The designers could not find a satisfactory location for the berm in the downstream channel; therefore, the option was not investigated further.

An end sill (3) was then used at the end of the present apron to force a jump upstream. Two end sill heights were investigated, 4.5 and 9 ft, with appropriate tailwater levels for 50% and 100% of the PMF. Flow impinged on the face of the end sill, causing a jet to go over the top and dive back down on the other side. This flow condition, produced by inadequate tailwater, would create an erosion hole downstream from the sill that could undermine the RCC apron.

Observations during these tests indicated that energy had to be dissipated or the flow spread more evenly across the dam from the existing spillway to produce a reasonable apron length with normal tailwater levels. A "hump" (4) was constructed on the bench area to spread the flow exiting the spillway over the dam section to the right. This technique has been used effectively in tunnel spillways to redistribute flow. The "hump" was constructed in a pyramid shape in a manner that was compatible with RCC construction techniques. The initially small structure soon became too large to reasonably construct and the option was abandoned.

A flow vane was used to divert flow toward the dam section. The vane is most effective if placed in the existing spillway chute, but designers preferred not modifying the existing spillway chute given its good condition. Therefore, the vane was placed at a 45° angle to the left spillway wall immediately at the end of the spillway chute. The 46.68-ft-long vane, with a vertical face, extends across the spillway from the left wall at a height of 18 ft (fig. 15).

Installing the vane significantly alters the flow depths adjacent to and upstream and downstream from the vane. Some water still flows over the vane, but the vane deflects a large portion of the flow from the left side of the spillway toward the dam, greatly improving downstream flow conditions. The flow depths were measured at various locations downstream from the spillway along lines parallel to the left spillway wall at distances of 50 and 100 ft away from the left wall (fig. 16). These flow depths will be used to determine the loading on the RCC protective covering.

The vane backs flow up into the spillway chute, increasing the water surface profile along the left wall. In turn, downstream depth decreases because only a small amount of flow goes over the vane. The water surface profile comparison along the left wall, with and without the vane during the PMF flow, is shown on figure 17; flow depths are given in table 5.

The vane effectively spread the flow across the downstream sections below the spillway and dam. Spreading the flow decreased the required extent of the RCC apron and produced a triangular shaped hydraulic jump more toward the river channel. This vane location and geometry are recommended for the final design.

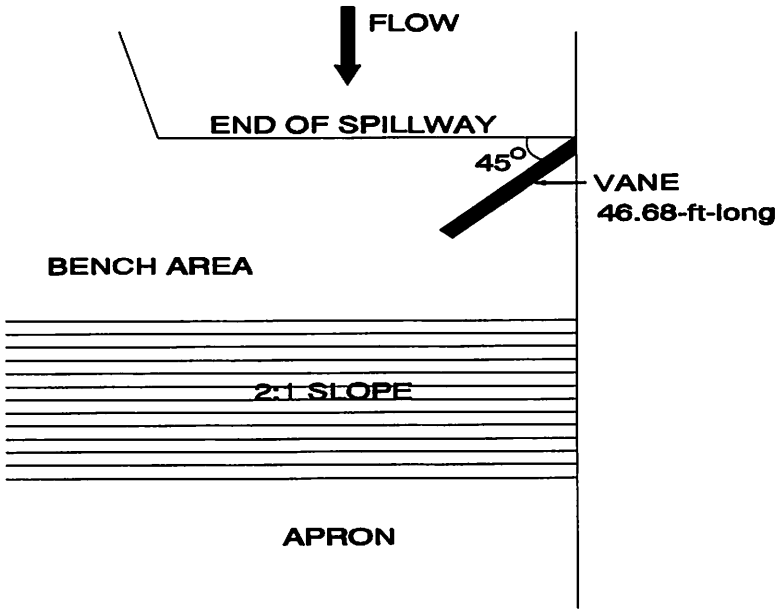

Figure 15. - Location and geometry of the flow vane installed to spread the flow exiting the spillway across the dam.

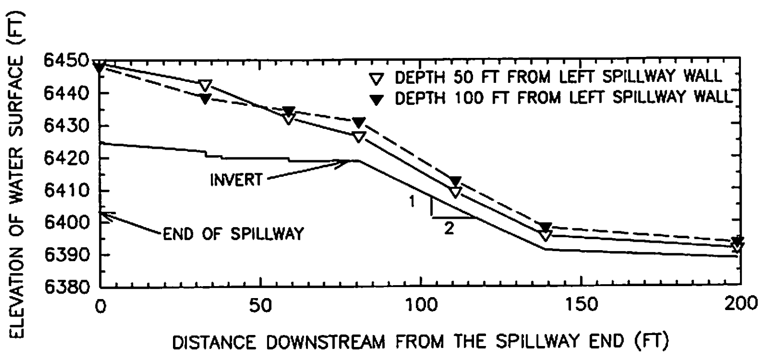

Figure 16. - Flow depths 50 and 100 ft from the left spillway wall downstream from the end of the spillway, during the PMF.

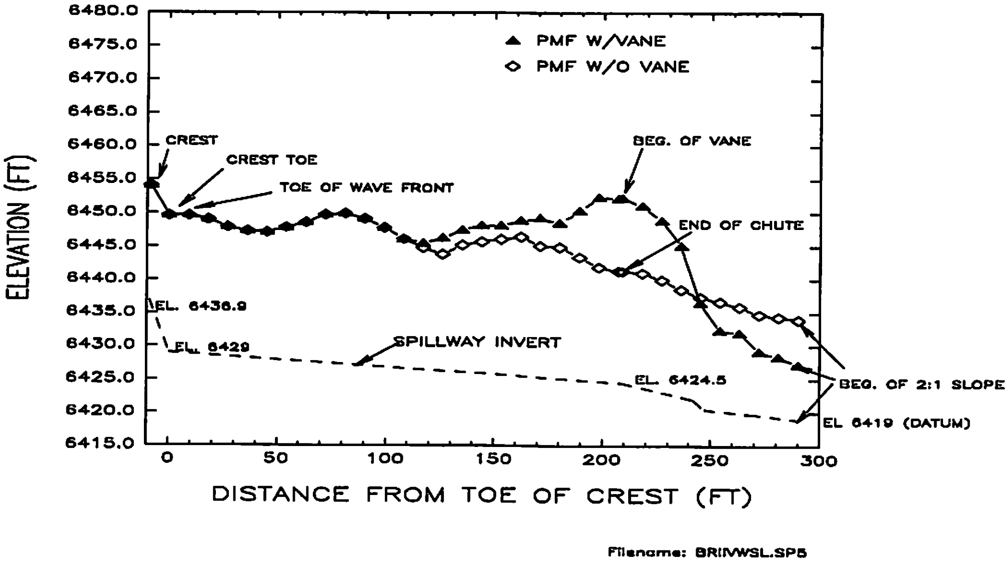

Figure 17. - Water surface profile along the left wall, with and without the vane installed, under the PMF.

The loading on the vertical face of the vane was measured at nine locations (fig. 18). The loading is highest at the intersection with the left wall, then decreases along the length of the vane as the flow sweeps across the face. The loading profile is given on figure 18 and table 6 in the appendix and shows the decrease in pressure head from the full flow depth at the base of the vane.

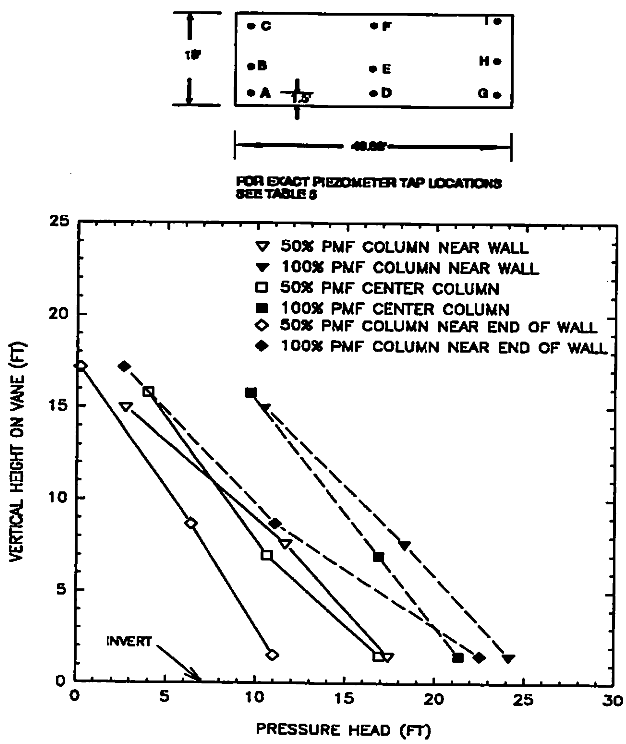

Figure 18. - Piezometer tap locations and pressures measured on the vertical face of the vane.

The overall flow conditions, with the right spillway wall modified, the vane installed, and the sloping apron downstream, were greatly improved over the initial design. However, the downstream apron still needed additional lengthening to adequately protect the downstream area from erosion during the PMF. The apron was extended an additional 75 ft, ending 300 ft downstream from the end of the spillway. The actual apron length downstream from the toe of the 2:1 slope is 159 ft. The wall still ended 227 ft downstream from the end of the spillway. The exact geometry of the left wall height and length will depend upon the topography and required excavation. A wing wall is recommended at the downstream end of the wall to prevent erosion caused by eddy currents behind the wall. Figures 19a and 19b show the final recommended designs for Black Rock Dam at flows of 50% and 100% of the PMF.

Figure 19a. - The recommended design for the existing spillway area operating under 50% of the PMF.

Figure 19b. - The recommended designs for the existing spillway at Black Rock dam operating under the PMF.

Summary

Flows experienced at Black Rock Dam during the PMF will be safely passed through the spillway and over the dam by implementing the following recommendations:

- Raise the left spillway wall to contain a flow depth of 27.75 ft.

- Continue the left spillway wall straight for about 300 ft downstream from the end of the spillway chute. The height and exact length of the wall will be determined by the topography behind the wall. RCC will cover all areas exposed to flow from the spillway and the dam overtopping.

- Design the right spillway wall to contain the maximum reservoir level upstream from the dam crest. Downstream from the two approximately 5-ft-wide transition steps, the wall should taper down, or follow the steps down, to the level of the spillway invert.

- Construct an 18-ft-high vane on the bench area immediately downstream from the end of the spillway oriented at 45° to the left spillway wall.

- Extend the RCC apron downstream from the 2:1 slope a distance of 159 ft. The apron will connect with the toe apron required for the center and right abutment overtopping flows.

APPENDIX

Table 2. - Depths measured normal to the abutment slope for the 117° angled wall.

Distance (ft) from the right abutment wall	Depths for 50% of the PMF (ft)	Depths for 75% of the PMF (ft)	Depths for 100% of the PMF (ft)
39.6	10.5	15.75	17.5
57.6	11.63	16.5	20+
75.6	12.75	17.25	20+
93.6	12.38	18.38	20+
111.6	11.25	17.25	20+
129.6	10.5	16.13	19
147.6	9.75	15.75	18.5
165.6	10.88	14.63	18

Table 3. - Depths measured normal to the abutment slope along the 127° angled wall.

Distance (ft) from the right abutment wall	Depths for 50% of the PMF (ft)	Depths for 75% of the PMF (ft)	Depths for 100% of the PMF (ft)
22.87	7.125	7.125	9
40.87	10.5	13.13	15.56
58.87	11.25	15.38	18
76.87	10.69	13.88	18
94.87	9.0	13.13	18
112.9	8.813	12.0	16.88
130.9	8.25	11.63	16.5
148.9	7.688	10.88	15.94
166.9	7.875	10.88	16.5
184.9	7.5	11.63	14.63
202.9	7.5	9.938	13.13
220.9	6	9.0	10.88
227	4.5	8.25	10.13

Table 4. - Depths measured normal to the abutment slope along the 135° angled wall.

Distance (ft) from the right abutment wall	Depths for 50% of the PMF (ft)	Depths for 75% of the PMF (ft)	Depths for 100% of the PMF (ft)
20.25	7.125	8.25	9.00
38.25	9.938	11.63	15.0
56.25	9.375	11.44	15.0
74.25	8.25	10.31	13.69
92.25	7.5	9.375	12.38
110.3	7.125	8.25	11.63
128.3	5.625	7.105	11.06
146.3	5.438	7.103	10.69
164.3	5.25	7.5	11.63
182.3	5.625	7.875	9.375
200.3	4.313	6.938	9.0
218.3	4.313	6.938	9.0
236.3	3.938	6.375	9.0
246.3	2.625	4.875	7.5

Table 5. - Water surface profile depths along the left spillway wall for the 18-ft-high vane installed downstream from the end of the spillway.

Distance downstream from the crest toe (ft)	Depth referenced to invert (ft)	Elevation above El. 6419.0 (ft)
-8.25	17.25	6454.15
0	20.63	6449.63
9	21.00	6449.80
18	20.44	6449.04
27	19.50	6447.91
36	19.13	6447.33
45	19.13	6447.14
54	20.06	6447.87
63	21.00	6448.61
72	22.31	6449.73
81	22.69	6449.91
90	22.13	6449.15
99	21.00	6447.82
108	19.50	6446.12
117	19.13	6445.55
126	20.06	6446.29
135	21.38	6447.41
144	22.31	6448.14
153	22.50	6448.13
162	23.44	6448.87
171	24.00	6449.24
180	23.44	6448.48
189	25.50	6450.34
198	27.75	6452.39
207	27.75	6452.20
208.95 (end of chute)	27.75	6452.25
217.95	27.31	6451.13
226.95	25.74	6448.88
235.95	22.68	6445.13
244.95	16.00	6436.50
253.95	12.58	6432.38
262.95	12.20	6432.00
271.95	10.13	6429.13
280.95	9.38	6428.38
289.95 (beg. of 2:1 slope)	8.25	6427.25

Table 6. - Pressures measured on the face of the vane.

Tap	Distance above invert (ft)	50% of PMF	100% of PMF
A bottom by wall	1.5	17.39	24.23
B middle by wall	7.62	11.63	24.30
C top by wall	15	2.70	8.93
D bottom center	1.5	16.92	23.29
E middle center	6.97	10.62	16.27
F top center	15.79	3.96	9.86
G bottom end	1.5	10.98	13.86
H middle end	8.7	6.37	10.73
I top end	17.16	0.18	2.16

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.