CHAPTER 3

SLUICES FOR CONCRETE GRAVITY DAMS

Section I. Basic Considerations

3-1. Location. Sluices for concrete dams are generally located along the center line of spillway monoliths (plate C-18). When more than one sluice per monolith is required they are spaced appropriately in each monolith (plate C-19). A sluice should never be located close to or straddling a monolith joint. Since it is also general practice to place crest piers on the center line of spillway monoliths, the sluice air vent intakes can be placed in the crest pier, eliminating any danger of submergence during spillway flow. Air vents should not be cross-connected below the highest possible pressure grade line. In some cases it may be desirable to locate the sluices in the nonoverflow section of the dam. Such a location requires either (a) a separate energy dissipator or (b) a careful design for discharging into the spillway energy dissipator.

3-2. Size, Shape, and Number. The sluices for concrete gravity dams usually have a relatively small cross-sectional area. One of the principal reasons for making the sluices small in cross section is adverse structural effects of large openings in a concrete gravity section. In addition, the use of a large number of small sluices, each controlled by individual gates, provides a finer degree of regulation than could be obtained from a smaller number of sluices of larger cross-sectional area. The flood control sluices installed in Corps of Engineers' dams are predominantly rectangular in cross section. The size of sluices usually varies from 4 ft 0 in. by 6 ft 0 in. to 5 ft 8 in. by 10 ft 0 in., depending on discharge requirements. Larger sizes may be indicated in certain cases. All sluices should be large enough for inspection, maintenance, and repair purposes.

3-3. Elevation and Alignment.

a. General. The reservoir operational requirements normally play an important part in determining the elevation of the flood control sluices. The inlets of the sluices must be set low enough to drain the reservoir to the required limits of drawdown (ER 1110-2-50[d]). In a dam for flood control only, the reservoir is normally dry and the sluice inlet elevations are set at, or slightly above, the streambed with due consideration of the sluice outlet elevation relative to stilling basin design. In a multipurpose dam with fixed reservoir storage allocations and in which high reservoir stages may be maintained for long periods of time, it may be desirable to have both high- and low-level sluices (plate C-18). Low-level sluices are sometimes desirable for the passage of sediment through a reservoir and for aiding in water quality control if a special intake tower is not provided. If the sluice intake is permanently or frequently submerged, the servicing and inspection necessary for maintenance are more costly than for a high-level sluice. A high-level sluice usually requires that the outlet portal be sloped to direct the flow along the face of an ogee spillway section or into a stilling basin. The invert may slope on a straight line from the intake to the outlet portal, or curve downward at some point downstream from the intake. Setting the outlet portal at a lower elevation than the intake reduces the pressure at critical locations such as the intake, gate slots, and bends. An area reduction is usually provided in the vicinity of the outlet portal of sluices to assure positive pressures in these sluices when operated under full gate openings, or the sluice is enlarged downstream of the gate to ensure open-channel flow at full gate openings. Area reductions may be used to spread the emerging jet.

b. Bends. Flow around conduit bends results in acceleration of flow along the inside of the bend accompanied by a local pressure reduction and the potential for cavitation (particularly for short-radius bends). Cavitation is not likely to occur in bends where long-radius curves are used. Pressure drop coefficients to evaluate cavitation potential for 90-deg bends are given in plate C-20. The minimum pressure occurs at 22.5 deg and 45 deg from the beginning of curvature for circular and rectangular conduits, respectively. Since the computed minimum pressure is an average pressure, the guidance given in paragraph 2-16 should be adhered to.

Section II. Sluice Intakes

3-4. General. Sluice intakes are integral parts of concrete spillways, and are usually rectangular in shape and flared in four directions. The curved entrance is followed by the sluice passage, normally having a height-width ratio of about 1.5:1 to 2:1. In some cases considerable economy in stop log costs can be effected by projecting the intake curves upstream beyond the face of the dam. This permits a reduction in the required size of the stop log or bulkhead gate. Bulkhead slots must extend vertically above the maximum reservoir pool or be provided with slot covers. Open roof slots for closure bulkheads at Kinzua Dam permitted flow through the slot and resulted in extensive cavitation damage downstream (item 20). Plate C-21 shows typical designs for flush and protruding sluice intakes.

3-5. Trash Protection. The intake may be equipped with struts or trashracks, depending upon the need for protection against clogging and debris damage to gates and turbines.

a. Trash Struts. A simple trash strut usually of reinforced concrete with clear horizontal and vertical openings not more than two-thirds the gate or other constricted section width and height, respectively, should be adequate for highly submerged flood control outlet conduits. The purpose of such struts is to catch trees and other large debris which may reach the entrance but would not pass through the gate passage, thereby possibly preventing closure of the gates. Trash struts should be located to effect local net-area velocities not greater than 15 fps. A flow net or model test should be used to determine local velocities through this area (items 99, 101, and 135). The struts should be circular cylinders or have rounded noses and square tails, depending upon the structural design requirements and economy. Teardrop designs are not required if the local velocity guidance is maintained. Trash strut losses are usually included in the overall intake loss. If necessary to consider separately, use of equation 2-12 is recommended with a loss coefficient K value of 0.02. V in this equation is the flow velocity in the uniform conduit section just inside the intake. Trash struts should be provided with a working platform located above conservation pool elevation to facilitate removal of debris. Additional information on the design of trash struts is given in EM 1110-2-2400.[j]

b. Trashracks. Trashracks are provided where debris protection for downstream devices such as valves or turbines is required (item 22). Such racks are designed to retain debris of such size and type of material that could result in damage to these devices. Because of danger of overstressing from clogging, trashracks should be located in lower velocity areas than trash struts and must be provided with raking or cleaning facilities. They should be designed for safe operation with 50 percent clogging. Such devices can be fabricated from circular bars and pipe. Trashracks should not be located in velocities exceeding 3 to 4 fps. Where additional strength is required, elongated sections with rounded noses and tails can be used. Trashrack head losses depend on the flow velocity and area construction (items 22, 39, 100, 108, and 135). The design of vibration-free trashracks is necessary to prevent failure from material fatigue. It is especially important where reverse flow can occur (items 21, 37, 53, 63, and 110).

3-6. Entrance Curves.

a. General. The curved converging section, which begins at the upstream face of the dam or intake structure and terminates in tangency to parallel walls, is commonly referred to as the entrance section.

The curves that determine the rate of convergence are designated as entrance curves. It is the function of the entrance section to guide the flow with minimum disturbance until it is contracted to the dimensions of the gate passage or to the upstream transition of an ungated intake. If the entrance curve is too sharp or too short, negative pressure areas may develop in the entrance section where the jet is inadequately supported or improperly guided. On the other hand, a long and gradual entrance curve may require an unnecessary amount of expensive forming. The objective is to design an entrance of minimum length in which positive pressures can be maintained at all flows.

b. Circular Inlets. A bell-mouthed entrance, which conforms to or encroaches very slightly into the free jet profile of a circular orifice, eliminates occurrence of negative pressure in localized areas at the entrance to a circular conduit (see p 414 of item 101). An elliptical entrance curve for a circular conduit will satisfy the required streamlining and jet contact requirements if the curve is expressed by the following equation:

$$\frac{X^2}{(0.5D)^2} + \frac{Y^2}{(0.15D)^2} = 1 \qquad (3\text{-}1)$$

where X and Y are coordinates measured parallel to and perpendicular to the conduit center line, respectively, and D is the diameter in feet.

c. Noncircular Inlets. The sluices of a concrete dam are commonly rectangular in cross section. WES (item 128) has tested entrance curves of various shapes. A laboratory-tested elliptical curve is shown in figure a, plate C-22, with the pressure drop coefficients. This simple ellipse is normally satisfactory. For designs of high-head dams and when the conduit has insufficient length to produce substantial back pressure, the compound elliptical curve (fig. b, plate C-22) should be used. HDC 211-1/2[n] shows the effect of upstream face slope of the dam on the entrance curve pressures.

3-7. Intake Energy Losses. Intake head losses are considered to include all the energy losses between the reservoir and the sluice proper. The head loss includes the form losses generated by the entrance curves, bulkhead or stop log slots, gate passage and gate slot, air vents, and the transition between the intake and the sluice proper. They also include the friction losses occurring in the intake structure. Intake losses are experimentally determined (model and prototype) by assuming that the fully developed turbulent friction gradient exists between the conduit exit portal and the intake as shown in plate C-2. On the basis of limited model and prototype intake loss data for sluices, an intake loss coefficient value of 0.16 is recommended for capacity design and a value of 0.10 when high velocity is critical. When gate slot losses are not included in the intake loss, a value of 0.01 for each gate may be considered. If trashracks are provided this value should be increased in accordance with data referenced in paragraph 3-5b.

Section III. Gate Passage, Gates, and Valves

3-8. General. The gate passage may be defined as the passageway in which the gate leaves operate. The hydraulic design problems of the gate passage are often closely associated with the structural and mechanical problems in the design of the gate, gate frames, and gate hoist. One of the most important problems in design of gates and appurtenant features is to eliminate cavitation. A basic condition is whether the gate will be required to operate partially open or will only be operated fully open. When high-head gates are operated under partial opening, they may be subject to severe cavitation and vibration and have a high air demand. When valves are used for regulation they are commonly placed at or near the downstream end of the outlet conduits. This location permits the valves to discharge freely into the atmosphere and eliminates most of the cavitation potential. In some cases, however, the spray so produced may be troublesome to power plants and switchyards. Gate passages of circular cross section are designed when necessary to accommodate circular gates or valves, such as knife or ring-follower gates or butterfly, fixed cone, or needle valves. Rectangular gate passages are used for ordinary slide, tainter, and tractor or wheel-type gates.

3-9. Gate Types.

a. Vertical Lift. Vertical-lift gates for outlet works are defined according to their method of movement. Due to the friction between the gate and the vertical guides, slide gates are generally operated by hydraulic cylinders. Tractor and fixed-wheel gates are used where closure of large openings is required. Tractor gates move on an endless chain of rollers on each side of the gate. Fixed-wheel gates have a series of wheels down each side of the gate which bear on vertical guides in the gate slots. Vertical-lift gates are operated either by cables or a rigid stem connection to the hoist mechanism. Cable-suspended gates operate in open wet wells which fill to the reservoir pool elevation when the gate is closed; therefore, the hoist mechanism is located at an elevation above the maximum pool level. This type of operation is not usually used for gates which operate partly open for long periods of time because of possible vibration. See paragraphs 4-18 and 4-19 for design problems concerning cable-suspended gates. Hydraulically operated gates are preferred for high heads and for long periods of operation at partial openings. These gates have rigid riser stems that recess into bonnets or extend to a higher floor level where the hydraulic hoist mechanism is located. The hydraulically operated slide gate is used preponderantly in designs for service gate installations in sluices of concrete dams. The rectangular slide gate generally has a height greater than the width to minimize both the flexure on the horizontal members and the unit loads on the vertical guides, and to reduce the possibility of binding in the slot. The cross-sectional shape of the gate passage in the sluice is usually the same as the shape of the gate. The upstream face of vertical-lift type gates must be flat rather than "bellied," as some gates were in the past, and the 45-deg lip should terminate in a 1-in. vertical extension (see plate C-23). Rating curve computations are discussed in paragraph 4-16 and in Appendix D.

b. Tainter Gates. Tainter gates have been used in the Pacific Northwest as service gates in sluices operating under extremely high heads (>250 ft). The characteristics of the tainter gate are favorable to its use for accurate reservoir regulation in both concrete and embankment dams. Advantages of the tainter gate over the vertical-lift type gate include: gate slots are not required in the walls of the gate passage, which is favorable in partly open gate operation; a relatively small hoist capacity is required because the direction of the resultant water load is through the trunnions; and the friction between the gate seals and the gate passage walls is low. A disadvantage of the tainter gate is that the entire gate cannot be easily lifted out of the well for maintenance. Tainter gates are placed in an enlarged section of the sluice and some have eccentric trunnions to facilitate movement and sealing under a very high head. The enlarged gate section may include an invert step-down as well as side and roof offsets to provide for complete sealing and for aeration of the jet which most frequently discharges as open-channel flow downstream at full gate opening. Under this condition, back pressure in the intake section is essentially nonexistent and the boundary layer is not fully developed. A model study is usually required to resolve pressure and vibration problems in pressure flow conduit designs. Discharge coefficients of a partially opened tainter gate in a rectangular conduit are shown in plate C-24. In general, the discharge coefficient can be considered the same as the contraction coefficient based on a study of the jet profile (HDC 320-3[n]).

3-10. Control Valves.

a. Valve Hydraulics. Knife gate, needle-type, fixed-cone, and various commercial valves have been used for flow control. Discharge rating curves for a valve discharging freely into air or into an enlarged, well-vented conduit can be developed from the equation

$$Q = CA\sqrt{2gH} \qquad (3\text{-}2)$$

where

Q = discharge in cfs

C = discharge coefficient

A = nominal conduit or valve flow area in ft^2

H = energy head immediately upstream and generally measured from the center line of the conduit in feet of water

g = acceleration due to gravity in ft/sec^2

Discharge coefficients for freely discharging valves of many types have been determined empirically and will be presented in subsequent discussions on specific valve types. Head loss across in-line valves in pressure conduits can be computed by equation 2-12 using the dimensionless valve-loss coefficient K determined experimentally for the particular valve and valve opening.

b. Butterfly Valves. Butterfly valves have been used extensively for cutoff valves but are not recommended for flow regulation. There is evidence that the butterfly valves in the 11-ft-diam flood control conduits at Summersville Dam may have contributed to the failure of the 9-ft-diam fixed-cone valves immediately downstream (item 80).

c. Needle-Type Valves. The needle valve opens and closes by the horizontal movement of a needle; the valve is closed when the needle is advanced to its extreme downstream position. The water flows in an annular passageway first diverging and then converging past the needle. Discharge from needle valves can be computed using equation 3-2, where A and H are the area and energy head, respectively, at the inlet end, and C is a discharge coefficient. Kohler and Ball (in Davis and Sorensen, item 24) show the full open coefficient to be about 0.60 when the ratio of outlet diameter to inlet diameter is 0.95. Thomas (item 120) gives discharge coefficients for partly open 86-in. needle valves. The hollow-jet valve is a modification of the needle and the needle moves upstream to close the outer casing of the valve. Model tests of the hollow-jet valve for Anderson Ranch Dam showed fully open discharge coefficients of approximately 0.70. Thomas also presents discharge coefficients for partly open valves in item 120. Nag presents a good summary of the characteristics, the uses, and the limitations of free discharge regulating valves in item 78.

d. Fixed-Cone Valves. The fixed-cone valve is similar in principle to the hollow-jet valve except that the cone pointing upstream on the downstream end is stationary and a sleeve of the outer casing moves downstream to close the valve. The shape of the issuing jet is a hollow cone. The discharge coefficient curves for fixed-cone valves are shown in plate C-25. The coefficients for the six-vane valve are based on tests by TVA (item 29). A comparable coefficient curve for a four-vane valve reproduced from HDC 332-1[n] is also shown in this plate. Model-prototype confirmation of the hydraulic characteristics of these valves has been studied by Lancaster (item 58). The shell of a six-vane valve has been found to be less likely to vibrate than that of a four-vane valve. In a number of cases, flow-induced vibration of fixed-cone valves has resulted in serious and costly damage (items 71 and 80). Hoods can be designed for these valves to control the spray of the jet (items 31 and 81).

e. Commercial Valves. Many types of commercially available valves are available for small conduits and water-supply systems. Some of those most commonly used are the knife gate and other gate valves. Head loss coefficients for lenticular- and crescent-shaped opening, in-line gate valves are given in HDC 330-1.[n] Knife gate valves are recommended for free discharge installations.

3-11. Metering Devices. Where accurate monitoring of outflow is required the inclusion of a metering device in the system should be considered. Many schemes can be considered, varying from venturi and elbow meters to acoustic and electronic systems. The installation of such devices eliminates the need for extensive calibration of gates and valves under varying operating conditions and generally results in flow measurements with errors from about ±5 percent to ±1 percent. It is necessary that all flow measuring devices of these types be installed according to standard specifications for proper, cavitation-free operation. If the provision of metering equipment is contemplated, WES should be consulted relative to available types and to their installation and operation requirements and limitations.

3-12. Gate Passageway Requirements. Normally, when reservoir outlet flows require regulation the following are provided:

a. Two or more gate passages such that if one passage is inoperative, a reasonable flow regulation as pertains to project purposes is obtained.

b. Emergency gate provision (tandem or transferable) for each service gate passage so that if a service gate is inoperative in any position, closure of the gate passage can be made with the emergency gate for any pool level.

c. Bulkhead provisions for each gate passage for inspection and maintenance of the service and emergency gates. As a minimum, the bulkheads must be capable of being installed at the lowest pool elevation that has a reasonable frequency and length of occurrence sufficient for inspection and repair purposes. All judgment factors involved in the above should be fully discussed in the design memorandum presentation.

3-13. Gate Slots. The guide slots of rectangular gates produce a discontinuity in sidewalls which may cause cavitation, unless specially designed. It has been common practice to use metal-liner plates downstream from the gate slots to protect the concrete from the erosive action of cavitation. The recommended guide lines for metal liners are given in paragraph 3-16. The gate slot in the roof of the gate chamber and air vent slots present similar design problems. Design details for slide gate roof, side, and air vent slot details are shown in plate C-23. Pressure coefficients (item 123) for detailed examination of this gate slot design for high heads (>250 ft) are given in figure a, plate C-26. To obtain dimensional local gate slot pressure data, the pressure coefficients given in this plate are multiplied by the flow velocity head in the gate passage and algebraically added to the back-pressure gradient elevation at the gate slot. Tests by Ball (item 6) show that doubling the downstream taper length from 12 to 24 units reduces the severest pressure drop coefficients (C) from -0.16 to -0.12 for comparable slot geometry. Therefore, it is recommended that for heads >250 ft the taper downstream of the gate slot be modified to 1:24. For conservative estimates of minimum pressures at gate slots where streamlining is not provided, the pressure coefficients in figure b, plate C-26, should be used. In detailed design studies it may be desirable to check the gate slot design for potential incipient cavitation. This can be done by solving equation 2-19 for the absolute conduit pressure p_o necessary for cavitation and comparing it with the computed minimum pressure at the slots. Plate C-27 gives incipient cavitation coefficients σ_i for various slot geometries. These values were obtained using relatively large scale (1:3) plastic models to reduce possible errors from scale effects. A σ_i value of 0.4 is recommended to check cavitation potential. For conservative design, the computed minimum pressure should be appreciably higher (15 ft or more) than the incipient cavitation pressure. The head losses for gate slots are generally included in the composite intake loss discussed in paragraph 3-7. When gate slot losses are not included in the intake loss, a loss coefficient K value of 0.01 is recommended for each pair of gate slots for use in equation 2-12.

3-14. Gate Recess. Hydraulically operated control gates recess into bonnets and cable-suspended gates into wet wells. The necessary dimensional clearances for gate operation are usually based on mechanical and structural requirements rather than hydraulic. The primary hydraulic consideration is the relative upstream and downstream clearance at the roof recess when the gate passage is operated at part gate opening. The upstream clearance at the roof should be appreciably larger than the downstream clearance to assure maintenance of a hydrostatic head in the well or bonnet for gate stability. If the downstream clearance exceeds the upstream clearance the gate well can be sucked dry and the gate may float or catapult or oscillate under certain operating conditions (see para 4-18b).

3-15. Gate Seats. In general, the gate seat is flush with the floor of the gate passage.

3-16. Steel Liners. Steel liners in concrete conduits have been used where experience indicates cavitation is likely to occur such as downstream from control gates and valves where a high-velocity jet occurs. For heads above 150 ft, a metal liner should extend 5 ft downstream from the gate. For heads below 150 ft, no liner should be required. If a liner is necessary, it should not terminate at a monolith joint or in a transition.

3-17. Air Vents. The following guidance is recommended for air vent design:

a. Control valves and gates that are located a considerable distance upstream from the exit (i.e., do not discharge into the atmosphere) require air vents. An air vent is required for each service gate. Air vents are not required for emergency gates when those gates are located immediately upstream of air-vented service gates. Extreme caution must be observed if the emergency gate is used for regulation. Air demand will create very low pressures in the service gate recess. The attendant conditions must be carefully analyzed to prevent damage and/or danger to personnel.

b. The size of air vents can be determined as per HDC 050-2[n] which assumes that the maximum air demand occurs at a gate opening of 80 percent fully open and the maximum air velocity in the vent does not exceed 150 fps. It is further suggested that air vents be designed so that the head loss through the vent not exceed 0.5 to 1.0 ft of water (i.e., air vent outlet pressure head of -0.5 to -1.0 ft of water). Although air vents are usually designed assuming incompressible flow, high-velocity local flow should be checked to determine if flow is incompressible (item 109).

c. Air vent passages should use generous bend radii and gradual transitions to avoid losses and, particularly, excessive noise.

d. Air vent intakes should be so located that they are inaccessible to the public and they should be protected by grills. The intake entrance average velocity should not exceed 30 fps.

e. Interconnected air vents (one main vertical stem manifolded to vent more than one gate) should be avoided; but if they are necessary, the connections should be above the maximum possible elevation of the pressure grade line at the air vent exit opening to prevent crossflow of water.

f. The air vent exit portal should be designed to assure spread of air across the full width of the conduit. The air vent should terminate into a plenum located in the conduit roof and immediately downstream of the gate. The plenum should extend across the full width of the conduit and should be vaned so that the air flow is evenly distributed. Plate C-23 illustrates a typical air vent exit into the gate chamber.

Section IV. Sluice Outlet Design

3-18. General Considerations. Generally, sluices should not be designed for combined spillway and sluice operation. However, in cases where large sluice capacity is required for diversion flows or normal reservoir regulation, combined operation may be considered and evaluated in terms of economic, hydrologic, and hydraulic benefits to be obtained. Potential benefits include (a) reduction in spillway length with savings in spillway and stilling basin construction costs, (b) reduction in maximum head on the spillway, and (c) more advantageous use of reservoir surcharge to reduce peak outflows. Simultaneous spillway and full sluice operation should be limited to conditions of thick (at least 10 ft) spillway nappe flow over the outlet to minimize the possibility of negative pressures at the sluice exit portal (item 15). With thinner nappes, the sluice flow should be limited to 40 to 70 percent gate openings to obtain maximum air intake to relieve low pressures at the exit portal and on the spillway face immediately below (item 140). Experience with combined operation has been limited to structures not exceeding 150 ft high. Caution should be used in designing for greater heights where very high velocities and thinner spillway nappes would occur. In general, sluices should be closed when spillway operation begins. In projects not model-studied for combined flow operation, combined flow should only be permitted when the free flow capacity of the spillway is expected to be exceeded and the structure is endangered. The sluices should be opened and operated preferably only with a thick spillway nappe flowing over the sluice outlets. One sluice inoperative should not jeopardize the integrity of the dam. Operation and reservoir regulation manuals must reflect these restrictions.

3-19. Exit Portal Constructions. A sluice in a concrete dam is seldom long enough to develop the desired back pressure from friction losses necessary to prevent cavitation damage and it may be desirable to use an exit constriction. A 10 to 15 percent area constriction at the exit portal can be provided by gradually depressing the conduit roof from some point upstream to the exit portal or by a deflector formed in the exit portal invert (plates C-28 and C-29). Roof constrictions should be used when the sluice is curved vertically downward to terminate the conduit invert tangent to the sloping spillway face or to the spillway toe curve (plate C-28). This type of design does not aid in horizontal spreading of the sluice jet; but if jet spreading is required to improve stilling basin performance, it can be accomplished by flaring the sidewalls in combination with a roof constriction (plate C-30), or by use of sidewall flare with a tetrahedral deflector (plate C-29). Both designs require extension of the sidewall flares in the spillway face downstream of the exit portal. Tetrahedral deflectors are also used when the sluice forms an abrupt junction with the spillway face and the sluice flow spreads in a free fall into the tailwater (plate C-29). When the sluice is appreciably above the spillway toe curve and spreading of the sluice jet is not a problem, gradual depression of the sluice exit portal roof and curving the sluice vertically downward to a smooth junction with the sloping spillway face (plate C-30) is preferable to deflector blocks and the jet plunging into the stilling basin.

3-20. Sluice "Eyebrow" Deflectors. Extensive cavitation damage has occurred at exit portals during spillway flows with and without simultaneous sluice operation. This damage usually originates at low pressure areas where the outlet portal roof intersects the spillway face and progresses downward along the intersection of the sluice sidewalls and the spillway face. USBR studies (item 140) of the Folsom Dam spillway showed that when the junction between the sluice invert and the spillway face is abrupt, the spillway jet can impinge upon the sluice invert with part of the flow entering and intermittently filling the sluice. This restricts effective venting by the sluice gate air vent with subsequent subatmospheric pressure at the sluice outlet roof. The USBR tests also showed that impinging of the spillway flow on the sluice exit portal invert resulted in flow separation from and undesirable low pressure on the spillway face downstream. The use of "eyebrow" deflectors on the spillway face (plate C-31) effectively lifted the spillway jet away from the sluice invert and permitted adequate venting of the exit portal by the sluice gate air vent. However, undesirable low pressures at full sluice gate opening were still evident immediately downstream on the spillway face. Deflectors of this type have been model-tested by the Corps of Engineers for Detroit, Red Rock, and other projects.