Appendix E
Design of High-Lift Locks

Section I
Filling and Emptying System

E-1. Objectives

The primary objectives in the design of a lock filling-and-emptying system are rapid fill-and-empty cycle; safety to vessels, structures, and personnel; economic construction; minimum maintenance; and smooth, uninterrupted operation.

E-2. Turbulence

The system must be designed so that turbulence and/or surging in the lock chamber does not cause excessive forces on hawser lines used to secure large vessels or create hazards to smaller craft that could be unmoored. Excessive surging could result in forces large enough to break mooring lines, causing damage to the service gates and vessel and endangering operating personnel. Comparison of model tests and prototype observations has shown that when a lock is designed so that certain hawser forces are not exceeded in a model, the prototype will be satisfactory for the moored vessels as well as small craft. These limiting hawser forces as measured in a model are 5 prototype tons (short tons) for barge tows and 10 prototype tons for single vessels (ships) up to 50,000 prototype deadweight tons. Hawser forces for larger vessels are allowed to exceed 10 tons, since they will be required to have more mooring lines than smaller vessels.

E-3. Flow

For high lifts, the flow into the lock chamber must be equally distributed if objectionable turbulence and hawser stresses are to be avoided while accomplishing acceptable filling times. Through a series of model tests of specific projects (Table E-1) and general studies, a balanced flow system has been developed for various locks. This system eliminates the surge and oscillation inherent in the sidewall port culvert and end filling systems by distributing flow uniformly throughout the lock chamber. During filling of the lock when the filling valves are open and the emptying valves are closed, flow enters culverts in each sidewall through intakes in the upper pool and is carried to the midpoint of the lock chamber where it is equally divided and directed to the upstream and downstream ends of the chamber. Flow in each end of the lock chamber is then divided into distribution culverts and discharged through a manifold of small ports into the lock chamber. During emptying of the lock when the emptying valves are open and the filling valves are closed, water from the lock chamber enters the distribution culverts through these small ports and is carried to the midpoints of the lock chamber where it is equally divided into the sidewall culverts and discharged into the lower pool.

Section II
Crossover Culverts

E-4. Methods

The portion of the system near the midpoint of the lock where flow from each wall culvert is divided and directed to the ends of the chamber is designated the crossover culverts. Two methods of dividing flow have been used:

Table E-1
Specific Locks With Balanced Flow Filling-and-Emptying System

Name	Location	Lift	Lock Chamber Size
Bankhead	Warrior River, AL	69 ft 21 m	110 ft x 670 ft 33.5 m x 240.2 m
Bay Springs	Tennessee-Tombigbee Waterway, MS	86 ft 26.2 m	110 ft x 670 ft 33.5 m x 204.2 m
Lower Granite	Snake River, WA	105 ft 32 m	86 ft x 675 ft 26.2 m x 205.7 m
Trinity River (proposed)	Trinity River, TX	60 ft 18.3 m	84 ft x 655 ft 25.6 m x 199.6 m
Walter Bouldin (proposed)	Coosa River, AL	130 ft 39.6 m	84 ft x 630 ft 25.6 m x 192 m

(a) The side-by-side culvert method where flow is divided by a vertical wall (Figure E-1).

(b) The over-and-under culvert method where flow is divided by a horizontal splitter (Figure E-2).

The over-and-under crossover culvert (horizontal flow divider) is preferred because it provides a more stable distribution of flow and is less likely to result in cavitation. Also, this method is more hydraulically efficient than the side-by-side method. In fact, the only reason for using the side-by-side method would be the cost advantage that may result under certain foundation conditions because the over-and-under crossover requires more depth to construct.

E-5. Divider Piers

The divider pier is an important feature of the side-by-side crossover culvert because it provides a means for directing 50 percent of the flow to each end of the lock chamber and results in more stable flow conditions through the crossover culverts. However, this area is subject to cavitation that can occur in cores of vortices shed from the divider piers with high lifts. Therefore, this method of division is not recommended with lifts greater than 60 ft (18.3 meters (m)).

E-6. Combining Culverts

With either crossover culvert system, flows from the two wall culverts discharge into a common culvert in each half of the lock so that the entire distribution system will be used even though only one wall culvert is in operation. These are called combining culverts. A relatively constant cross-sectional area is maintained from the wall culvert through the crossover and combining culverts. With the over-and-under crossover culvert system, combining of flow is accomplished as shown in Figure E-2, and with the side-by-side crossover culvert, combining of flow is accomplished as shown in Figure E-1. With the latter system, distribution of flow in the combining culvert with only one wall culvert operating is very sensitive to the location of the downstream edge of the separation pier. If the downstream edge of the pier is too short, excessive flow passes to the side of the combining culvert opposite the active culvert; if too long, excessive flow remains on the side of the combining culvert adjacent to the active culvert.

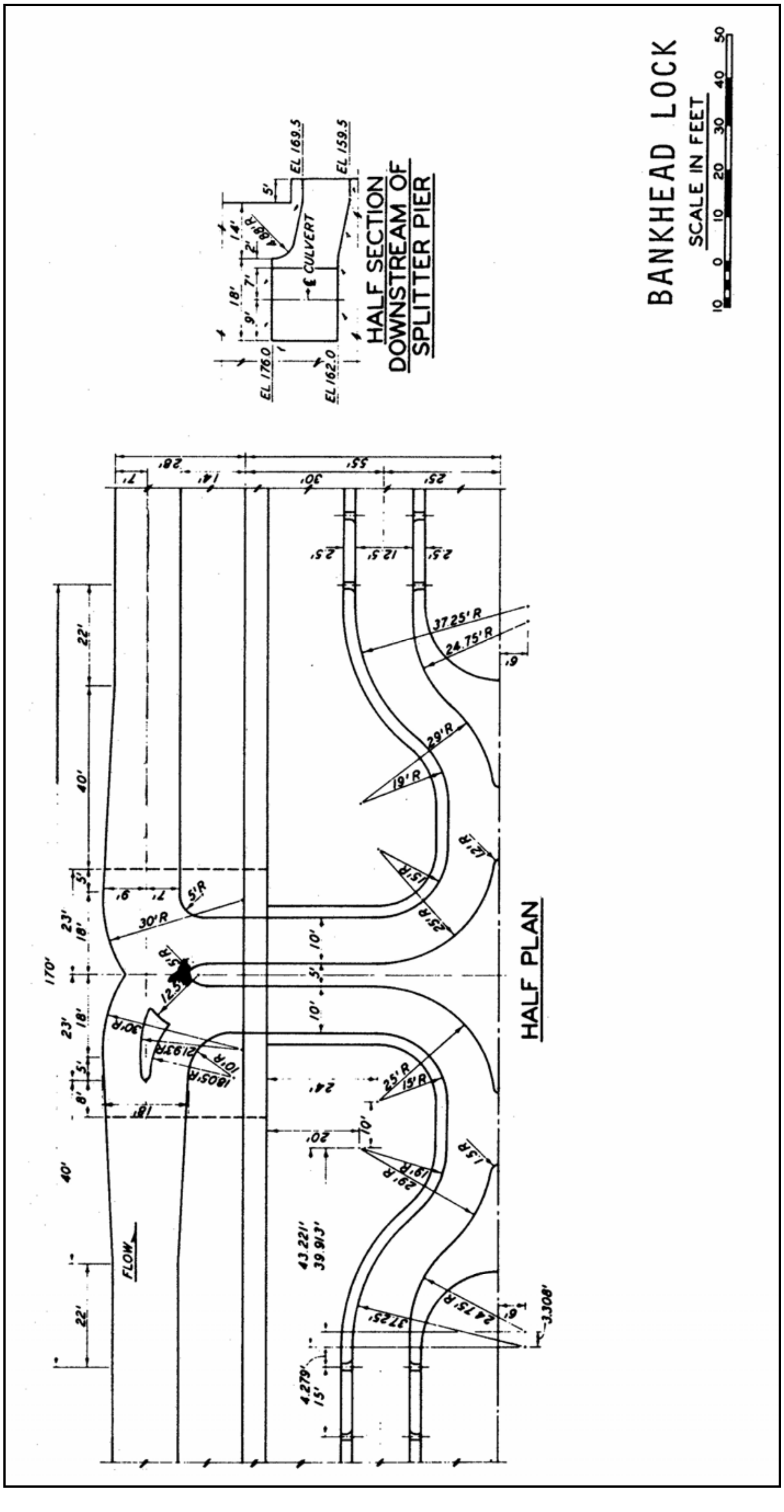

Figure E-1. Balanced flow filling and emptying. Side-by-side crossover culverts with two distribution culverts in end of lock

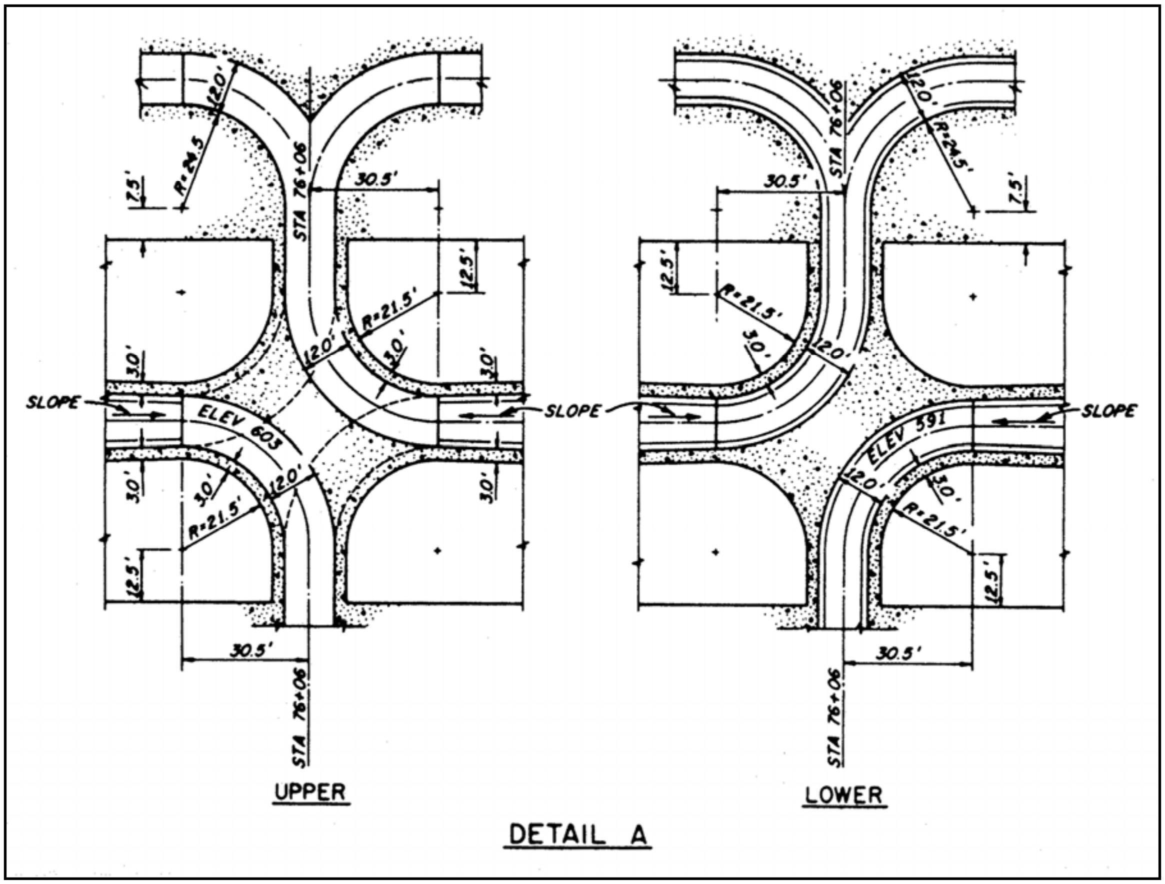

Figure E-2. Balanced flow filling and emptying. Over-and-under crossover culverts with two distribution culverts in each end of lock

E-7. Distribution Culverts

From the combining culvert, flow is redivided into two or four distribution culverts in each end of the lock as shown in Figures E-1 and E-2. The exact conditions under which two or four distribution culverts are needed have not been clearly established, but this depends upon lift, culvert size, and lock chamber length-to-width ratio. In the Bankhead Lock and Bay Springs Lock, two distribution culverts in each half of the chamber were adequate. In a series of general tests with a 110- by 1,270-ft (33.5- by 387.1-m) lock, four distribution culverts were required. Thus, with a length-to-width ratio of 6.1, two distribution culverts were adequate, but with a length-to-width ratio of 11.5, four distribution culverts were required. In the Lower Granite Lock, with a length-to-width ratio of 7.9, four distribution culverts were used. For locks proposed on the Trinity River, length-to-width ratio of 7.8, model tests showed that two distribution culverts were adequate, but the maximum lift was only 60 ft (18.3 m). In the proposed Walter Bouldin Lock with a lift of 130 ft (39.6 m) and a length-to-width ratio of 7.5, two distribution culverts produced satisfactory hydraulic conditions in model tests.

E-8. Cross-Sectional Area

Certainly, the four distribution culverts result in a more symmetrical flow pattern in the chamber than do two culverts, but it also is a more costly system with increased hydraulic losses. Regardless of whether two or four distribution culverts are used in each end of the chamber, it is desirable for the combined cross-sectional area of these culverts to be greater than the cross-sectional area of the wall culverts. This not only has a favorable influence on filling and emptying times, but also reduces bursting pressures during filling and collapsing pressures during emptying in the crossover and combining culverts.

E-9. Port Manifolds

In each of the distribution culverts a manifold of ports discharges flow into the lock chamber. These ports extend over at least 50 percent of the length of the chamber. In designs with four distribution culverts (one pair in each end) the port manifolds are centered on the one- and three-quarter points of the chamber, and each manifold extends over at least 12.5 percent of the total length of the lock. The size of the ports ranges from 4.20 to 6.28 ft^2 (0.39 to 0.58 square meters (m^2)). A port area to distribution culvert area ratio of approximately 1.0 results in good distribution of flow in the lock chamber. Port spacings of 14 to 18 ft (4.27 to 5.49 m) were used in the various designs discussed earlier and spacing appeared to have very little effect on flow conditions. The prime objective in port spacing is to use as much available length of the lock chamber as possible.

E-10. Baffles

A large portion of the energy of the jets issuing from the ports is dissipated in turbulence in trenches along the distribution culverts. Baffles on the walls of the trenches are used to prevent upwelling of the jets from the ports.

E-11. Bottom Filling and Emptying

The bottom longitudinal filling-and-emptying system unquestionably is the best system developed to date for high-lift locks in the United States. The locks that have been built using this system have operated very efficiently with very little turbulence in the lock chamber. For example, the Lower Granite Lock fills in about 8.1 min with a lift of 105 ft (32 m) and the Bankhead Lock fills in 7.7 min with a 69-ft (21-m) lift. The water surface in both of these locks is extremely smooth during the entire filling cycle. Model tests indicate that the Bay Springs Lock will fill in about 8.3 min with a lift of 86 ft (26.2 m).

Section III
Filling-and-Emptying
Culvert Gate Valves

E-12. Reverse Tainter Gates

The filling-and-emptying culvert valves of high-lift locks are very important in the overall design of the system. Reverse tainter gates have been used as the control valves in all high-lift locks recently constructed in the United States. When a large volume of air is drawn into the culverts, the air may pass through the ports and erupt in the lock chamber. The resulting disturbances would be hazardous. By reversing the tainter gates, that is, placing the trunnions upstream from the skin plate and sealing against the downstream end of the valve well, air is prevented from entering the culvert at the valve recess during the opening period if the pressure gradient drops below the top of the culvert.

E-13. Tainter Valves

Three structurally different types of reverse tainter valves (horizontally framed, double skin plate, and vertically framed) have been used in the United States. The horizontally framed valve is desirable structurally, but the double skin plate and vertically framed are less susceptible to critical hydraulic loads and load variations during the opening cycle.

E-14. Cavitation

Prevention of cavitation downstream from the valves is a very difficult problem for designers, particularly as lifts increase to values greater than 100 ft (30.5 m). High velocities and low pressures are induced as flow accelerates immediately downstream from the valves during the valve opening period. In some instances, the local flow acceleration is sufficient to lower the local pressure to the vapor pressure of water and form cavities within the flow. These cavities collapse rapidly or implode either in the water or against the downstream boundaries as they enter the increased pressure that results from the decreased velocity of flow as it expands and decelerates in the culvert downstream of the valve. This has resulted in lockmasters reporting loud pounding noises indicating cavitation implosions within the flow. In some instances, these booms have been violent enough to shake the lock walls and break windows. The implosion of the cavities against solid boundaries results in rapid pitting or damage to valves and appurtenances and to the concrete culverts.

E-15. Pressures

In some designs, pressures low enough to cause cavitation are avoided by submerging the culvert at the location of the valve so that the pressure gradient is maintained above the top of the culvert. However, as lifts increase, it becomes increasingly costly to provide adequate submergence. Through prototype tests at some of the high-lift locks on the Columbia River it was found that admitting a *controlled* amount of air into the culverts at each valve virtually eliminated the pounding noises. Air was drawn through a vent placed downstream from the valve into the culvert system during the valve opening period, was entrained as small bubbles in the highly turbulent flow, and emerged in the lock chamber so entrained that it merely caused the water to look milky. It was concluded that the air cushioned the collapse of the large cavities, eliminated shock pressures, and thus eliminated the pounding noises. This procedure allowed the culverts to be placed at a much higher elevation, thus minimizing excavation costs. Several locks have been constructed in the United States using this procedure, and no operation difficulties or hazardous conditions have been reported where pressures on the culvert roof were low enough to draw air during the valve opening period.

E-16. Culvert Expansions

a. Through model tests it was found that expanding the culvert roof upward downstream from the valve (Figure E-3) would increase pressures on the roof of the culvert just downstream from the valve. Also, in these tests it was found that the location of the expansion with respect to the valve directly affected the pressure on the roof of the culvert in the area immediately downstream from the valve. Thus, the use of expansions downstream from the culvert valves is a very practical means of controlling the pressures and allowing the valves to be set at a more economical elevation.

b. Expansions started at locations immediately downstream from the valve to a distance of 6.5 times the valve height (Figure E-3). Valve energy loss coefficients are essentially the same with no roof expansion, and with roof expansions beginning 4 and 6.5 times the valve height downstream from the valve. Thus, culvert expansions that begin 4 valve heights or more downstream have no effect on the loss coefficient for valve openings of 30 percent or greater. Expansions beginning within a distance of 4 valve heights of the valve increased energy loss coefficients as the expansion was placed closer to the valve.

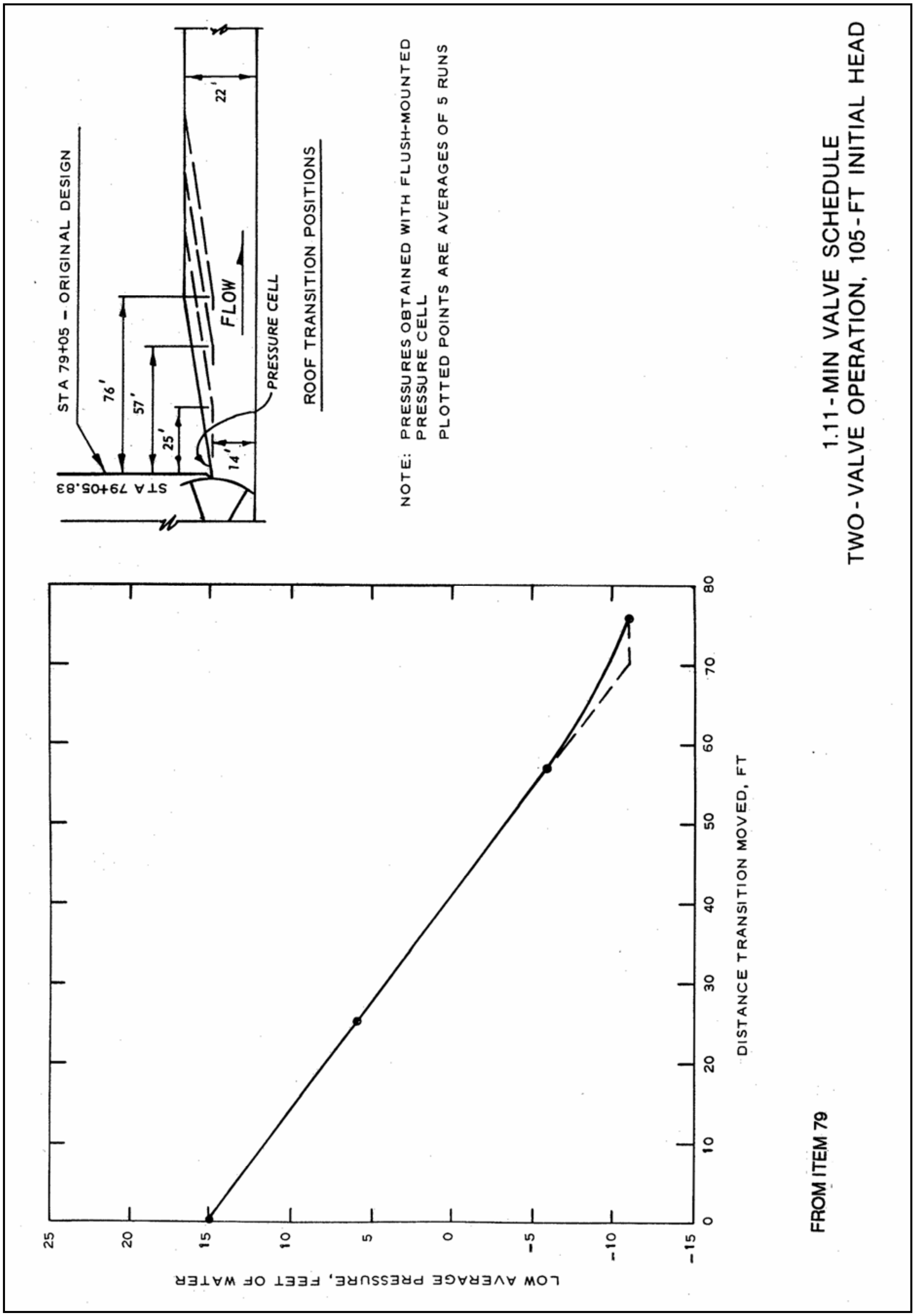

Figure E-3. Effect of culvert expansions on valve pressure drop