DESIGN CONSIDERATIONS REGARDING CAVITATION IN HYDRAULIC STRUCTURES

by

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Cavitation in hydraulic structures results from an adverse combination of flow passage shape, flow velocity, and pressure head at the point or area of consideration. The problems created by each different shape must be studied separately. The velocity-pressure head relationship, however, presents the same type problem for each study. The probability of cavitation occurring at any point in a structure varies directly as the velocity and inversely as the square root of the ambient pressure head.

Advances in the science of construction methods and materials has permitted the building of higher and higher dams. In 1915, the 350-foot high Arrowrock Dam on the Boise River in Idaho was the highest in the world. Today, Arrowrock is No. 25 on the list of high dams in the United States. As available head and velocity of flow have increased, the probability of cavitation in outlet works and spillways has increased. Consequently, the problems confronting design engineers regarding protection against cavitation damage becomes increasingly complex.

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When a damaged area appears in an operating installation, a study is made to determine if cavitation caused the damage. If the damage is determined to have been caused by cavitation, a search is made for the cause of the cavitation. Sometimes the cause is readily determined, sometimes difficult to determine, and in some cases it is impossible to arrive at a meeting of minds among engineers studying the problem. However, the study of corrective measures and repairs to damaged installations, and design considerations pertaining to new construction, go hand in hand. Research studies are made both to aid in design criteria for new construction, and to determine methods which can be used to correct improperly designed or poorly constructed operating installations.

Damaging cavitation can generally be traced to 1 of 3 major sources: inadequate construction control of the walls of flow passages, improper operating procedures, or improper hydraulic design. Figure 1 shows several types of surface irregularities which can and should be controlled during the construction stage. However, these irregularities are often overlooked and become a source of much trouble during the operating phase.

Extensive model studies have been performed to determine velocity-ambient pressure limits to prevent cavitation occurring at various surface irregularities. Figure 2 is a photograph of an operating laboratory apparatus with a 90° offset extending 3/8 inch into the flow, and with a substantial cavitation cloud forming on the sharp corner. Figure 3 shows the cavitation damage resulting from an offset extending 1/4 inch into the flow. This offset was caused by a misalinement between the concrete forms and the steel gate frame in the outlet works at Palisades Dam. The relatively slight preliminary damage may be easily repaired. However, if allowed to continue, the roughened surface caused by the cavitation will be the source of continuing cavitation and extensive damage may result as is graphically illustrated in Figure 4, one of the outlet works conduits at Grand Coulee Dam.

Surface irregularities may be removed or rendered harmless by correcting the flow surface to some known dimension. Prior to the construction of the TVA's Fontana Dam, considerable laboratory work was performed to establish surface alinement tolerances for the Fontana Tunnels1/. From these studies a shape factor was determined for application to obstructions in the tunnels, Figure 5. Two allowable minimum pressures are shown to allow a variation in obstruction lengths depending on the adapted minimum low pressure. The flow velocity in the Fontana Tunnels was about 150 feet per second.

1/ Numbers refer to references at end of the paper.

Model studies have been conducted in the USBR Hydraulic Laboratory to determine the velocity-ambient pressure relationship at which incipient cavitation will occur for various shapes of surface irregularities.

Figure 6 shows the results of the tests concerning square edged offsets into the flow. These studies were made in a conduit with a fully developed turbulent boundary layer. Computations have shown that if these offsets were in a zone with a blunt velocity profile[2/], all of the curves would fail approximately where the 1/4-inch offset curve appears on the chart. Subsequent to the studies of the 90° into the flow offsets the flow passages of the test apparatus were redesigned to produce a very blunt velocity profile at the test station. The results charted in Figures 7 and 8 are based on the blunt velocity profile. Figure 7 shows permissible head-velocity relationships for various degrees of chamfered corners. Figure 8 shows the same relationships for rounded corners.

Studies were made to determine the proper shape of the upstream nose of splitter piers in high velocity conduits[3/]. The elliptical shapes with various major to minor axis ratios were tested with the results as shown in Figure 9.

When cavitation damage is found, and the source of the cavitation ascertained, the general procedure is to repair the damaged area and remove or correct the source of the cavitation if possible. In a situation where corrective measures are not feasible, or if there is a question as to the adequacy of the corrective measures taken, a repair material resistant to cavitation attack may be used. At the Army Engineers' Lucky Peak Dam[4] the source of the damaging cavitation was not readily apparent. The damage pattern indicated that vortices sufficiently violent to produce cavitation pressures started the damage, then the damaged surface induced further cavitation and consequently continuing cavitation damage, until the floor of the outlet structure downstream from the control gate was destroyed. In this instance the damaged area was repaired by forming the flow boundaries of steel plate, Figure 10. This repair method is effective since steel is vastly superior to concrete in resistance to the attack of cavitation. Pressure studies of the Lucky Peak outlet works flow passages indicated that the gates had been operated in a range of openings (6 inches to 1 foot) which tended to produce adverse pressures. A revised operating criteria was issued which prohibited extended operation of the gates at openings smaller than 2 feet. The combination of resistant repair material and revised operating procedures should eliminate the difficulties at Lucky Peak Dam.

At Grand Coulee Dam, the exit end of the outlet conduits consisted of cones which reduced the tunnel diameter from 102 inches to 93 inches, see Figure 11. These cones were designed to maintain positive pressures in the tunnels and at the control gates during operation. The junction of the steel liner of the cone and the concrete trough downstream formed a break of 20.8:1. With the velocities at Grand Coulee Dam this break in flow surface was sufficient to cause cavitation and the resultant damage as shown in Figures 4 and 12. It is known that admitting air to a low pressure area will reduce the damaging effect of cavitation and since at Coulee Dam the outlets were of such a shape that air could be readily admitted to the downstream end of the cone (Sections A-A and B-B, Figure 11) this method was considered to be one possibility for correcting the difficulty. An aeration groove (Detail Z, Figure 11) was cut into several of the Grand Coulee outlets just downstream from the steel-lined cone. Previous work on gate slots[5] was used to determine the proper dimensions of the groove, and the current work on surface irregularities concerning chamfers determined the shape downstream from the aeration groove.

Some of the outlets showed relatively mild cavitation damage. It was thought that an epoxy mortar patch might be sufficient to resist the damaging effect of the cavitation. Figure 12 shows the application of epoxy mortar to a minor damaged area. The surface is first sandblasted, then covered with a prime coat of epoxy and filled to grade with an epoxy mortar. Feathered edges may be tolerated with this material.

Two adjacent outlets, one repaired with an epoxy mortar patch, and the other corrected with an aeration groove, were operated under about 235 feet of head for 1,800 hours. The one corrected with the groove* showed no damage while the one repaired with a patch suffered damage comparable to that shown in Figure 4. In this instance the admission of air through a properly shaped groove adequately protected the installation from cavitation attack. A resistant repair material was not acceptable as a solution to the problem.

In the outlet works at Glendo Dam in Wyoming a minor area of cavitation damage was found at the beginning of a diverging section downstream from the control gates, and another at the stoplog slots. Major cavitation damage had occurred on the chute blocks[6/]. Air

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*Small area of overbreak, and areas where the cavitation damage extended below the surface of the aeration groove and bush-hammered surface downstream, were patched with epoxy mortar. These patches were unaffected by the 1,800 hours of operation.

was admitted into the low-pressure area at the break in the diverging walls to correct the difficulty here. The stoplog slots were in such a position that they could be easily eliminated from their initial position and new ones installed away from the high-velocity stream. The chute blocks, however, were of such a design and in such a position that simple repair was not a solution. The blocks were completely redesigned and their new hydraulic characteristics necessitated a redesign of the baffle piers. In this instance the major difficulty was corrected by a complete change in hydraulic design.

These examples tend to point out the need for documentation of the findings concerning cavitation, and the corrective measures taken to eliminate damaging cavitation. Specifications have been changed to become more restricting as damaging cavitation appears in operating installations. In 1934 the specifications for Hoover Dam cautioned the contractor: "Special care shall be taken in the form work and finishes in all tunnels which will be subject to high velocities, and all projections or offsets on the surface shall be removed by rubbing or grinding with carborundum or by other methods satisfactory to the contracting office." In 1959 the specifications for Trinity Dam concerning concrete finishes and tolerances contain 9 pages of information including a clause to grind all irregularities to a bevel not more abrupt than a ratio of 1:100 height to length. A greater understanding of cavitation has led to design methods and procedures more nearly in line with actual needs. As sources of trouble appear and are corrected in an operating installation, similar sources of potential difficulty are circumvented for installations still on the drawing board. Future studies should add to the information given in these charts and examples, and thereby be of further aid to design engineers who are investigating cavitation damage in operating installations, and in the design of new installations.

REFERENCES

1. TVA Technical Monograph No. 68

2. Cavitation Damage of Roughened Concrete Surfaces, ASCE Journal of Hydraulics Division, October 1959

3. Hydraulic Model Studies of Vaquero Dam Outlet Works, USBR Hydraulics Laboratory Report Hyd 449

4. Stilling Basin Experiences of the Corps of Engineers, ASCE Journal of the Hydraulics Division, June 1957

5. Hydraulic Characteristics of Gate Slots, ASCE Journal of the Hydraulics Division, October 1959

6. Hydraulics Model Studies of Glendo Dam Outlet Works, USBR Hydraulic Laboratory Report Hyd 461.

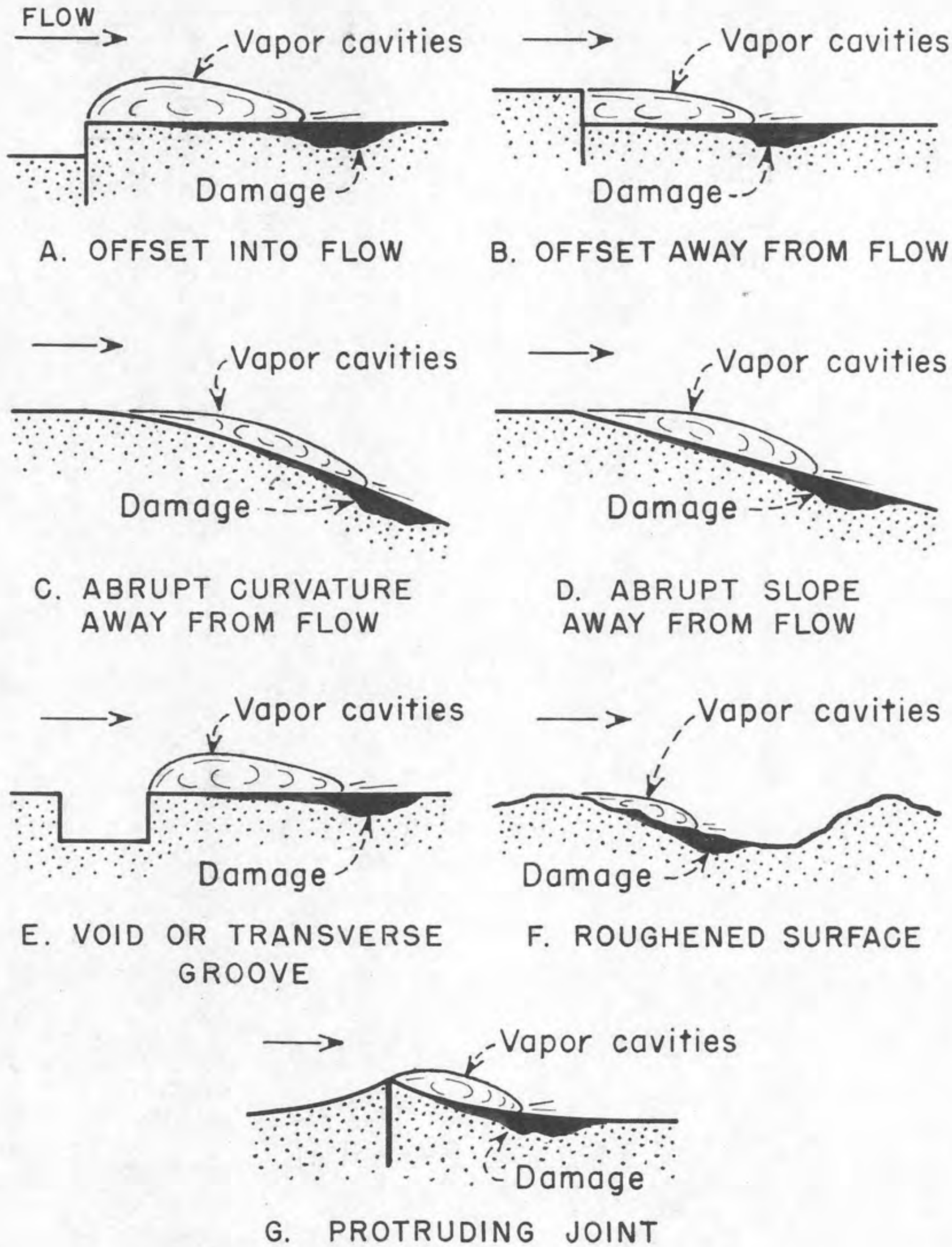

FIGURE 1. POSSIBLE OCCURRENCE OF CAVITATION AT FLOW SURFACE IRREGULARITIES

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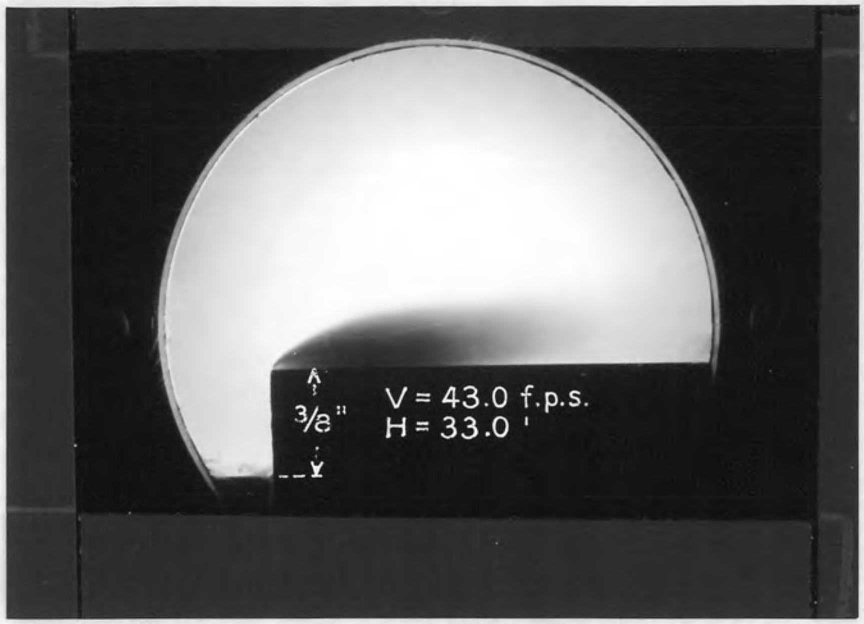

FIGURE 2 -- 90° Offset Into The Flow

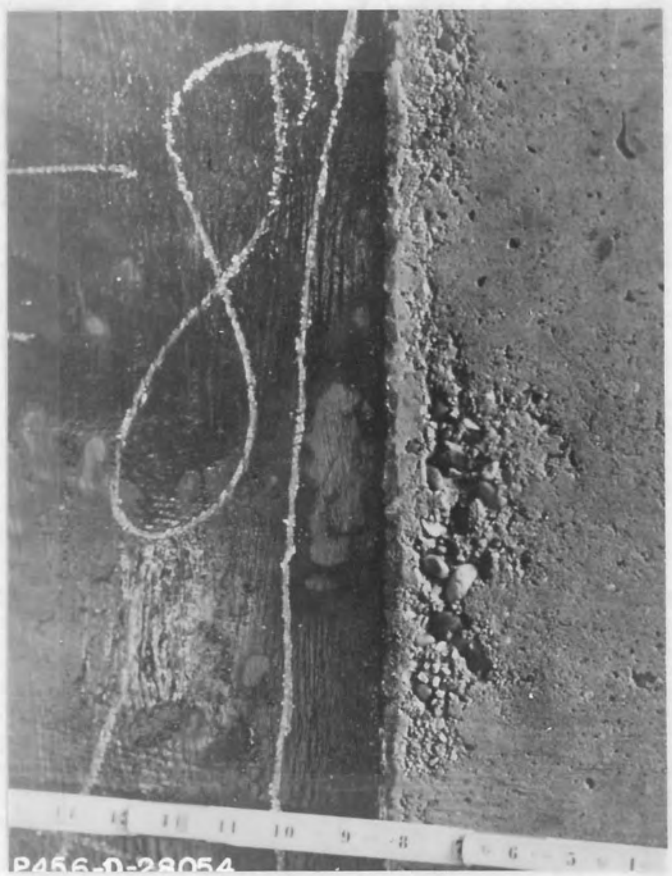

FIGURE 3 -- $\frac{1}{4}$" Offset Into The Flow, Corner Naturally Rounded

FIGURE 4 -- Extensive Cavitation Damage in an Outlet at Grand Coulee Dam

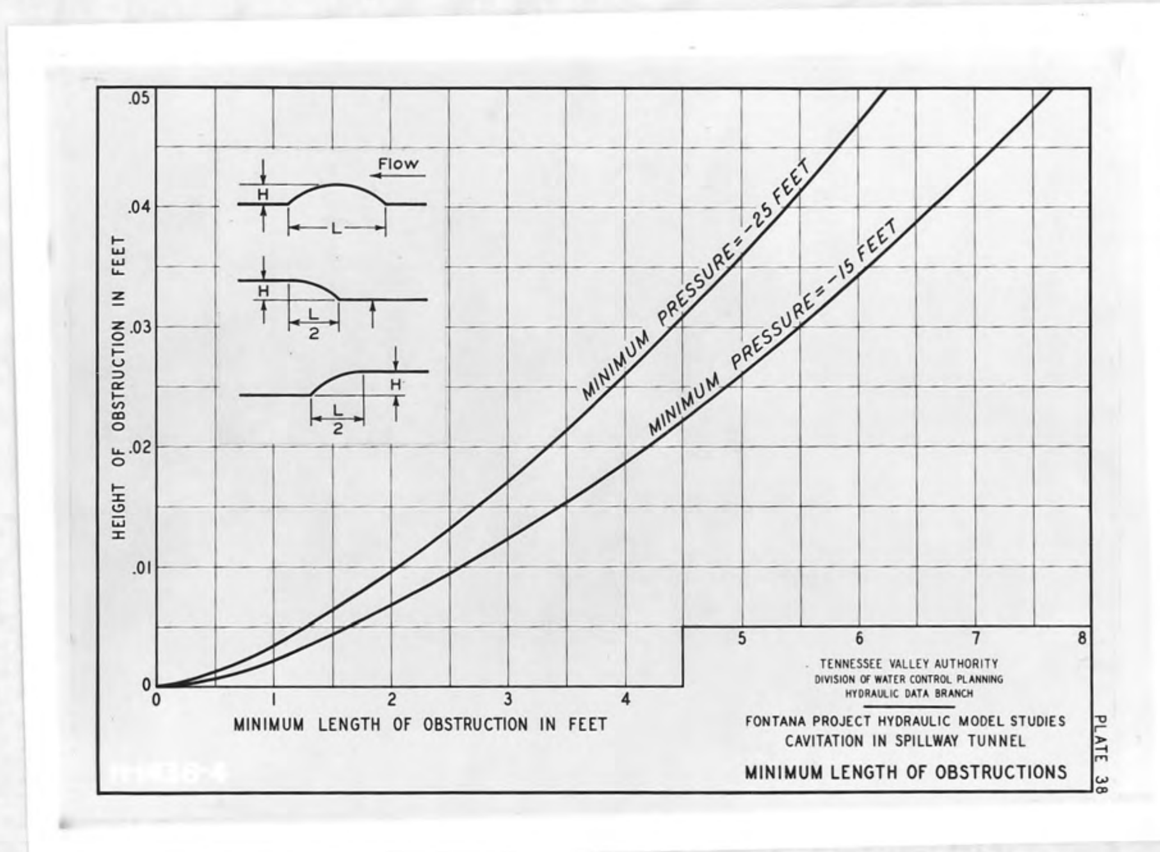

FIGURE 5 -- Velocity 150 fps

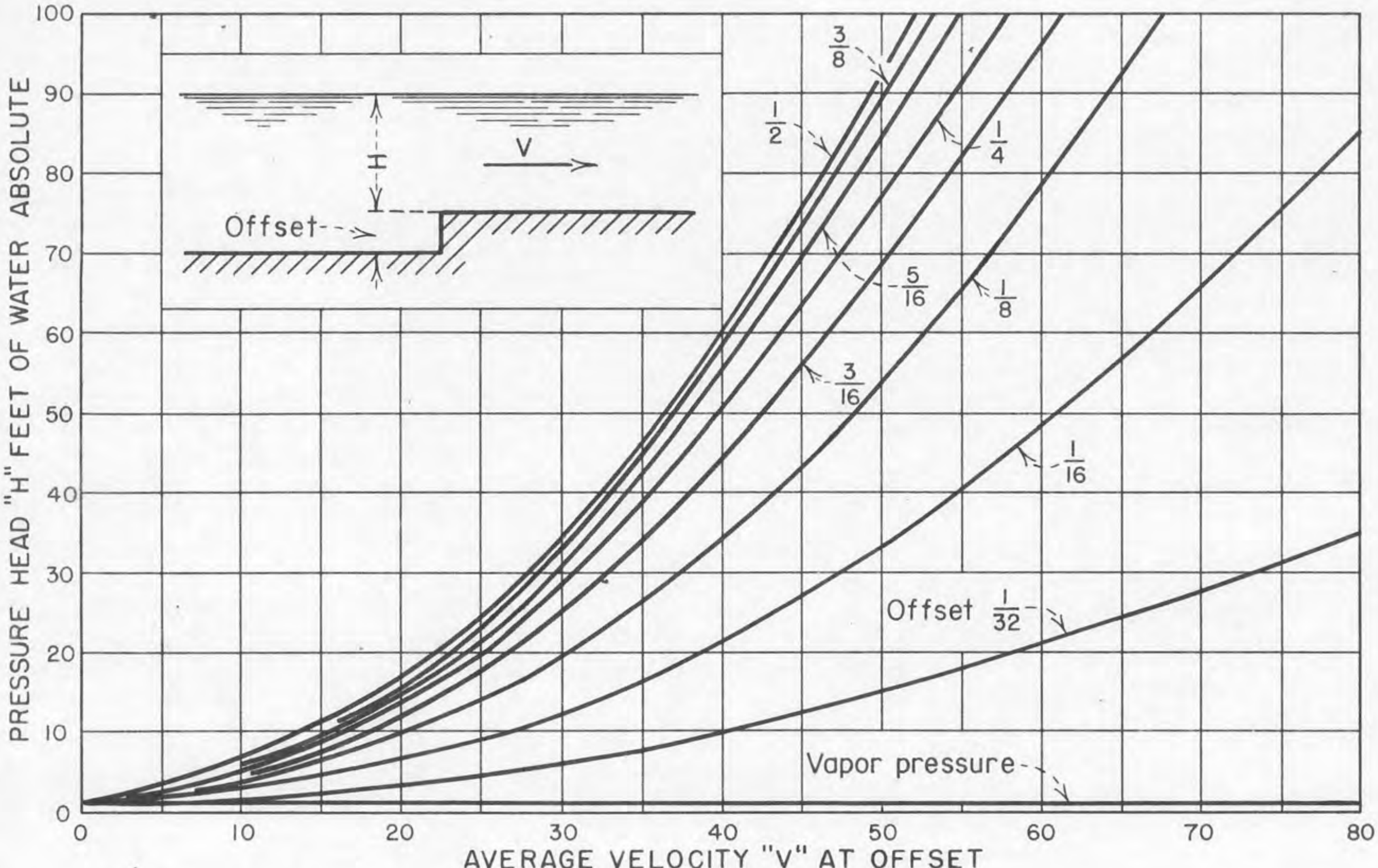

FIGURE 6.- HEAD-VELOCITY RELATIONSHIP FOR INCIPIENT CAVITATION-ABRUPT, INTO-THE-FLOW OFFSETS

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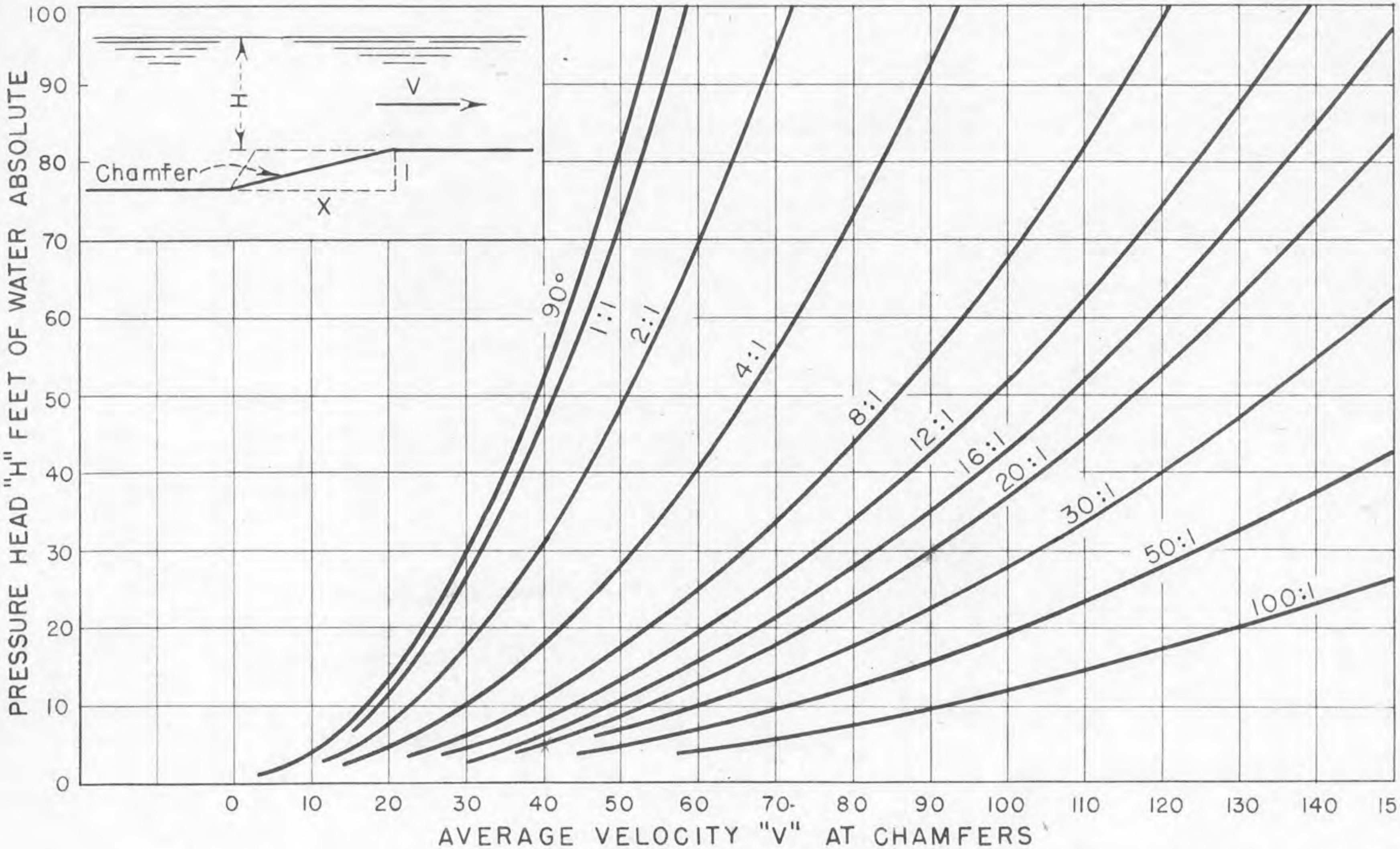
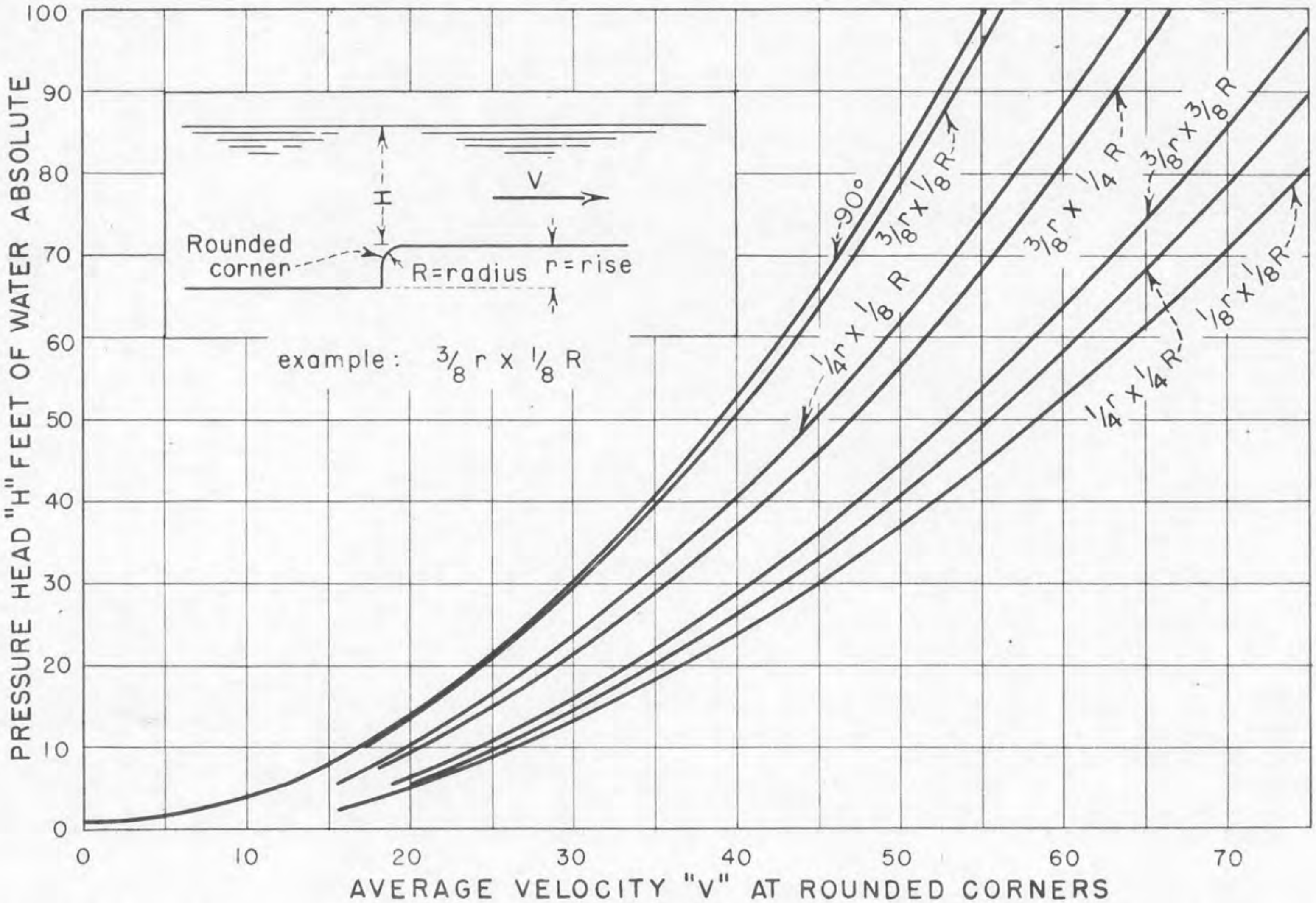


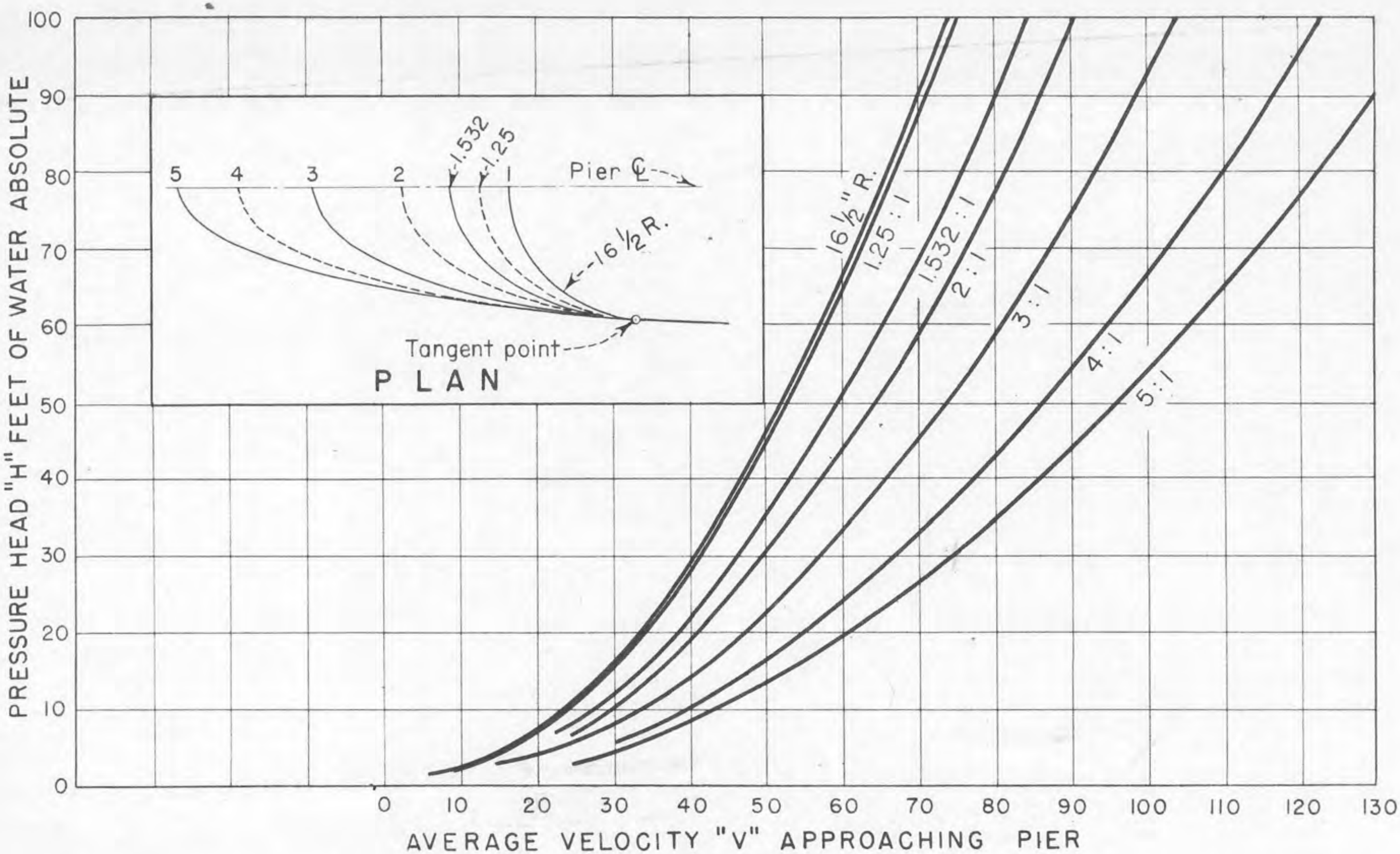
AVERAGE VELOCITY RELATIONSHIP FOR INCIPIENT CAVITATION - INTO THE FLOW CHAMFERS

Figure 7



AVERAGE VELOCITY RELATIONSHIP FOR INCIPIENT CAVITATION - ROUNDED CORNERS

Figure 8



AVERAGE VELOCITY RELATIONSHIP FOR INCIPIENT CAVITATION - ELLIPTICAL PIER NOSE SHAPES

Figure 9

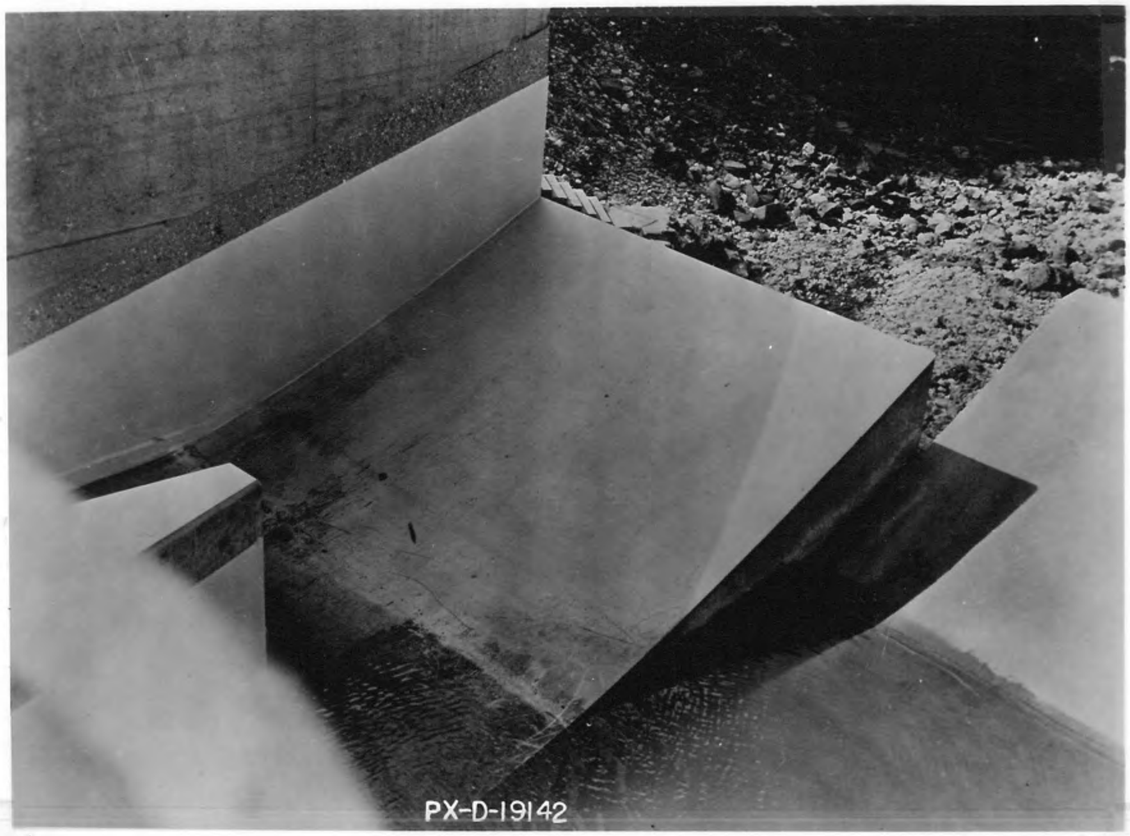
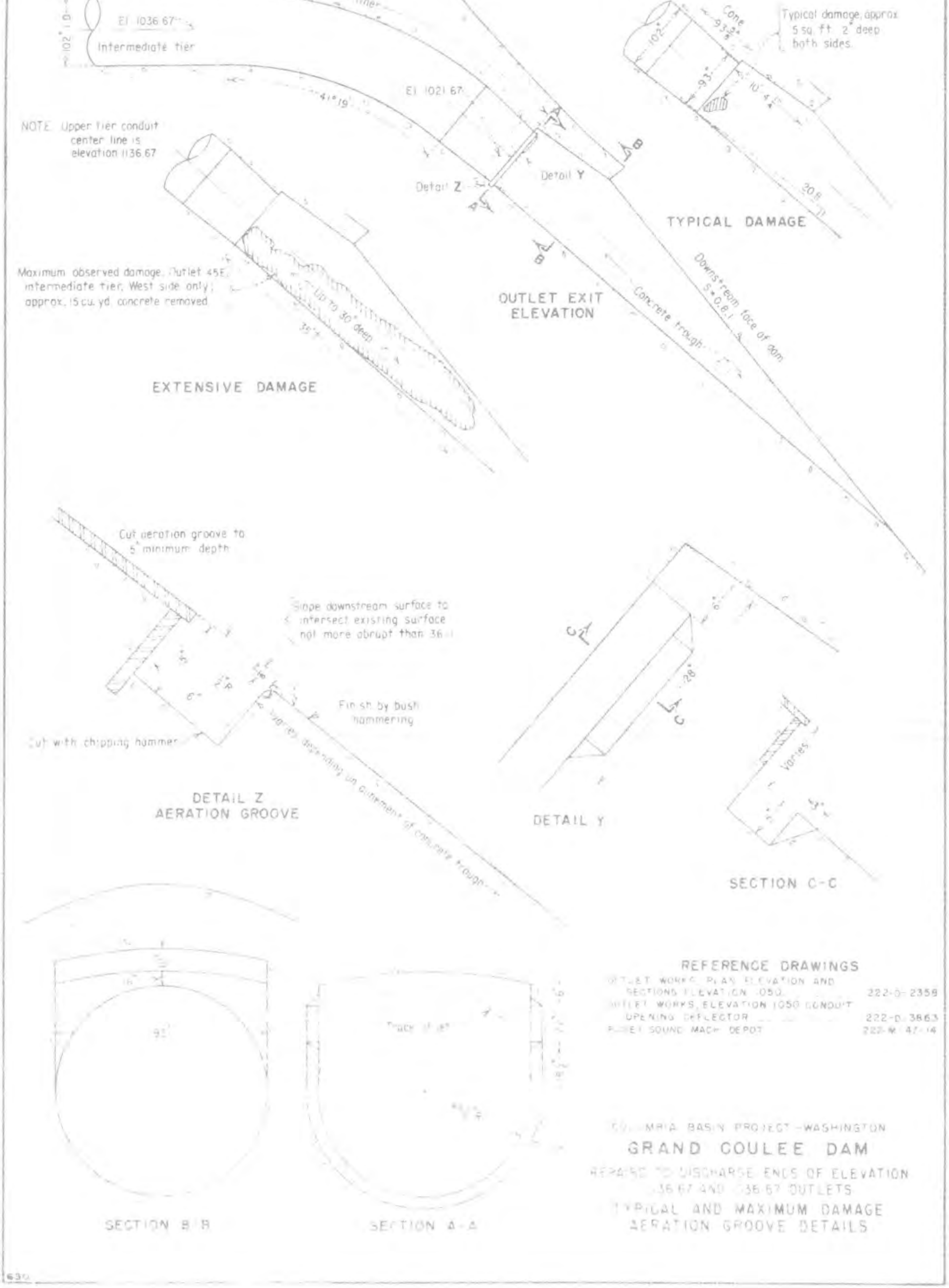


FIGURE 10 -- Steel Clad Flow Boundaries,

Lucky Peak Dam

Figure 11



Steel liner
El. 1036.67
Intermediate tier
El. 1021.67
NOTE: Upper tier conduit center line is elevation 1136.67
Detail Z
Detail Y
Cone
Typical damage, approx. 5 sq. ft. 2" deep both sides.
TYPICAL DAMAGE
Maximum observed damage, Outlet 45E, intermediate tier, West side only; approx. 15 cu. yd. concrete removed
Up to 30" deep
OUTLET EXIT ELEVATION
Concrete trough
Downstream face of dam
EXTENSIVE DAMAGE
Cut aeration groove to 5" minimum depth
Slope downstream surface to intersect existing surface not more abrupt than 36:1
Finish by bush hammering
Cut with chipping hammer
Varies depending on alinement of concrete trough
DETAIL Z
AERATION GROOVE
DETAIL Y
Varies
SECTION C-C
SECTION B-B
SECTION A-A
REFERENCE DRAWINGS
GRAND COULEE DAM
TYPICAL AND MAXIMUM DAMAGE
AERATION GROOVE DETAILS

FIGURE 12 -- Epoxy Mortar Patch in an Outlet Tunnel

at Grand Coulee Dam