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Hoover Dam Tunnel Spillway Damage

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An Overview of Hoover Dam Tunnel Spillway Damage

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Introduction

The Hoover Dam tunnel spillways have provided the Bureau of Reclamation hydraulic laboratories with new and continued opportunities for applied research. Early in the feasibility investigations for the original design and construction of the Boulder Canyon Project it became evident that new design and construction technologies would have to be developed to successfully accomplish the mission. The Bureau of Reclamation Engineering and Research laboratories were expanded to lead this endeavor. The two most prominent laboratories in this period were the Concrete and Hydraulic Laboratories. During the peak years (1930-1936) of the Boulder Canyon Project design and construction, four hydraulic laboratories played important roles in developing the hydraulic structures for Hoover Dam. These laboratories, all in Colorado, were located at Montrose, Fort Collins, and two sites in Denver. Presently all of the Bureau laboratories, including the sole surviving hydraulic laboratory, are located at the Engineering and Research Center in Denver, Colorado.

The scope of the Boulder Canyon Project was massive. Four 50-ft-diameter tunnels, two on each side of the river, were driven through the canyon walls to divert the river discharge during construction. Ultimately, all of the tunnels were modified for further use as spillways, outlet works, or power penstocks in the completed structure (fig. 1). The outside tunnel in each abutment became a part of the spillway system while the two inner tunnels housed the river outlet works and power penstocks.

Original Investigations

Several spillway alternatives were investigated. The requirements of a high reservoir water surface that had to be maintained for power revenue, a massive flood control pool and unprecedented discharge capacity were challenging criteria. The selected design consisted of twin tunnel spillways with flow control at the reservoir accomplished by two side channel inlet structures, each with four 100-ft (30.48 m) long by 16-ft (4.88 m) high drum gates. The axis of each side channel spillway is nearly normal to the dam axis.

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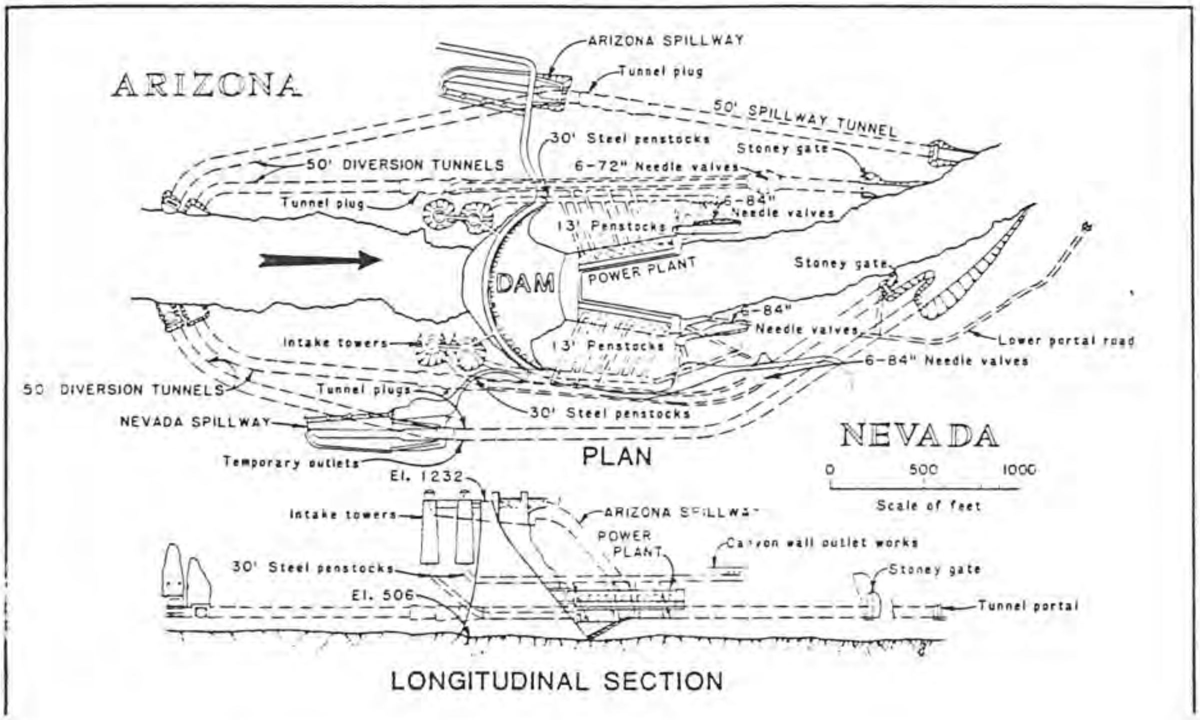


Figure 1. - Plan and section of Hoover Dam.

Construction of the dam and appurtenances was completed in 1936, but the spillways were not used until 1941. At that time a relatively small average discharge of about 13,555 ft^3/s (384 m^3/s) was passed through each spillway for about 4 months. During this operation one of the Arizona drum gates inadvertently dropped, increasing the discharge to 38,000 ft^3/s (1076 m^3/s) for several hours.

Inspection after this operation revealed essentially no damage in the Nevada tunnel spillway, but massive erosional damage in the Arizona tunnel spillway, near the vertical curve at the diversion tunnel plug. Several possible causes for this damage were discussed, with the most probable being that an abrupt misalinement in the tunnel invert deflected the high velocity flow causing subatmospheric pressures and the formation of vapor pockets. Subsequent implosion of these vapor pockets further downstream caused cavitation damage which destroyed the integrity of the concrete lining and eventually led to the massive erosional damage. The tunnel misalinement was corrected and the concrete damage repaired - leaving a surface finish similar to terrazzo.

In discussing possible protective methods, it was suggested that air introduced into the flow near the concrete surface might provide a "cushioning" effect and prevent cavitation damage. Model studies were performed on a 1:60 scale model of the tunnel spillway to develop a method of naturally injecting air into the spillway flows. After tests on many different schemes, a 2-1/2-ft (0.76-m) high sill, across the invert of the tunnel and a short distance downstream of the tunnel entrance, was developed (fig. 2). Subsequent air measurement tests indicated large quantities of air

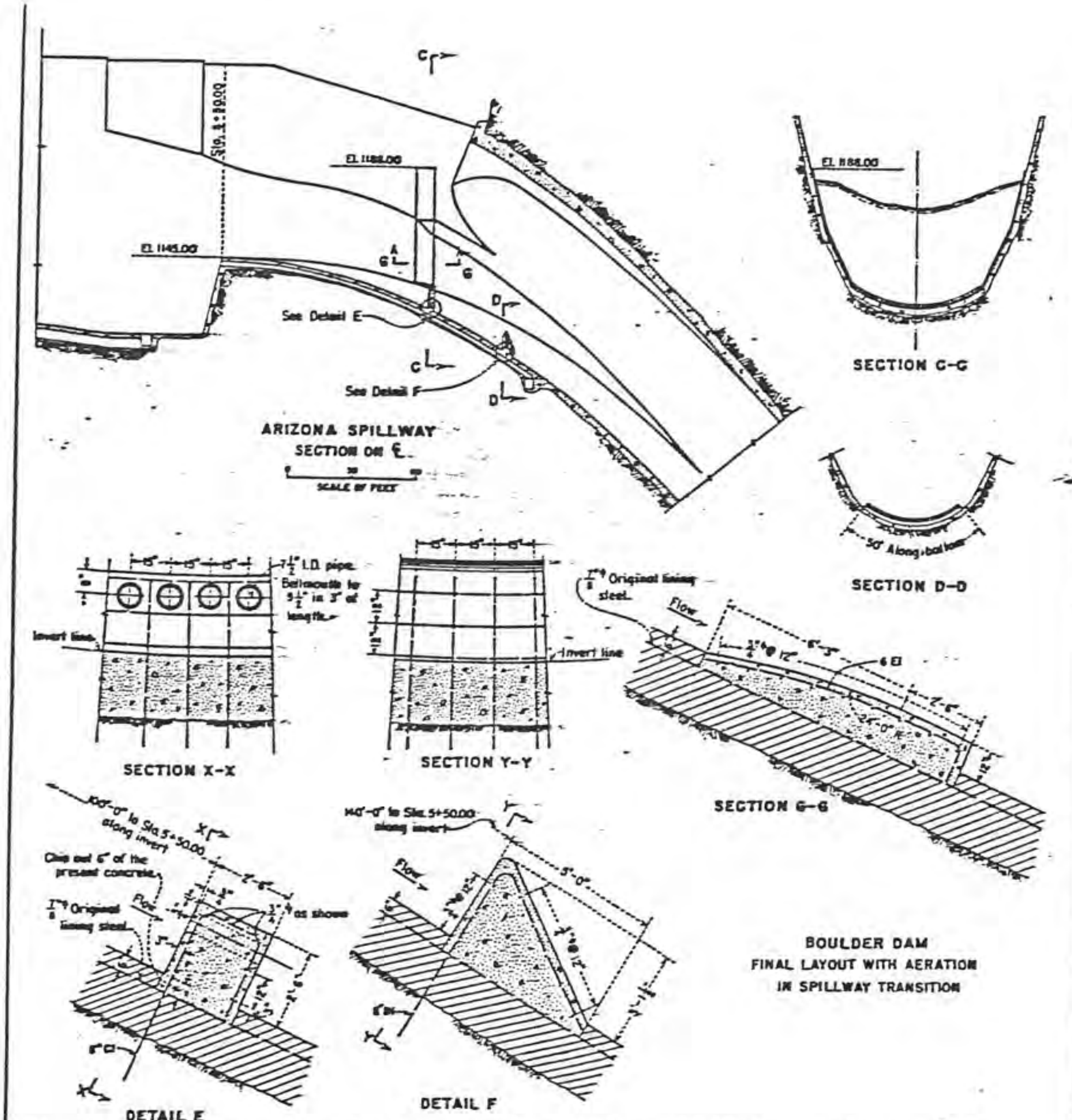


Figure 2. - Aeration device developed from 1942 hydraulic model studies.

intake at the deflectors but no air near the invert at the vertical curve. Sills and dentates at the P.C. of the vertical bend and in the bend itself failed to supply air to the desired areas. Because of the negative results these air induction tests were discontinued.

Recent Investigations

The tunnel spillways were not used again until the 1983 floods. Comparatively low flows [less than 10,000 ft^3/s (283 m^3/s)] through each spillway were discharged for several hundred hours. Minor cavitation damage occurred, more in the Nevada than the Arizona tunnel. Since it is known that this type of damage is cumulative, it was decided that aeration devices should be installed in both tunnels.

Since the unsuccessful model studies of the late 1930's, much has been learned about cavitation theory. Cavitation is the formation of a void or "bubble" within a liquid. In hydraulic structures, cavitation occurs when local pressure is reduced below atmospheric pressure, usually because of flow surface irregularities. The collapse of these cavitation bubbles as they entered areas of higher pressure caused damage to the flow surface in 1983 at Glen Canyon and Hoover Dams. Providing aeration where the potential for cavitation exists will reduce or eliminate cavitation damage.

Technology has been developed which predicts cavitation damage by relating pressure to velocity. The parameter which defines this relationship is the cavitation index, σ:

$$\sigma = \frac{P_o - P_v}{1/2\rho\ V^2}$$

where P_o = reference pressure
P_v = vapor pressure
ρ = fluid density
V = flow velocity

From past experience, cavitation in hydraulic structures has occurred when the velocity increases or pressure decreases such that the cavitation index drops below 0.20.

Locations for providing aeration in hydraulic structures are based upon this index and the tunnel geometry downstream. [Falvey, Henry T., Cavitation in Hydraulic Structures, Bureau of Reclamation Monograph, Denver, Colorado, (yet to be published).] For Hoover Dam spillways, the aerator was located at Sta. 8+75 where σ = 0.184 and the flow had already dropped over 200 ft (61 m) through the tunnel. The flow surface upstream of the aeration device will be carefully finished.

An aeration device is composed of a ramp, slot, and downstream transition from the slot to the original lining. These portions of Hoover's aerator design were initially determined based upon designs from Yellowtail and Glen Canyon aeration devices. However, because the design of aeration devices and their effect on downstream flow patterns was still in the developmental stage, a model study was performed.

Aeration devices were studied with a 1:52.174 scale model of Hoover Dam's Arizona tunnel spillway. The model included a portion of the reservoir, the side channel inlet structure (without controlling drum gates), and the 50-ft (15.24-m) diameter tunnel which is inclined 50° to intersect the long, almost horizontal diversion tunnel - ending with a flip bucket (fig. 3). Test discharges ranged from small flows of 5,000 ft^3/s (142 m^3/s) to a maximum of 200,000 ft^3/s (5663 m^3/s) which is the design capacity of each spillway tunnel.

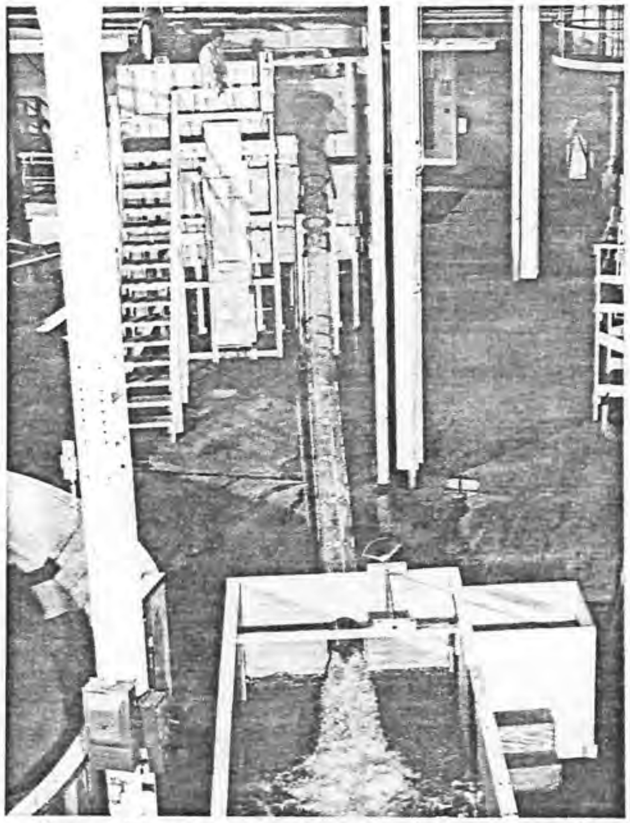


Figure 3. - Overall view of Hoover Arizona spillway model.

Turbulent flow from the side channel inlet structure, and the flip bucket geometry, produced major aerator design considerations. Flow over the side channel spillway crest created a roller upon impacting the floor and opposite wall of the side channel basin. Flow direction in the basin changed almost 90° before entering the tunnel. Turbulence caused by the changing flow direction and the roller increased in magnitude as the discharge increased. This turbulent flow condition remained throughout the inclined portion of the tunnel and caused many modifications to the original aeration device design to prevent the vent from filling with water.

Flip buckets were added in the spillway tunnel exits in 1944 to prevent erosional damage in the river channel downstream. The resulting area constriction at the flip buckets produced three different flow phases:

- Free flow until the tunnel exit closes off at approximately 135,000 ft^3/s (3823 m^3/s)

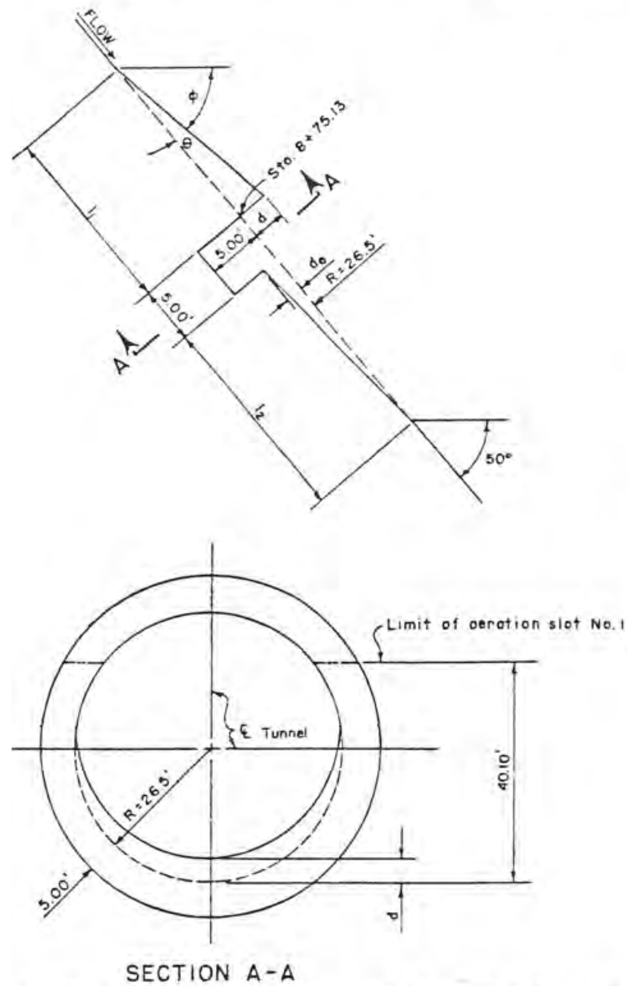
- A transient hydraulic jump in the almost horizontal an steeply inclined sections of the tunnel for discharges between 135,000 (3823) and 185,000 ft^3/s (5239 m^3/s).

- Pressure flow for discharges exceeding 185,000 ft^3/s (5239 m^3/s).

These flow conditions were all considered in the aeration device design, even though recommended operation is under free flow conditions. Addition of the aerator and subsequent enlargement of the vent area produced a more stable flow condition and reduced the extremely large pressure fluctuations at the tunnel exit when the hydraulic jump was present in the tunnel.

The initial design for Hoover's aeration device was based upon previous successfully tested air vent installations. The location of the aeration device (Sta. 8+75) was determined by computing cavitation indices over the full range of discharges while maintaining a free water surface throughout the entire structure. Preliminary aeration devices are shown schematically on figure 4. For the final design significant changes were made to these preliminary designs, particularly to the ramp invert height [from 1.2 (0.37) to 3 ft (0.91 m) high], ramp angle (from 6 to 10°), and aeration area (elimination of the groove). These changes were necessary to provide a large aeration area under the jet and prevent submergence of the slot during normal operation.

The turbulent, spiraling flow at the aerator location greatly affected the final aerator design. Most design changes were made to help contain this flow and prevent water from filling the slot. Eliminating the aeration groove by beginning the transition back to the original tunnel lining at the base of the upstream ramp



DIMENSION	AERATION SLOT		
	NO. 1	NO. 2	NO. 3
d	1.20'	3.00'	3.00'
l_1	11.46'	17.26'	17.26'
l_2	18.75'	18.75'	15.00'
d_o	1.25'	1.25'	3.00'
θ	6°	10°	10°
ϕ	44°	40°	40°

Figure 4. - Preliminary aeration devices tested during recent hydraulic model studies.

allows the slot to drain automatically and will be easier to construct. Operation of the model for the flow of 20,000 ft^3/s (566 m^3/s), with the final aeration device installed, is shown in figure 5. The dramatic changes from the original geometry revealed the value of laboratory modeling.

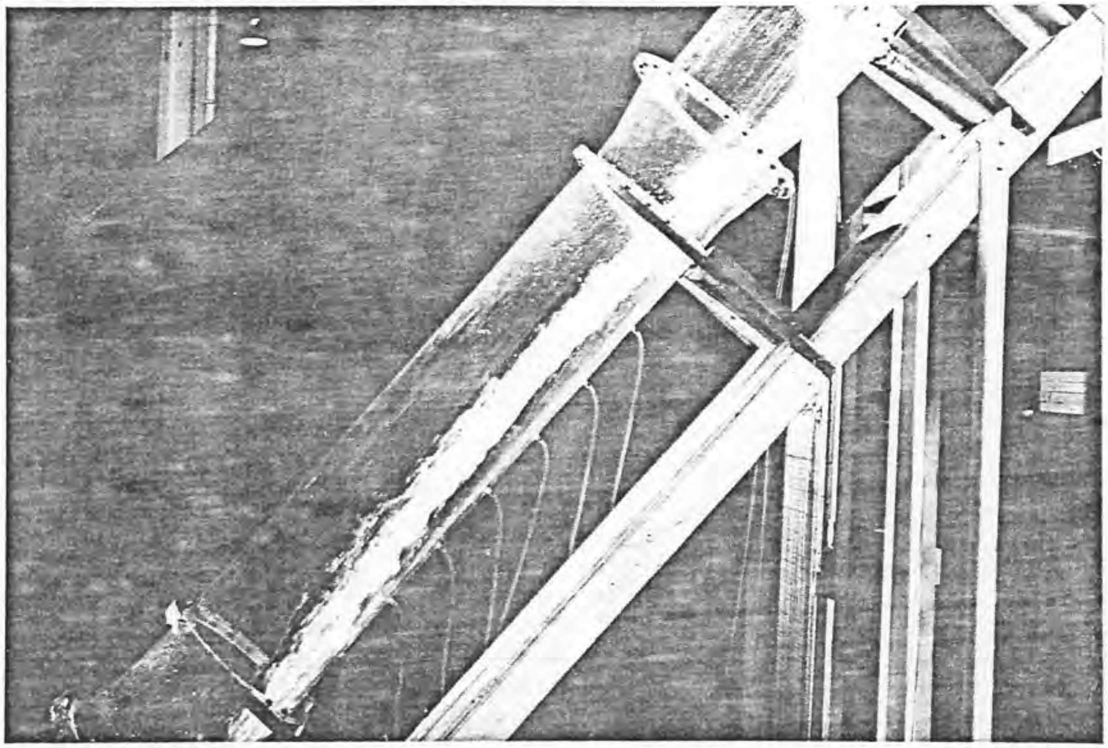


Figure 5. - Final aeration device passing 20,000 ft^3/s.

Proposed Modifications

The final design of the aeration devices for the Arizona and Nevada spillways is identical in size and location. In prototype, the overall length of each device (fig. 6) is 42.25 ft (12.88 m) with the upper 17.25 ft (5.26 m) consisting of the ramp area. This ramp projects 3 ft (0.9 m) into the flow at the invert and feathers to the original concrete surface at 35° on each side of the tunnel crown. The lower 25 ft (2.62 m) of the device consists of a concentric 5-ft (1.52 m) offset away from the flow which transitions back to the original tunnel lining at a rate of 5 ft (1.52 m) along the flow to 1 ft (0.3 m) perpendicular to the flow. The beginning of the 5-ft (1.52 m) offset is at invert Sta. 8+75 and approximately 275 vertical feet (83.8 m) above the elbow invert. This location and configuration provides aeration to the flow and protects the elbow area from cavitation damage.

The current schedule for construction of the aeration devices and repair of the damage from the 1983 spill is as follows:

Begin Nevada aeration device construction and spillway repair	October 2, 1985
Complete Nevada spillway work	May 15, 1986

Begin Arizona aeration device construction and spillway repair	October 1, 1986
Complete Arizona spillway work	May 15, 1987

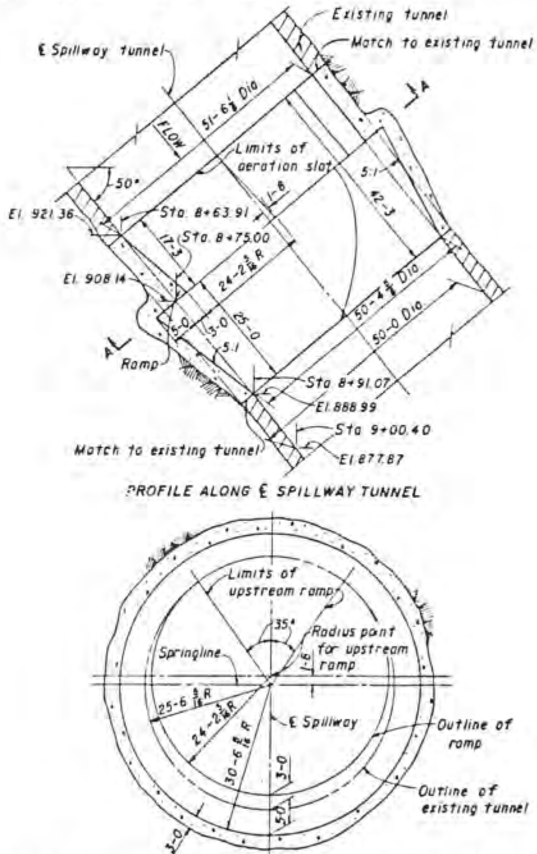


FIGURE 6.-PROTOTYPE AERATION DEVICE CONFIGURATION

This schedule keeps one of the spillways operational should releases be required from Lake Mead. The time between the work in the two spillways is provided in the event spring runoff inflow exceeds the capacity of the river and power outlets and the available storage. The schedule also allows for the majority of the work to be completed prior to anticipated construction of the new Hoover Dam visitor facilities.

During installation of the aeration devices, damage from the 1983 spill will be repaired. Damage to the Arizona spillway is relatively minor with only four small areas of cavitation damage in the elbow area. These will be repaired by using underwater grinding techniques which will eliminate the expense of dewatering the Arizona spillway tunnel. Damage in the Nevada spillway is more extensive with approximately 20 yds^3 (15.3 m^3) of the tunnel lining in the elbow area removed during the 1983 spill. Repair of this damage will require dewatering of the tunnel - probably by use of a bulkhead and sump pumps at the end of the tunnel.

In addition to repairing the cavitation damaged areas, much work will be required to restore smooth, uniform concrete flow surfaces. Calcite deposits, concrete spalling, old form lines, etc., must all be ground to acceptable bevels to prevent cavitation damage due to offsets. Required bevels are 15 run:1 rise approaching the aeration device and 20 run:1 rise immediately upstream of the aeration device offset and in the downstream area. Special attention will be concentrated on the area immediately upstream of the aeration device as this will be the area of the highest velocities and thus the highest cavitation potential. New concrete in the aeration device ramp will need to be kept within stringent construction tolerances in order to avoid cavitation producing offsets.

Provisions for instrumentation are being included in the Nevada spillway aeration slot and elbow areas. Locations are shown in figure 7. The purpose of the instrumentation is to collect prototype data on aeration slot performance. Theoretical computations, model study data, and prototype data can then be evaluated for conformance. The instrumentation is being placed in the Nevada spillway only. The reasons include: the geometry of the Nevada and Arizona spillways are nearly identical; the Nevada spillway alinement provides a better directional release of flows into the river channel and would normally be used before and more often than the Arizona spillway; and the costs of fabricating and installing the instrument boxes, installing the instrumentation, collecting the data, and reducing the data will be minimized.

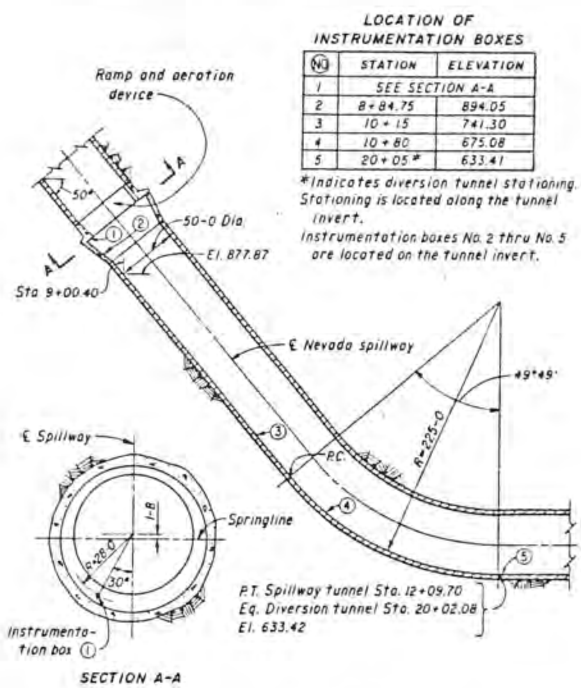


FIGURE 7.- NEVADA SPILLWAY INSTRUMENTATION LOCATION

The instrument boxes will be installed during the spillway repair construction. Because of the relatively infrequent use of the spillways, the instrumentation will not be added until just prior to use of the spillway. Because of the importance of the water and power in this area, no testing of the spillway or instrumentation is planned. The first "test" will come when releases are required through the spillway.

When it is anticipated that use of the spillway will be required, the instrumentation boxes will be equipped with remote data recording equipment. This precludes installation of conduits and wiring. Data collected will include pressures, velocities, and hopefully, air-water concentrations downstream of the aeration device. This data will be useful for updating the current aeration device information and will be applied to future designs.

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HYDRAULIC MODEL STUDIES OF HOOVER DAM, ARIZONA, TUNNEL SPILLWAY - AERATOR DESIGN

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16. ABSTRACT

Recent cavitation damage in steeply sloped tunnel spillways has prompted investigation of aerator design. The hydraulic model of the Hoover Dam Arizona tunnel spillway included the side channel spillway, the steeply sloped tunnel with a vertical bend and the long, almost horizontal, section ending with a flip bucket. An aerator was installed in the physical model according to the location determined by a mathematical model and the final aerator dimensions determined during the physical model study. The final design for the aerator included a ramp extending to 35° either side of the crown with a ramp angle of 10° and a 3-ft invert height. The air slot and downstream transition section were formed by a concentric 5-ft offset away from the flow which returned to the original tunnel lining on a 5:1 chamfer. This aerator geometry provided air underneath the jet until the slot was submerged by the bucket. Pressures were measured downstream of the aerator, through the vertical bend, and at the flip bucket.

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HYDRAULIC MODEL STUDIES OF HOOVER DAM, ARIZONA, TUNNEL SPILLWAY - AERATOR DESIGN

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Research and Laboratory Services Division
Denver Office
Denver, Colorado

Month 1992

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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The model study was initiated to design an aerator for the Hoover Dam tunnel spillways Designers who requested the study and provided assistance included Harold Blair, Robert Quint, and Steve Higinbotham.

Dr. Henry Falvey provided technical assistance in aerator design. Cheryl States drafted model drawings and gathered data. The model was constructed by the Hydraulics Branch shop personnel. Photography was by Wayne Lambert.

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GLOSSARY

d	=	ramp height
θ	=	ramp angle
a	=	angle of inclined tunnel
o	=	angle of inclined tunnel minus ramp angle α - 0
d_o	=	depth of offset away from invert
l_2	=	length of downstream transition section
p	=	fluid density
o	=	cavitation index
p_o	=	reference pressure
p_v	=	vapor pressure
V	=	flow velocity
x	=	horizontal distance under the jet from the downstream end of the ramp
L	=	cavity length under the jet = $\dfrac{x}{\cos \alpha}$
y	=	depth of flow normal to surface
S_o	=	tunnel slope = $\tan \alpha$
g	=	gravitational constant
Q_a	=	air flow rate
Q_w	=	water discharge

INTRODUCTION

Hoover Dam, Boulder Canyon Project, is located on the Colorado River 36 miles southeast of Las Vegas, NV, on the Nevada-Arizona state line. The dam eliminated the constantly recurring cycles of flood and drought in the southwest. Hoover Dam forms Lake Mead which provides irrigation water and hydropower to southern California, Arizona, Nevada, and Mexico. Lake Mead is also a popular recreation site.

Two 50-ft-diameter inclined tunnel spillways, each with a maximum design discharge capacity of 200,000 ft^3/s at reservoir elevation 1232, are major features of the dam. Upstream of the tunnels are two side channel spillways, each controlled by four 100- by 16-ft drum gates (fig. 1). The spillways have passed flows only twice in their history - in 1941 and 1983. Normally releases are made only through the powerplant.

In 1941 extensive damage to the concrete tunnel lining occurred in the Arizona spillway. The damage was thought to be a result of a tunnel invert misalignment which produced cavitation and subsequent erosion. The tunnel misalignment and damaged concrete lining were repaired. Flip buckets were also added to both tunnel exits to prevent erosion of the steep-walled canyon downstream (fig. 2). In the spring of 1983, the spillways operated again but with smaller, shorter duration discharges. Cavitation and erosion damage occurred in the elbow area of the Nevada spillway, producing a hole 35 ft long, 6.83 ft wide, and 3 to 4 ft deep. This cavitation damage, although minor compared to that of 1941 and the extensive damage at Glen Canyon Dam, prompted the model study. Hoover Dam model studies were conducted from December 1983 to February 1985. The Arizona spillway was modeled to determine the correct location and configuration of an aerator for both tunnel spillways.

Introducing air between the jet and the flow surface may reduce the potential for cavitation damage. Previous experiences at other spillways of similar geometry - Yellowtail (Colgate, 1971) and Glen Canyon (Pugh, 1984) - demonstrated that aerators reduce the potential for cavitation damage. This model study was conducted to determine the optimum aerator location and geometry for the Hoover Dam tunnel spillways. The model study was necessary because no standardized aerator design criteria are available. Addition of these aerators should prevent future cavitation damage.

RESULTS

1. The aerator should be located at Sta. 8+75 in both spillway tunnels.

2. The aerator consists of an upstream ramp, a slot or area for air passage, and a transition back to the original tunnel lining. The ramp lifts the jet allowing aeration between the jet and the flow surface. The slot supplies air from above the free water surface to the underside of the nappe. The transition downstream of the slot returns the offset created by the slot back to the original lining. Final aerator dimensions are shown on figure 14.

Renumber fig. 3 etc.?

3. With the aerator and a free water surface for all flows, a maximum discharge of 203,000 ft^3/s is attained through each spillway at reservoir 1232.

4. The flip bucket at the end of the spillway tunnel produced several different flow conditions. For discharges above 135,000 ft^3/s the flow area constriction at the flip bucket caused a transient hydraulic jump in the tunnel Large pressure fluctuations occurred in the flip bucket area while the hydraulic jump was in the tunnel. These fluctuations continued as the jump moved upstream until the tunnel entrance was sealed and the tunnel became pressurized. Pressure flow ended the fluctuations, but the maximum spillway capacity decreased to 191,000 ft^3/s at reservoir elevation 1232. The magnitude of the model pressure fluctuations caused concern for the structural integrity of the prototype tunnel. Therefore, operating capacity for each spillway tunnel should be restricted to 135,000 ft^3/s. To produce a free water surface in the tunnel for all flows, the area constriction at the flip bucket must be alleviated. This can be accomplished by providing a flow area at the flip bucket equal to or greater than that produced by removing 40 ft of the tunnel crown to the width of the flip bucket vertical side walls.

APPLICATION

The geometry of future spillways should be determined so that cavitation producing pressures will not occur. If this is not feasible, and the spillway geometry and flow velocities indicate the potential for cavitation, a means of providing aeration must be established.

The general aerator configuration developed for the Hoover tunnel spillways could be used in the design of aerators for other tunnel spillways. Combining the air slot and downstream transition back to the original lining is particularly applicable to any aeration device because this allows the slot to drain and requires less formwork during construction.

HYDRAULIC MODEL FEATURES

Similarity by Froude relationship was maintained by the model. (Is the preceding sentence to be replaced by "Since gravitational forces predominate, the model was designed on the basis of Froude number similarity."?? The model scale, 1:52.174, was based on the pipe size that would produce accurate results and the largest model for the space available. The model included a portion of the reservoir area and the entire Arizona spillway. The model is shown on figure 3.

The 486.75-ft-long side channel spillway was represented by a model length of 9.33 ft. Flow from the side channel spillway enters the tunnel which transitions from a flat-bottomed trough shape to a 50-ft-diameter tunnel. A 0.958-ft-diameter pipe on a 50° inclined slope represented the model tunnel. The 225-ft radius vertical curve scaled to a 4.31-ft radius curve and the nearly horizontal 1,390.6-ft-long downstream tunnel scaled to 26.65 ft. The terminal structure in the tunnel is a 105.67-ft-long flip bucket represented by a model length of 2.03 ft.

The 587.6-ft drop from the maximum reservoir water surface to the flip bucket scaled to 11.26 ft.

At maximum reservoir elevation 1232, the 26.6-ft head over the side channel spillway crest scaled to 0.51 ft, producing a maximum free flow discharge of 203,000 ft^3/s modeled by 10.32 ft^3/s. The four 100- by 16-ft drum gates were not modeled because it was determined that they would not affect the study results.

The overflow crest and spillway side channel were modeled using sheet metal. The transition section from the side channel to the tunnel was made of high-density polyurethane foam. The tunnel was modeled entirely of clear plastic with a removable section for the aerator. Clear plastic allowed all aspects of the tunnel flow to be observed. Water was supplied to the model by the permanent laboratory supply system and measured by Venturi meters. Reservoir elevations were measured upstream of the side channel overflow crest with a hook gauge. The correct tailwater was maintained using prototype tailwater elevations for the upper gauging station from drawing 45-D-908.

The model was tested with prototype discharges of 5,000, 20,000, 50,000, 100,000, 145,000, 175,000, and 200,000 ft^3/s. Documentation included visual observations of the flow patterns, pressure measurements along the tunnel invert downstream of the air slot, static and dynamic pressure measurements at the flip bucket, photographs, and video tape recordings.

Air demand or air velocities could not be measured in the model due to the slot configuration and the splashing produced by the turbulent flows. Also the relationship between model and prototype dynamic pressures and airflow rates were not determined. Research is **currently??** underway which will attempt to determine this relationship (Pinto and Neidert, 1982; Frizell, 1985).

INITIAL MODEL TESTS - NO AERATOR

Initial model testing was performed without an aerator to compare flow conditions before and after installation of the aerator (fig. 4). Initial testing indicated two flow conditions that greatly influenced aerator design:

- Spiraling, turbulent flow developing in the side channel spillway and continuing through the proposed aerator location. Previous model studies did not address turbulent flow through the inclined portion of the tunnel (Bureau of Reclamation, 1938).

- The flow area constriction at the flip bucket producing a transient hydraulic jump in the tunnel during high discharges. Flow over the side channel spillway crest creates a roller upon impacting the floor and opposite wall of the side channel basin. The flow then turns almost 90° before entering the tunnel (fig. 5). The turbulent spillway flow caused by these two phenomena increases as the discharge increases and continues through the transition and inclined portion of the tunnel (fig. 6). Effects of the turbulent flow on individual aerator designs are discussed in detail later in this report.

Pressures were measured to determine possible pressure changes caused by introducing air into the flow. Water surface profiles were noted to reference a comparison with the profiles created by addition of an aerator. After addition of the first aerator, it was evident that documentation of water surface profiles was not necessary. Observations of the flow patterns were enough to determine the applicability of the aerator design.

Flip buckets had been added to the spillway tunnel exits in 1944 to prevent erosion damage in the river channel downstream (Bradley, 1944). Initial model operation revealed three different tunnel flow conditions caused by the flow area constriction at the flip bucket:

- Free flow until the tunnel exit closes off at approximately 135,000 ft^3/s (fig. 7a). A transient hydraulic jump in the almost horizontal or the steeply inclined tunnel for flow rates between 135,000 and 185,000 ft^3/s (fig. 7b).

- Pressure flow for discharges exceeding 185,000 ft^3/s (fig. 7c).

Each of these flow conditions were considered during aerator design. Initial model operation revealed large pressure fluctuations at the flip bucket with the hydraulic jump in the tunnel.

AERATOR DESIGN CONCEPTS

Cavitation is the formation of a void or "bubble" within a liquid. In hydraulic structures, cavitation occurs when local pressure is reduced below atmospheric pressure, usually because of irregularities on the flow surface. As these bubbles enter an area of higher pressure, they collapse causing damage to the flow surface. The parameter which predicts incipient cavitation is a relationship between pressure and velocity known as the cavitation index or flow sigma:

$$\sigma = \frac{P_o - P_v}{1/2\ \rho\ V^2} \qquad (1)$$

where:

p_o = reference pressure

p_v = vapor pressure of liquid

ρ = fluid density

V = flow velocity

This relationship shows that the cavitation index decreases as the velocity increases. A computer program such as HFWS **(need to define??)** that determines the free water surface profile throughout the entire structure can be used to determine cavitation indexes. Hydraulic structures with a cavitation index greater than 0.20 have not experienced major cavitation damage.

Providing aeration to high-velocity flow reduces or eliminates **the potential for** (necessary?) cavitation damage. Aeration is most often achieved using aeration grooves or offsets. If possible, aerators should be placed where sigma is greater than 0.20 to provide air to the flow surface boundary throughout the entire area where cavitation may occur. In practice this is not always possible, in which case, the aerator may have to be placed downstream, where σ is <0.20, and the surface upstream carefully aligned and finished. Aerator design is based upon the correct configuration of a ramp or deflector, a groove or air slot, and a transition from the air slot back to the original flow surface. The following equations were used to determine the initial geometry of the aerator for Hoover Dam tunnel spillways; the parameters are defined in the glossary. **(These are quite simplified equations and should be used to determine the gross dimensions if an aerator with further refinement done using a physical model study.** (not clear?!? These equations will provide reasonable results assuming a standard installation is being proposed.

The ramp upstream of the aerator is required to lift the underside of the flow nappe over the air slot to allow air entrainment and to prevent the slot from filling with water. The jet trajectory is a function of the ramp height, ramp angle, flow velocity, and pressure under the nappe. The jet trajectory for shallow flow depths and neglecting reduced pressure under the nappe is given by:

$$y = x \tan \phi - \frac{gx^2}{2V^2 \cos^2 \phi} \qquad (2)$$

If possible, the jet from the ramp should impact at or downstream from the location of the minimum calculated cavitation index. To avoid excessively large fins, the jet trajectory should not impact in a concave vertical bend. The ramp angle is calculated to produce the desired jet impact area where the distance, x, to the impact area is estimated:

$$\cos^2 \phi \, (S_o - \tan \phi) = \frac{gx}{2V^2} \qquad (3)$$

The ramp height is then chosen so the aeration area will not be submerged or the downstream tunnel closed off by fins. Initial ramp height is estimated **as equal to 0.2 times the flow depth for the design discharge.** (what??) For circular conduits the ramp should be maximum at the invert and a feather out to zero at the free water surface of the design discharge. **Normally up to the springline will be adequate.** (adequate for what? not clear)

The aeration area is designed to provide adequate air quantities without exceeding a maximum air velocity of 300 ft^3/s. The air entrainment mechanism is a function of:

- Shear zones between the air and water surface
- Air-water mixture under the nappe
- Jet reattachment to the downstream surface
- Turbulence
- Viscosity and surface tension

These mechanisms are not fully understood; however, air demand may be estimated based upon the flow velocity of the water and the ramp angle upstream of the air slot. In circular conduits, the air slot must extend above the maximum water surface and the required airflow rate estimated by:

$$Q_a / Q_w = \frac{V^2 \cos^3 \phi \ (S_o - \tan \phi)^2}{4_{gy}} \qquad (4)$$

The airflow rate, Q_a, divided by maximum allowable air velocity, 300 ft/s, produces the initial estimate of the air slot area.

A transition back to the original flow surface is required downstream of the air slot. This transition is necessary to prevent the slot from submerging, to provide space under the jet nappe, and to prevent impingement of the jet on the sides of the tunnel. For a free draining air slot the transition should begin at the bottom of the vertical face formed by the ramp and slot and converge on a straight line back to the original flow surface.

These criteria?? will provide general guidelines for design of an aerator. Reasonable results for estimating aerator dimensions will be obtained using these guidelines. However, a hydraulic model study should be conducted to refine the aerator design. More research is needed before the air entrainment mechanisms are fully defined and easily applied to an aeration device. Also, extensive model prototype comparisons of air entrainment mechanisms are essential technology is constantly being updated (Henry T. Falvey, 1989).

Hoover Aerator Design

The previous guidelines and equations were used for the initial Hoover aerator design. However, during model testing several changes were made to the aerator that depart from these guidelines.

Cavitation indexes were computed throughout the entire spillway structure (appendix). These indexes predicted that cavitation producing pressures would occur, $\sigma < 0.20$, in the inclined tunnel and downstream of the vertical bend for several hundred feet (fig. 8). The increased pressure in the vertical bend would cause any cavities of low pressure to implode, producing damage to the concrete lining. Comparing these results with prototype tunnel spillway damage in 1941 and 1983 confirmed the computer program results (fig. 9). The location of the aerator for Hoover tunnel spillways was based upon the value of the cavitation index and the tunnel geometry. Because of the large area needing aeration and the complicated geometry farther upstream in the tunnel the aerator was placed at Sta. 8+75 where the cavitation index was 0.184 for the flow rate determined to be most critical. Because σ is <0.20 at this location the surface upstream must be carefully aligned and finished.

The original aerator geometry was determined using basic design guidelines. Two major changes were later incorporated into the geometry - the ramp extended beyond the tunnel springline and the air slot was combined with the downstream transition. All aspects of the aerator design will be discussed in more detail in the following sections.

PRELIMINARY AERATOR DESIGN

Three aerators were tested before the final design was determined. The original aerator design used the general design concepts and knowledge of previously designed tunnel spillway aerators. Turbulent approach flow and the transient hydraulic jump in the tunnel required significant modifications to the original aerator design. Each modification was the result of flow observations made during model operation.

For each design, the upstream ramp ended at Sta. 8+75; however, most other aspects of the original aerator geometry were modified. The dimensions for each preliminary aerator design are listed in the following table and shown schematically on figure 10.

Table 1. - Preliminary aerator dimensions.

Aerator No.	Ramp height d (ft)	Ramp angle (degrees)	Ramp length (ft)	Air slot dimensions (ft)	Downstream slot offset d_o	Slope of downstream transition	Transition length (ft)	Total aerator length (ft)
1	1.20	6	11.46	5 x 5 extends above theoretical max. w.s.	1.25	1:15	18.75	30.21
2	3	10	17.26	5 x 5 concentric	1.25	1:15	18.75	36.01
3	3	10	17.26	5 x 5 concentric	3	1:5	15	32.26

Table 2. - Geometry for other tunnel spillway aerators.

	Tunnel diameter (ft)	Tunnel slope α (degrees)	Ramp angle θ (degrees)	Ramp height d (ft)	Ramp length (ft)	Air slot	Downstream slot offset (ft)	Slope of downstream transition	Transition length (ft)	Total length
Glen Canyon	41	35	7.8	0.58	4.27	4 x 4	1.0	1:20	20	28.27
Blue Mesa	21	55	6	0.83	8	3 X 3 fully concentric	0.67	1:15	10	21
Yellowtail	32	55	6.34	0.25	2.25	3 X 3	0.5	75-ft radius	8.65	13.90

Aerator geometry and subsequent flow patterns will be described and evaluated in the following sections. A representative discharge of 20,000 ft^3/s was chosen for visual comparison of the flow through each aerator configuration.

Original Design (Aerator No. 1)

Typical proportions from previous aerators, shown in table 2, were used as guidelines to develop the initial Hoover aerator configuration.

A ramp angle and downstream transition section of similar magnitude to the previous aerators was chosen. A 6° ramp angle and a ramp height, d, equal to 0.2 times the flow depth at 15,000 ft^3/s were chosen. The ramp length was then calculated. Using a 15:1 sloping transition and choosing the downstream slot offset, d_o = 1.25, the transition length was determined (fig. 10).

Initial operation of the model with this aerator immediately showed the inadequacy of the design. Aeration was provided only for discharges less than 75,000 ft^3/s; at greater discharges the flow depth and turbulent water surface drowned out the air slot. Major problems of this original air slot design were:

- Inadequate ramp angle and height
- Flow depth that exceeded the top of the air slot

The flow depths were too large in proportion to the ramp angle and height to sufficiently lift the jet and provide adequate aeration. This observation was supported by the short cavity length under the jet downstream of the slot at 20,000 ft^3/s (fig. 11). As the discharge increased the jet returned to the invert sooner and provided less aeration under the nappe, until the flow depth exceeded the top of the air slot. Once this occurred the air slot became submerged and did not provide aeration for discharges exceeding 75,000 ft^3/s.

The hydraulic jump in the tunnel for discharges exceeding 135,000 ft^3/s affected the aerator performance. When the hydraulic jump was located in the vertical bend, slight fluctuations in the location of the jump caused the aerator to alternate between supplying air and being submerged. Very large pressure fluctuations in the vicinity of the air slot were produced under this condition. As the discharge increased, the jump gradually moved from the vertical bend up the inclined portion of the tunnel. The air slot then became fully submerged.

First Modification (Aerator No. 2)

Initial modifications to the aerator design increased the ramp angle from 6° to 10°, the ramp height from 1.2 to 3 ft, and extended the air slot completely around the tunnel circumference (fig. 10).

Aerator performance improved for all discharges. The increased ramp angle and height lifted the jet further from the invert increasing the cavity length under the jet and, thus, flow aeration.

Extending the air slot completely around the tunnel prevented the turbulent flows and large flow depths associated with free flow from totally submerging the slot. For discharges greater than 100,000 ft^3/s, the jet leaving the ramp impinged upon the downstream edge of the slot and on the transition. This created back flows that partially filled the slot. However, the slot was submerged only when the transient hydraulic jump moved upstream of the aerator. The concentric slot and increased ramp height greatly improved the aeration capability of the aerator (fig. 12). However, to prevent back flows into the slot, either the jet leaving the ramp had to be more confined or d_o, the offset away from the original tunnel invert, had to be increased.

Second Modification (Aerator No. 3)

The second modification increased the downstream slot offset from 1.25 to 3 ft and shortened the transition to return to the original tunnel lining to 15 ft on a 5:1 slope (fig. 10). These changes increased the aeration area available under the jet. Flow patterns for small discharges were not altered by these changes (fig. 13).

For free flow discharges exceeding 135,000 ft^3/s, the increased aeration area immediately downstream of the ramp provided a more stable flow condition. However, as the maximum free flow discharge was approached, turbulence in the jet leaving the ramp still caused return flow to the slot. The transient hydraulic jump did not totally submerge the air slot until approximately 175,000 ft^3/s had been reached. Final modifications were made to the aerator to prevent return flows to the slot.

FINAL AERATOR DESIGN

Both the upstream ramp and the downstream slot were modified for the final design. Previous modifications achieved adequate cavity length under the jet; however, when the flow depth exceeded the springline, turbulent flow still impinged on the side of the tunnel and returned upstream to the slot.

To confine the flow, the ramp was extended above the springline to 35° on either side of the crown. The ramp was formed by a 24.18-ft radius, whose center was 1.67 ft above the tunnel centerline (fig. 14). The ramp angle and invert height, 10° and 3 ft, respectively, were not modified. (The ramp length as constructed in the prototype was 17.25 ft). The aerator ramp usually (**??**) does not extend above springline due to the possibility of creating fins downstream or because of construction complications. However, in this case, an extended ramp was required to confine and direct the turbulent jet away from the side of the tunnel.

The downstream slot offset, d_o, away from the original tunnel invert had been increased to 3 ft in the previous design **(aerator No. 3??)**. The final modification eliminated the rectangular shape of the slot and began a 5:1 concentric conical transition back to the original tunnel lining at Sta. 8+75. An 8-ft-high face normal to the invert was formed at Sta. 8+75 by the 3-ft ramp and the 5-ft offset away from the invert. This modification prevented the area from filling with water during large free flow discharges and produced an efficient aerator design. Prototype construction of this configuration will require less formwork and no air slot drain.

Aerator Flow Characteristics

Spillway discharge capacity was not affected by addition of the aerator. A maximum discharge of 203,000 ft^3/s was attained at reservoir elevation 1232 without the flip bucket. With the existing flip bucket configuration, the spillway tunnel entrance became submerged at about 185,000 ft^3/s and produced flow similar to a submerged drop-inlet spillway where a large head increase is associated with a small increase in discharge. This flow condition will limit the maximum discharge to 191,000 ft^3/s at reservoir elevation 1232 (fig. 15).

The aerator was not submerged and will supply air during an free flow discharge. The aerator ramp lifts the jet over the slot and away from downstream flow surfaces, both invert and sides, providing a large aeration area. Even though air quantities could not be measured in the model, air was visibly present in the flow downstream of the aerator. For discharges up to and including 50,000 ft^3/s, the jet returns to the tunnel invert just upstream of the P.C. (??) of the vertical bend. Fins develop upon impact and travel through the vertical bend but dissipate quickly. These fins do not reach the tunnel crown nor choke off the tunnel (fig. 16). As the discharge increases, up to the 203,000 ft^3/s maximum, the jet trajectory returns to the invert closer to the slot but never submerges the aerator. Overlapping fins reach the tunnel crown for high flow rates but do not choke off flow and dissipate downstream of the vertical bend (fig. 17).

With the flip bucket at the tunnel exit free flow discharges are limited to 135,000 ft^3/s. Above this discharge the transient hydraulic jump in the tunnel causes intermittent, and eventually, total submergence of the aerator. The large aeration area produced by combining the slot and transition prevented submergence of the aerator for as long as possible (fig. 18); however, operation with the hydraulic jump in the tunnel is not recommended because of the large pressure fluctuations that occur at the aerator and the flip bucket. The tunnel is pressurized at about 185,000 ft^3/s and the aerator is totally submerged. Maximum discharge with pressure flow and the aerator submerged is shown on figure 19.

PRESSURE PROFILE DOWNSTREAM OF THE AERATOR

Pressures were measured along the invert downstream of the aerator location without the aerator and for each aerator design to provide information for the aerator design.

Pressures were recorded without the aerator, for comparison with theoretical computations from HFWS and then after the aerator was installed. Without the aerator, the pressures approximately reflected the flow depth, agreeing closely with theoretical predictions. Cavitation pressures would not be recorded in a model of this scale. However, the high velocities and low cavitation indexes in the inclined portion of the spillway (fig. 8) indicate that low-pressure cavities will form. The marked increase in pressure as the flow enters the vertical bend would cause these low-pressure cavities to implode. To prevent damage due to the collapse of these cavities, aeration should be provided to the flow boundary.

Without the aerator, pressures were positive through the inclined tunnel portion. With the aerator, pressures immediately downstream of the aerator are atmospheric as air is being drawn into the area under the nappe. A typical pressure profile for a discharge of 20,000 ft^3/s is shown on figure 20. This profile compares the theoretical and measured pressures without an aerator and shows the effects of the aerator on the invert pressures.

INVESTIGATION OF FLOW CONDITIONS AND PRESSURES PRODUCED BY THE FLIP BUCKET

The flip buckets inside the tunnel exits greatly reduced the flow area (fig. 2) (Bradley, 1944). Initial operation of the Arizona spillway tunnel revealed the effects of this flow area constriction at the flip bucket. For discharges less than 135,000 ft^3/s free flow occurred. A transient hydraulic jump formed at the flip bucket for discharges greater than 135,000 ft^3/s. The jump traveled upstream to the vertical bend, through the inclined portion, and eventually sealed off the tunnel entrance producing pressure flow at 185,000 ft^3/s. From the time the jump formed until pressure flow occurred an unstable flow condition existed in the tunnel (fig. 7).

The hydraulic jump formed compressed air pockets in the tunnel. Instability occurred with the explosive decompression of these air pockets as they were released from the tunnel exit. This unstable flow condition, between 135,000 and 185,000 ft^3/s, produced concern about the structural integrity of the prototype structure due to what seemed to be large pressure fluctuations in the model.

Static pressures were measured at the flip bucket, on both the ramp and crown for discharges of 145,000 and 175,000 ft^3/s. The measurements were taken at approximately Sta. 26+95 at elevations of 640 and 675 for the ramp and crown, respectively.

The static pressures were obtained with 25-lb/in^2 pace transducers and a strip chart recorder. Average static pressure was determined to be the center of the strip chart record (fig. 21). The average measured static pressures compare in magnitude to theoretical values including losses computed with HFWS. Large fluctuations, higher and lower than the average static pressure occurred. The maximum pressure fluctuations above the average value indicated pressures up to the available energy head. Fluctuations to 94 ft below the average also occurred; however, the pressures remained positive. The average pressures and the maximum fluctuations measured at the flip bucket with the static transducers are shown in table 3 (prototype values).

Table 3. - Pressures (ft) measured at the flip bucket.

Discharge (ft^3/s)	Sta. 26+95	Average pressure (ft)	Minimum pressure (ft)	Pressure fluctuations	
				Maximum (ft) ??	Minimum (ft)
145,000	Crown	130	–52	Available static head (no losses)	78
	Ramp	146	–83		63
175,000	Crown	146	–94	Available static head (no losses)	52
	Ramp	209	–58		151

Field tests of various hydraulic structures have shown that good conformance exists between average static pressure data measured on the model and the prototype. The average pressures measured in the model compare with theoretical values. The differential pressures, of the fluctuations from the average indicated a very unstable flow condition, but did not imply a clear relationship between the pressures and the flow conditions. The release of the compressed air pockets from the end of the tunnel produced erratic pressure spikes. The recording methods could not take data at a fast enough rate to ensure that proper responses by the static pressure cells were being recorded. The flow condition producing the instability will also exist in the prototype, but the magnitude of the fluctuations may not be the same.

To measure fluctuations about the average pressure, Kistler 100-lb/in^2 dynamic pressure transducers were flush mounted at the same test locations (Sta. 26+95). Data from these transducers were recorded onto a computer disk and a spectrum analyzer. Atmospheric and vapor pressures at elevation 5,300 ft are approximately 12 lb/in^2 and 0.2 lb/in^2, respectively, for both the model and prototypes. The model data for the crown transducer corresponding to a prototype discharge of 175,000 ft^3/s were statistically analyzed and plots were developed (fig. 22). The analysis of the data is in terms of model values.

To analyze the data it should be noted that the dynamic transducers measure gauge pressure, p_g ___. The dynamic data varies about the static average, p_s = 1.21 lb/in^2. The absolute pressure is equal to atmospheric pressure plus the measured gauge pressure and the static pressure:

$$p_{abs} = p_{atm} + (p_s + p_g)$$

A time record of the 8,192 data points taken at a rate of 500 Hz is shown on figure 22a. These pressure data are normalized about the maximum value of 3.507 lb/in^2, the zero pressure corresponds to the static average of 1.21 lb/in^2. Analyzing this record the same as the stripchart record from the static transducers (fig. 21) indicates a greater number of fluctuations occur below the static average, producing -0.13 (3.507 lb/in^2) = −0.45 lb/in^2 as an average of the dynamic data. This average value corresponds to 12.76 lb/in^2 (abs), slightly above atmospheric pressure. The minimum pressure fluctuation was −0.71 (3.50 1b/in^2) = −2.5 lb/in^2 according to 10.7 lb/in^2 (abs) or 1.3 lb/in^2 below atmospheric pressure. The range of fluctuation is 6.0 lb/in^2.

The histogram (fig. 22b) represents the frequency distribution of the pressure data. The maximum number of events occurs just below the static average, 0 lb/in^2, where about 18 percent of the data occur. Seventy-five percent of the data fall between + one standard deviation of the average of the dynamic data. This would indicate that the violent flow condition is being caused by 25 percent of the occurrences or perhaps just the isolated maximum pressures indicated on the time record (fig. 22a).

Figure 22c represents an envelope of the power spectrum (lb/in^2) of the energy in the time domain data. It is the FFT (??) of the time data and indicates that almost all of the energy occurs at a very low frequency, approximately 2.5 Hz. Because of this low frequency, the magnitude of the pressure fluctuations occurring in the model could be expected in the prototype. This is yet to be confirmed by direct comparison of model/prototype dynamic data. However, if magnitudes did scale linearly, pressures in the prototype varying from vapor pressure to available static head could be expected.

Unfortunately, the correlation between these dynamic model data and the prototype is not entirely understood. Neither the frequency nor the amplitude of the dynamic pressures from the Glen Canyon spillway model scaled accurately to the prototype (Frizell, 1985). Research is continuing to determine a correlation between model and prototype dynamic pressures. However, the observation of the violent flow conditions in the model is sufficient to recommend preventing spillway operation above 135,000 ft^3/s or modifying the flip bucket area to provide a free flow surface throughout the full discharge range.

Recommended Modification

To ensure safe passage of the maximum design discharge, modifications should be made to the flip bucket area. Alternative structural modifications include:

- Removing the flip buckets from their present location inside the tunnel and replacing them downstream allowing a free flow surface for all discharges.

- Removing the downstream 40 ft of the tunnel crown above the flip bucket ramps of both spillways to the width of the vertical side walls. This alternative was investigated in the model because it would be the most cost effective.

The flip bucket crown was progressively removed upstream from the end of the tunnel providing a free water surface for passage of higher discharges. As the opening on the crown was widened fins formed by the converging flip bucket walls were less confined producing a flatter jet with an accompanying reduction of spray (fig. 23). The recommended modification requires removing the downstream 40 ft of the tunnel crown to the width of the vertical side walls. This will permit passage of the design discharge of 200,000 ft^3/s per spillway.

It would be difficult to modify the Arizona spillway in this manner, because the end of the tunnel is flush with the very high steep canyon wall. The tunnel crown at the end of the Nevada spillway is exposed. If the crown were removed above the flip bucket ramp in the Nevada spillway allowing passage of 200,000 ft^3/s and the Arizona spillway capacity was limited to 135,000 ft^3/s, 83 percent of maximum flow could be passed.

The PMF (probable maximum flood) for Hoover Dam is currently being reviewed. The decision to modify the flip buckets will depend upon the outcome of this review. Without any flip bucket modification, discharge in each tunnel should be limited to 135,000 ft^3/s.

Future Prototype Testing

Prototype releases are quite rare on Bureau structures; therefore, whenever possible, prototype testing should be done to obtain vital information for determining or confirming model-prototype relationships. Prototype testing of static and dynamic pressures along the tunnel invert and air velocities in the aerator were performed at Glen Canyon Dam (Frizell, 1985). Should the Hoover Dam spillways release flows in the future, valuable prototype data pertaining to aerator design and scaling of dynamic pressures could be obtained.

During tunnel lining repair and installation of the aerators, steel instrumentation boxes were installed. In the future, should spillway releases be necessary, instrumentation for gathering data will be installed in these boxes. The boxes were located in the Nevada spillway invert as follows:

1. In the vertical face of the aerator formed by the ramp and slot, 30° above the invert centerline

2. Sta. 8+85, in the downstream aerator transition

3. Sta. 10+15, about 35 ft upstream of the P.C. of the vertical bend

4. Sta. 10+80, in the damaged area of the bend

5. Sta. 12+12 downstream of the P.T. (??) of the vertical bend

These instrument box locations are shown on figure 24. Hopefully as more prototype data are made available a correlation between model and prototype dynamic pressures and air velocities can be determined.

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APPENDIX

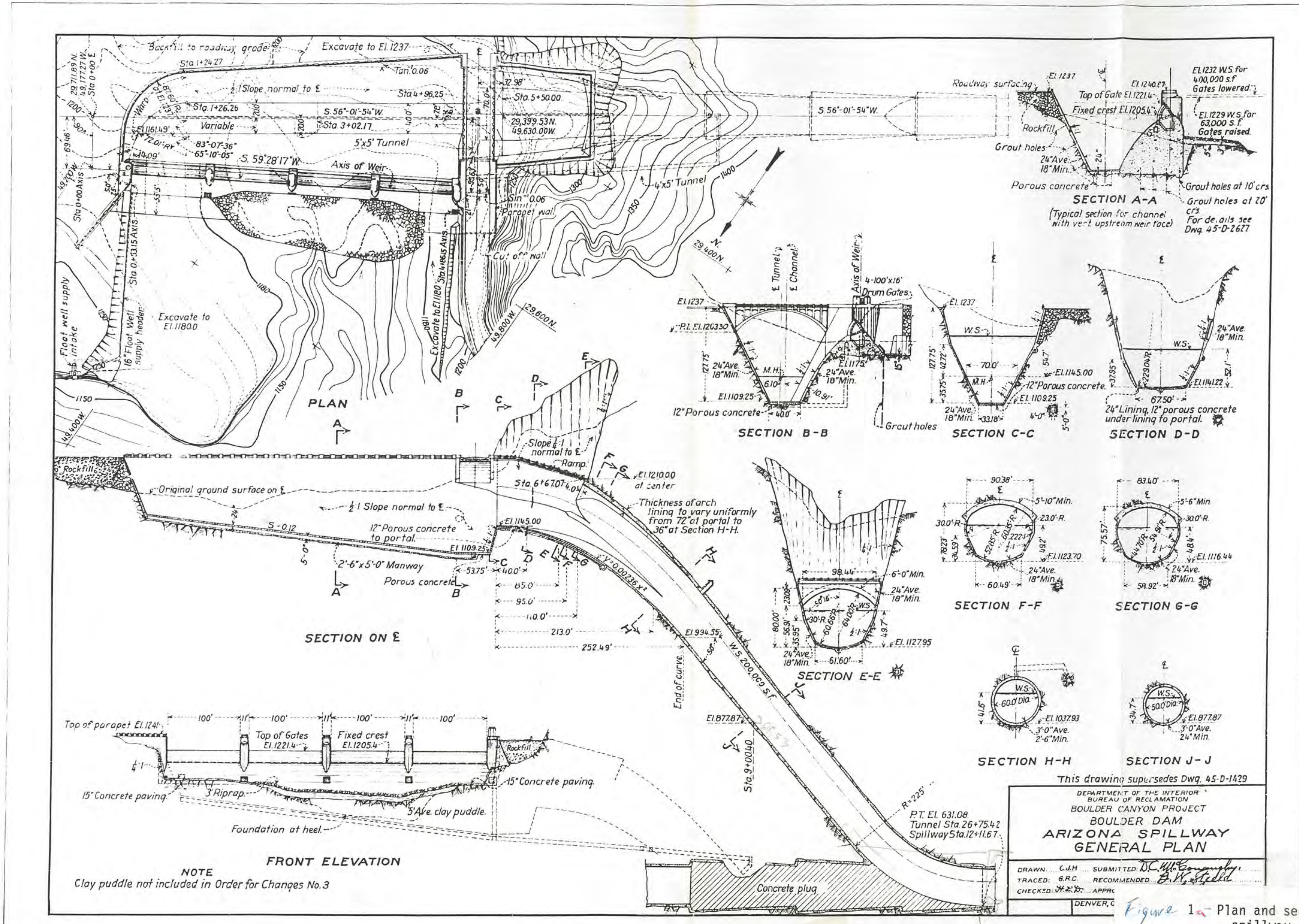
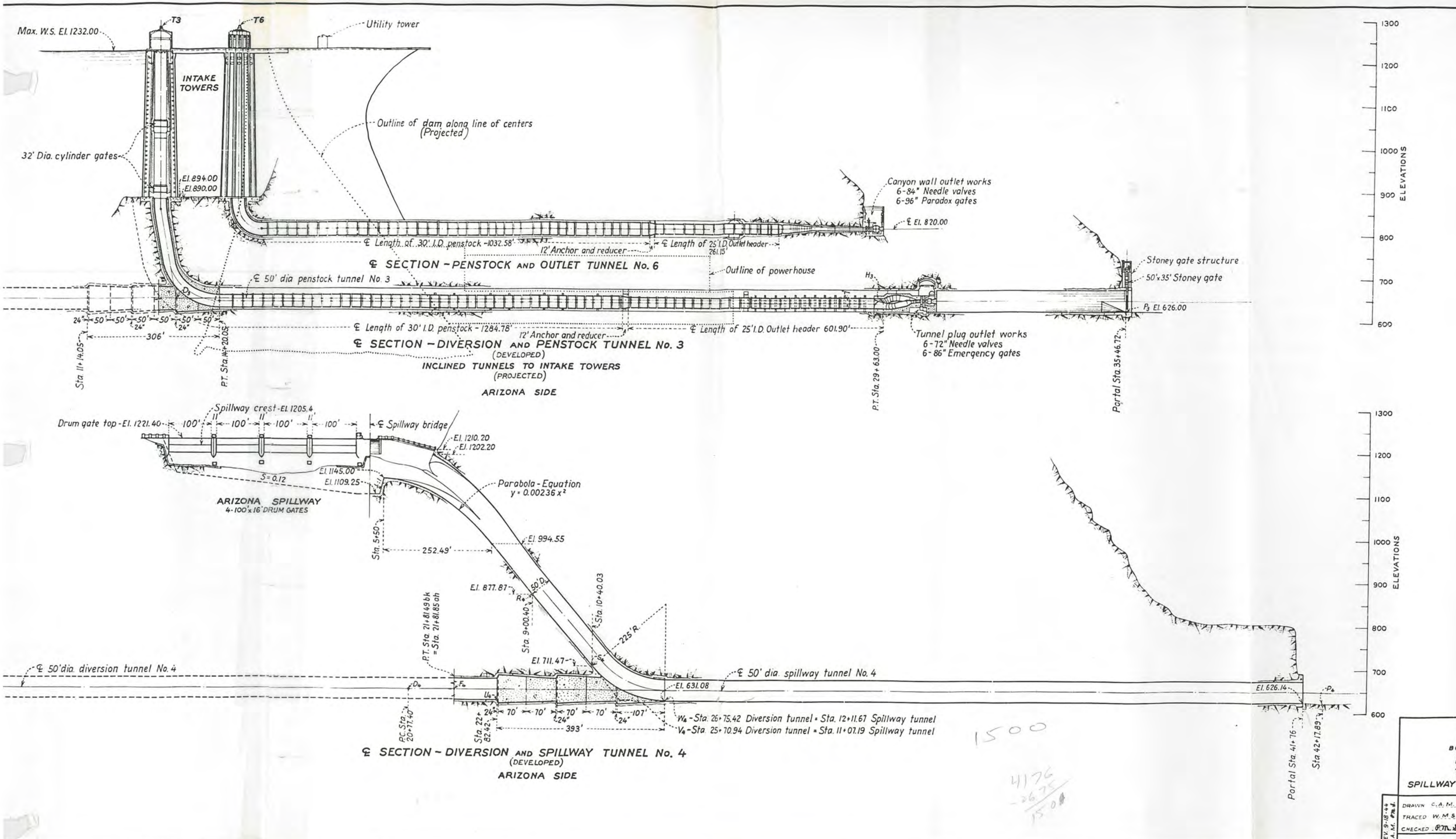


Figure 1a Plan and section of the Arizona s spillway and tunnel



Max. W.S. El. 1232.00
T3
T6
Utility tower
INTAKE TOWERS
32' Dia. cylinder gates
El. 894.00
El. 890.00
Outline of dam along line of centers (Projected)
Canyon wall outlet works
6-84" Needle valves
6-96" Paradox gates
℄ El. 820.00
℄ Length of 30' I.D. penstock - 1032.58'
12' Anchor and reducer
℄ Length of 25' I.D. Outlet header 261.15'
℄ SECTION - PENSTOCK AND OUTLET TUNNEL No. 6
Outline of powerhouse
Stoney gate structure
50'x35' Stoney gate
℄ 50' dia penstock tunnel No. 3
H3
P3 El. 626.00
24' 50' 50' 24" 50' 50' 24" 50' 50'
306'
℄ Length of 30' I.D. penstock - 1284.78'
12' Anchor and reducer
℄ Length of 25' I.D. Outlet header 601.90'
Tunnel plug outlet works
6-72" Needle valves
6-86" Emergency gates
Sta. 11+14.05
P.T. Sta. 14+20.05
P.T. Sta. 29+63.00
Portal Sta. 35+46.72
℄ SECTION - DIVERSION AND PENSTOCK TUNNEL No. 3
(DEVELOPED)
INCLINED TUNNELS TO INTAKE TOWERS
(PROJECTED)
ARIZONA SIDE
Spillway crest - El. 1205.4
Drum gate top - El. 1221.40
100' 11' 100' 11' 100' 11' 100'
℄ Spillway bridge
El. 1210.20
El. 1202.20
El. 1145.00
S = 0.12
El. 1109.25
ARIZONA SPILLWAY
4-100'x16' DRUM GATES
Parabola - Equation
y = 0.00236 x²
Sta. 5+50
252.49'
El. 994.55
El. 877.87
50' D.
Sta. 9+00.40
Sta. 10+40.03
225' R.
P.T. Sta. 21+49 bk
= Sta. 21+81.85 ah
El. 711.47
℄ 50' dia. diversion tunnel No. 4
℄ 50' dia. spillway tunnel No. 4
El. 631.08
El. 626.14
P4
P.C. Sta. 20+77.40
Sta. 22+82.42
24' 70' 70' 24" 70' 70' 24" 107'
393'
W4 - Sta. 26+75.42 Diversion tunnel = Sta. 12+11.67 Spillway tunnel
V4 - Sta. 25+70.94 Diversion tunnel = Sta. 11+07.19 Spillway tunnel
Portal Sta. 41+76
Sta. 42+17.89
℄ SECTION - DIVERSION AND SPILLWAY TUNNEL No. 4
(DEVELOPED)
ARIZONA SIDE
ELEVATIONS
1300
1200
1100
1000
900
800
700
600
1500
4176
-2675
1501
SPILLWAY A
DRAWN C.A.M.
TRACED W.M.S.
CHECKED P.M.S.
REV. 9-18-44 C.A.M.

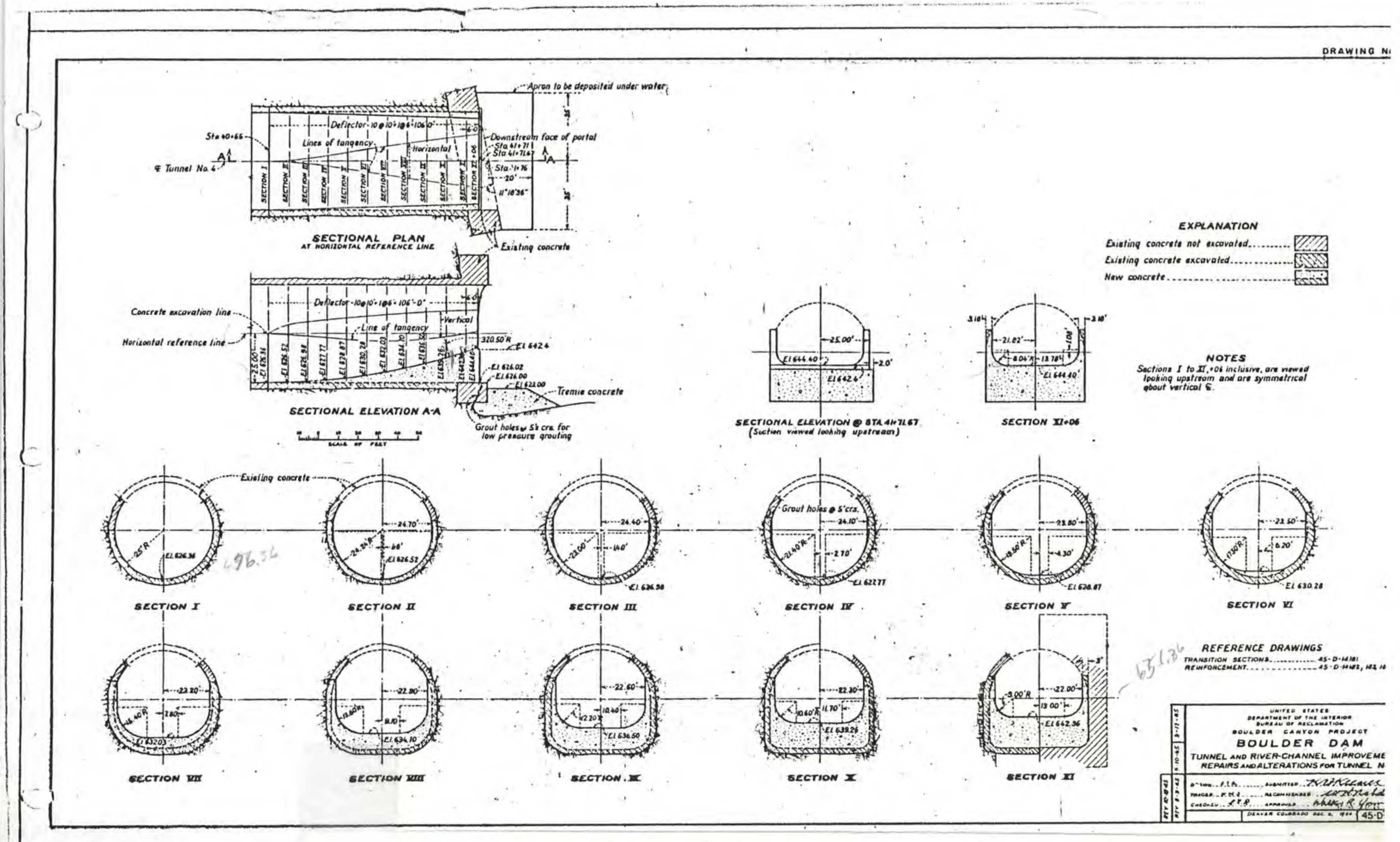


Figure 2 Flip bucket modification added to spillway tunnel exits in 1944

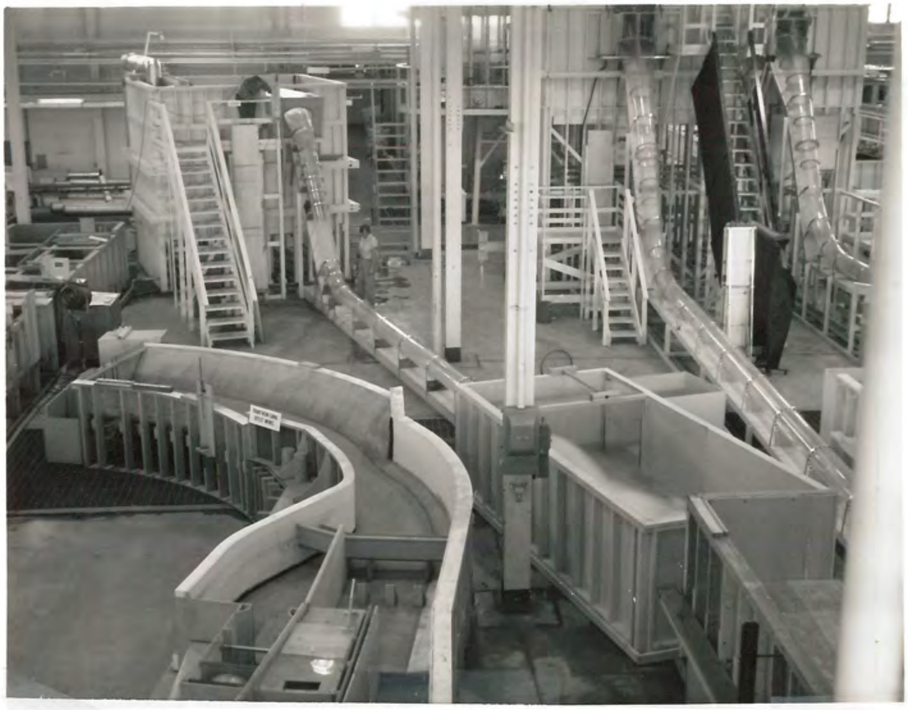
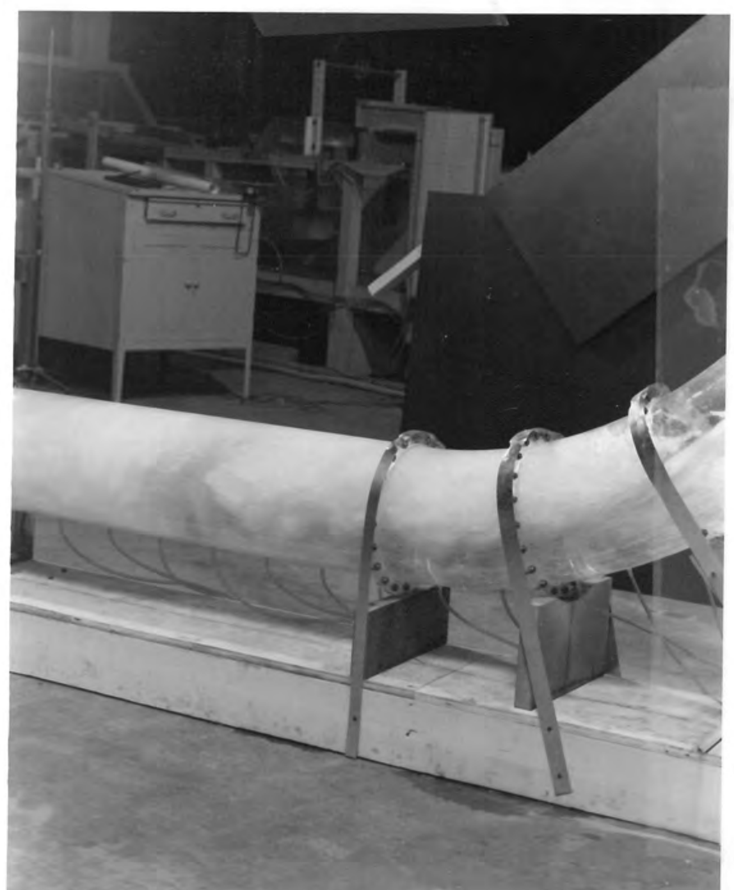


Figure 3.— Overall view of the Hoover Dam Arizona tunnel model

Figure 4.— Flow through the tunnel without an aerator

4 Stilling action in the side channel spillway for discharge of 100,000 ft^3/s

6a Flip bucket at the spillway tunnel exit discharging 135,000 ft^3/s with a free flow surface



6b The transient hydraulic jump in the tunnel at 145,000 ft^3/s

Figure 7 6c.- Pressurized tunnel flow at 190,000 ft^3/s

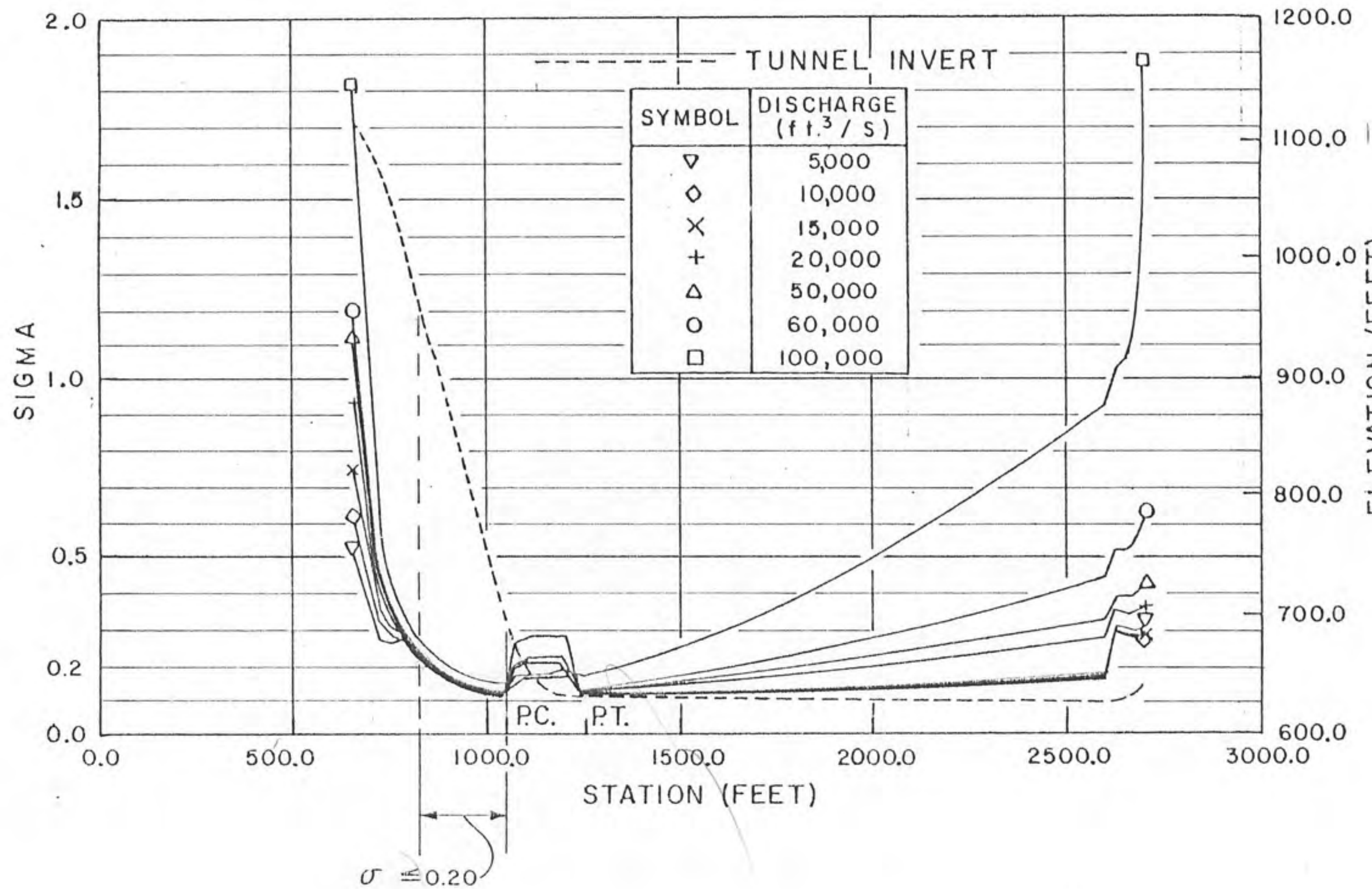


Figure 8. - Graphical representation of cavitation indexes for Hoover Dam Arizona Spillway.

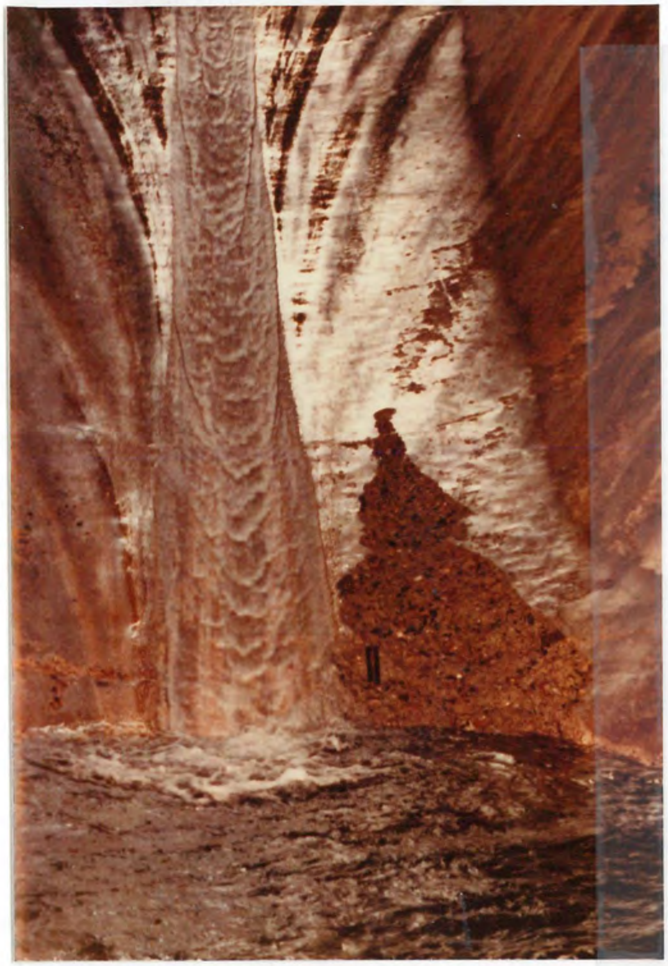
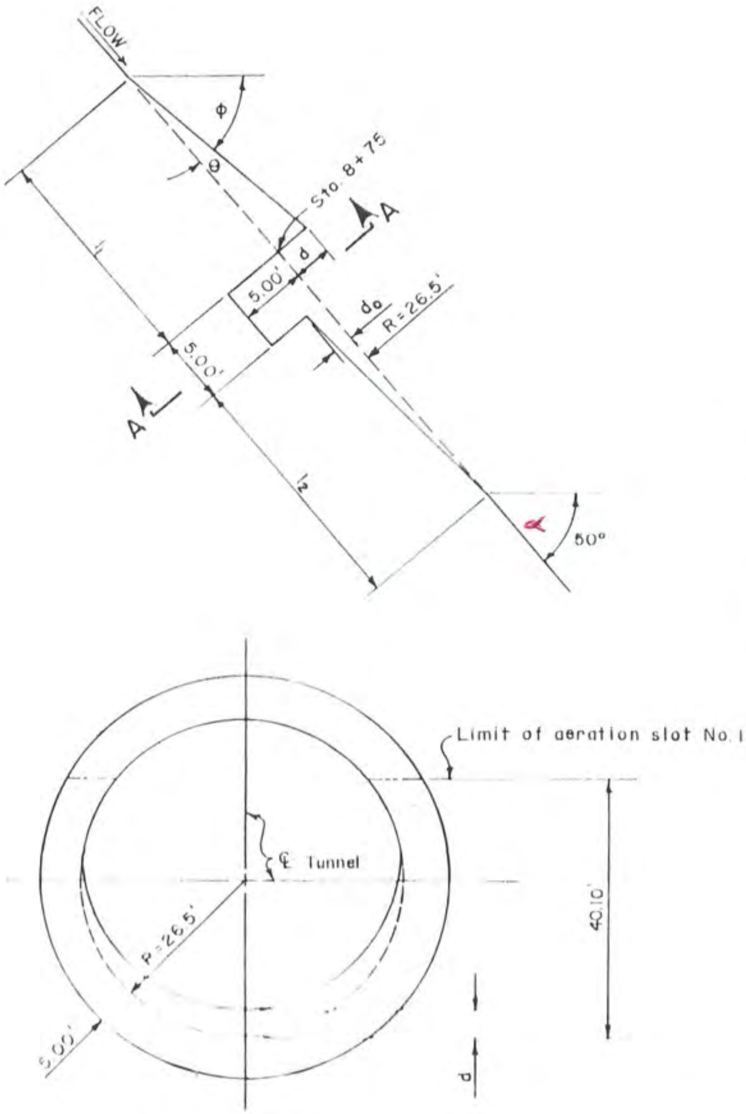


Figure 9 – Cavitation damage in the vertical bend of the Hoover Dam Nevada spillway (1983)



SECTION A-A

DIMENSION	AERATION SLOT		
	NO. 1	NO. 2	NO. 3
d	1.20'	3.00'	3.00'
l_1	11.46'	17.26'	17.26'
l_2	18.75'	18.75'	15.00'
d_o	1.25'	1.25'	3.00'
θ	6°	10°	10°
φ	44°	40°	40°

Figure 10. - Schematic of aerator designs

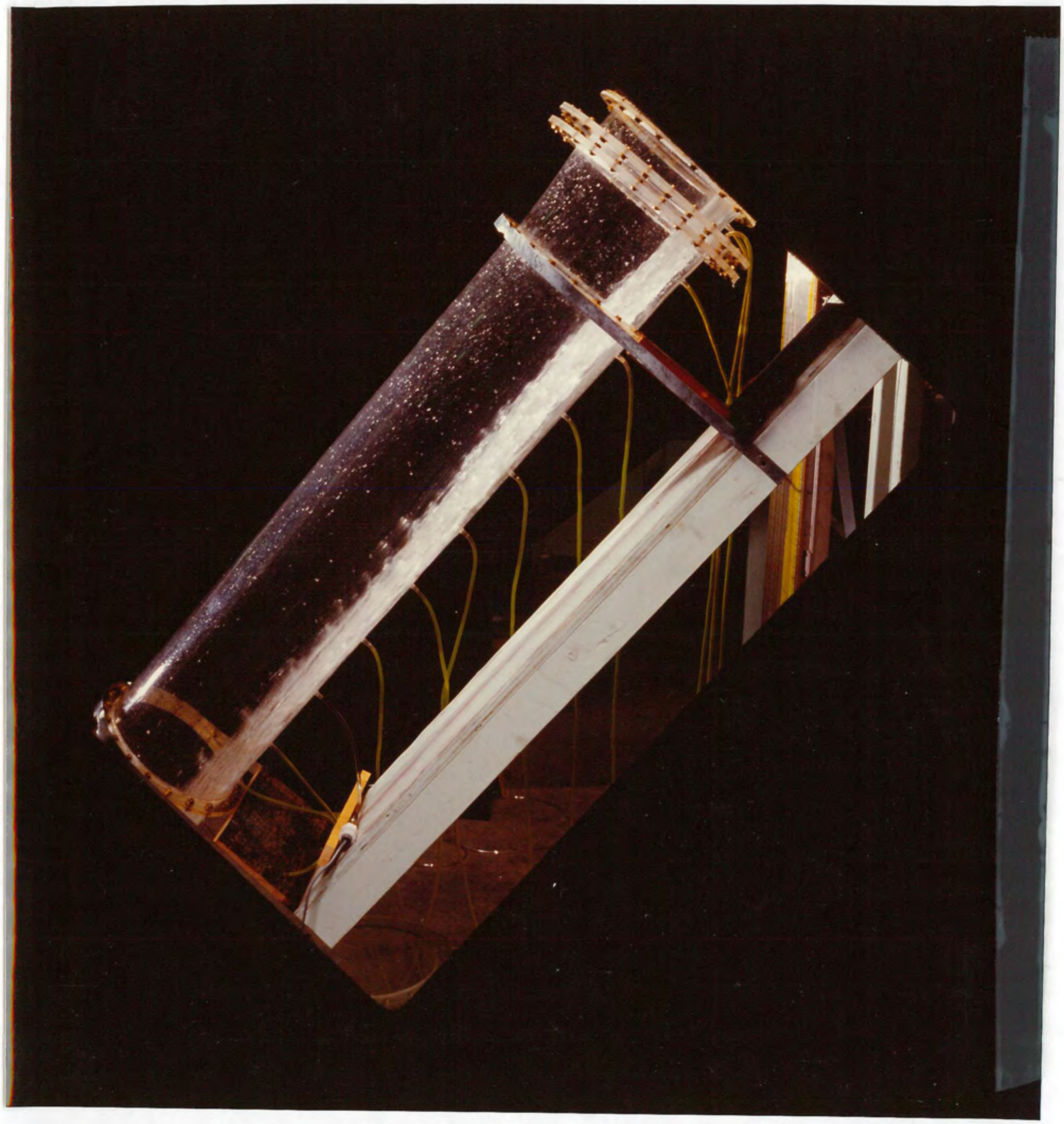


Figure 11.– Initial aerator design – flow of 20,000 ft^3/s.

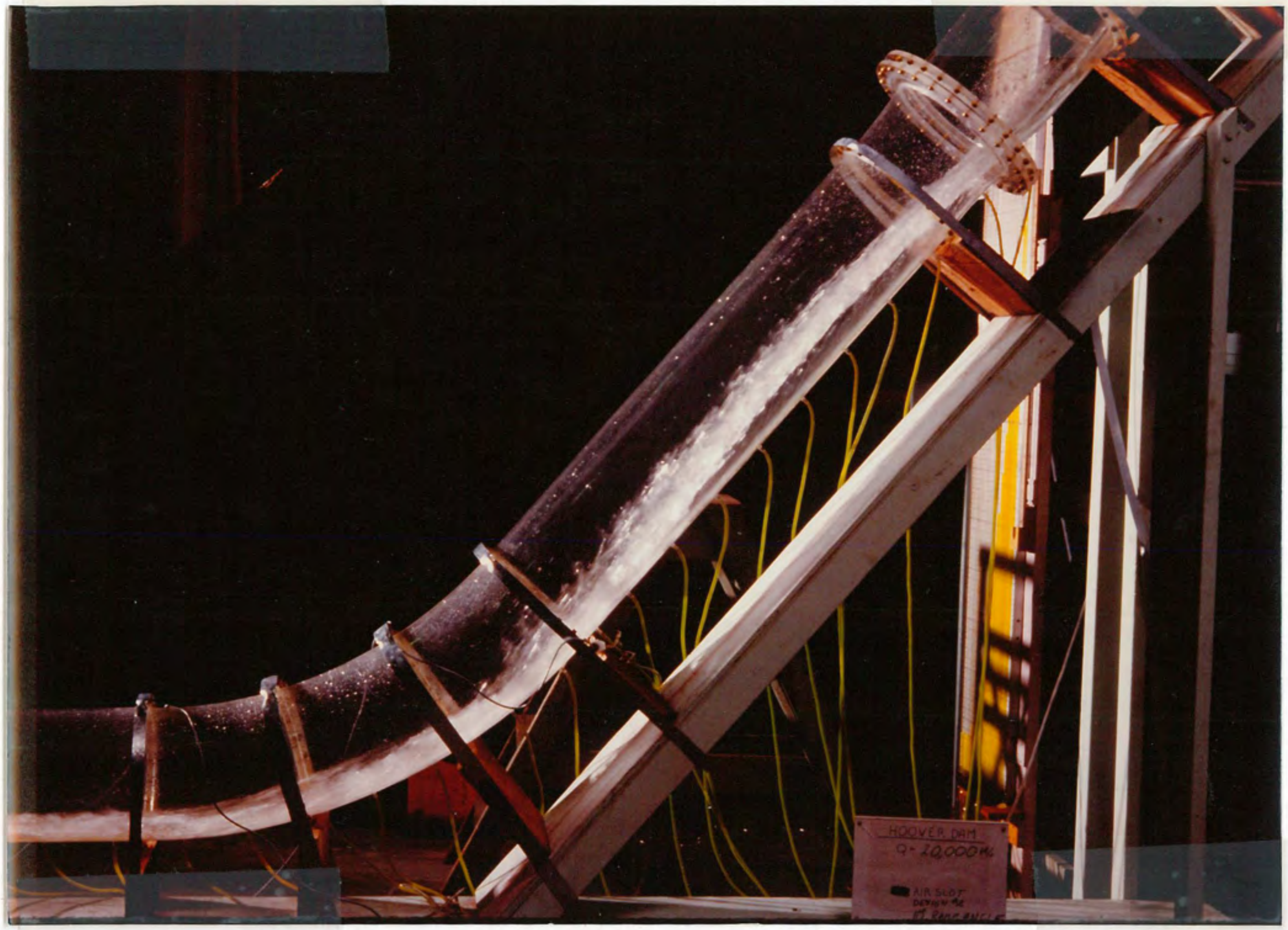


Figure 12-First modification of aerator design - flow of 20,000 ft^3/s

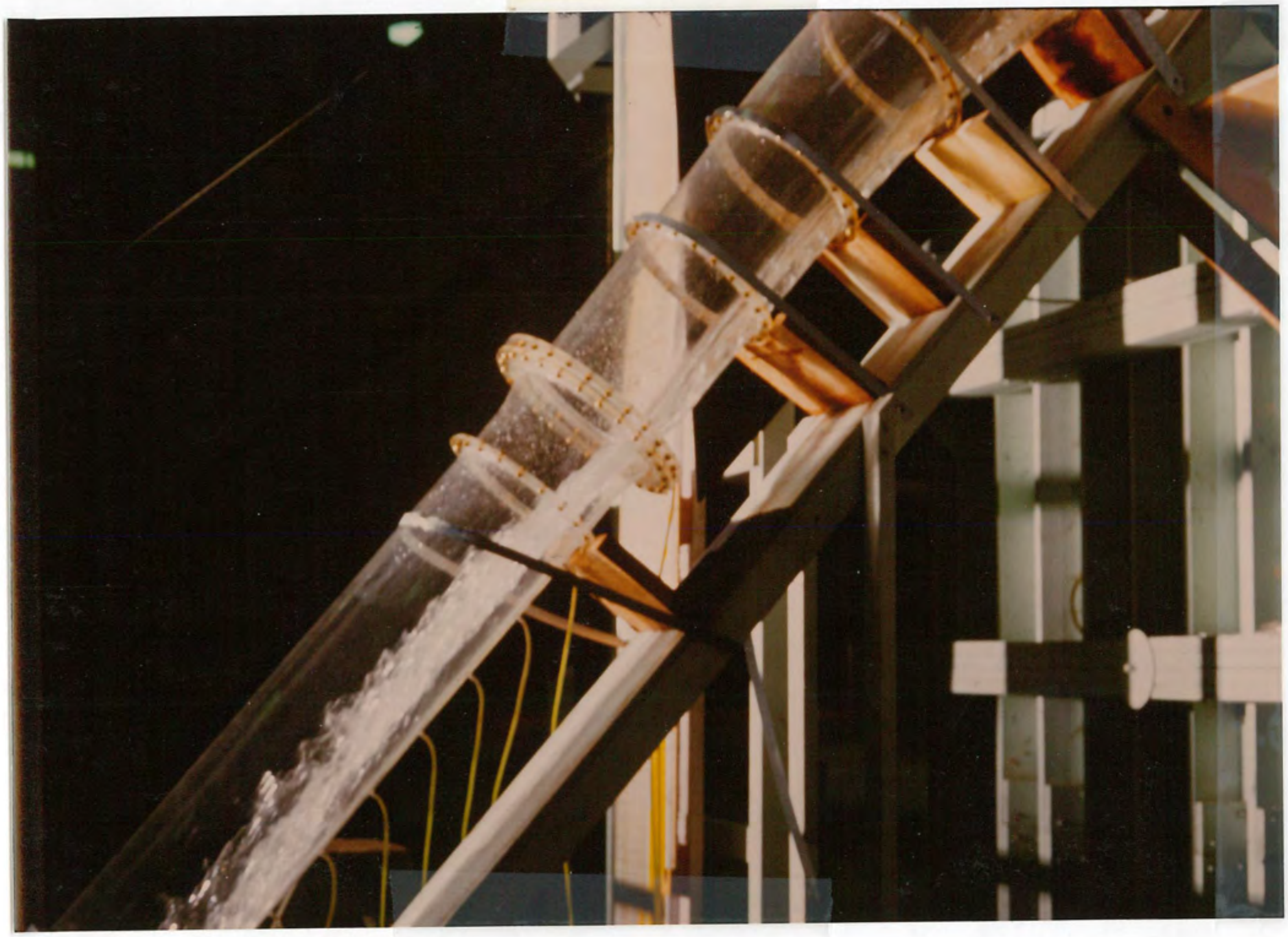
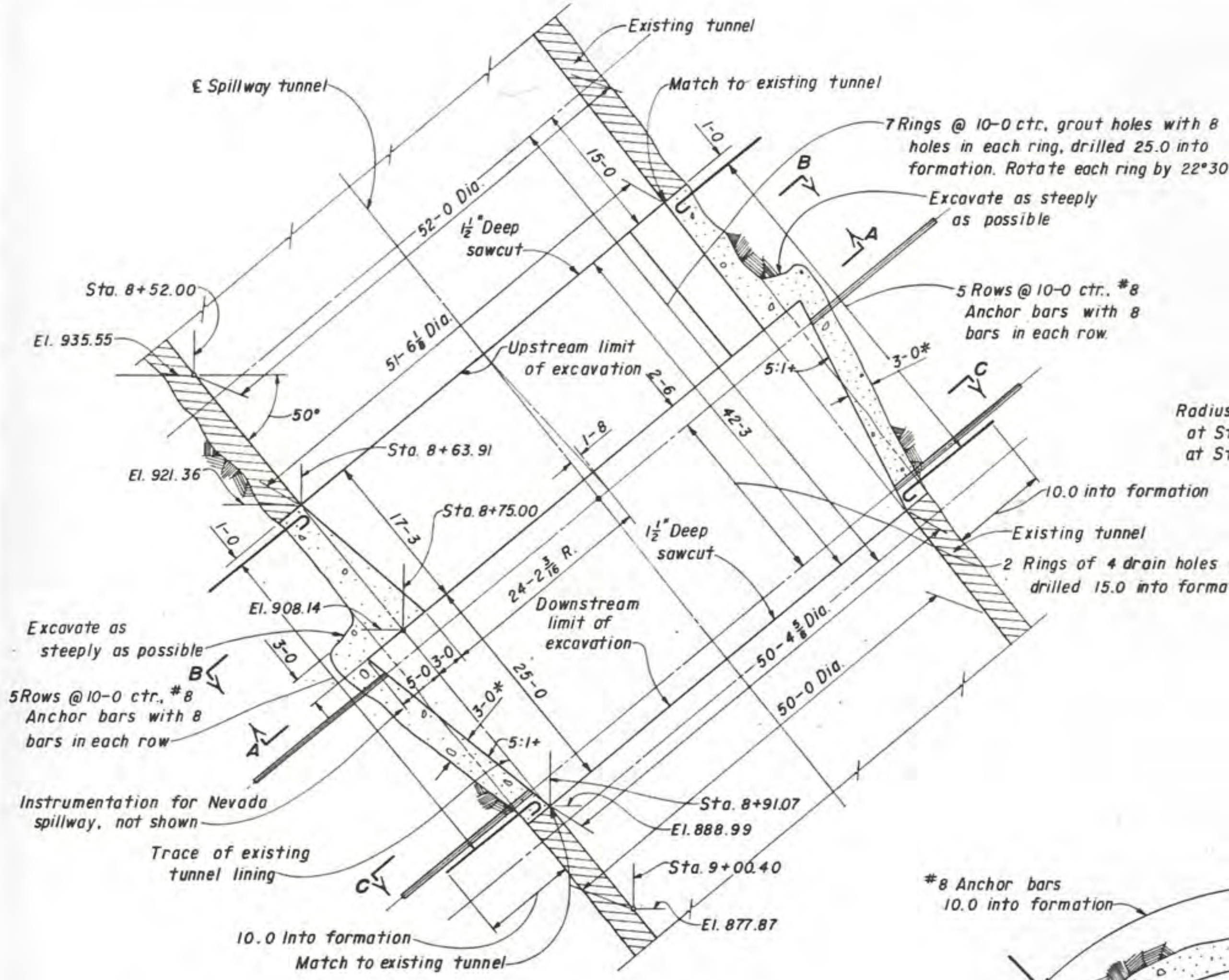
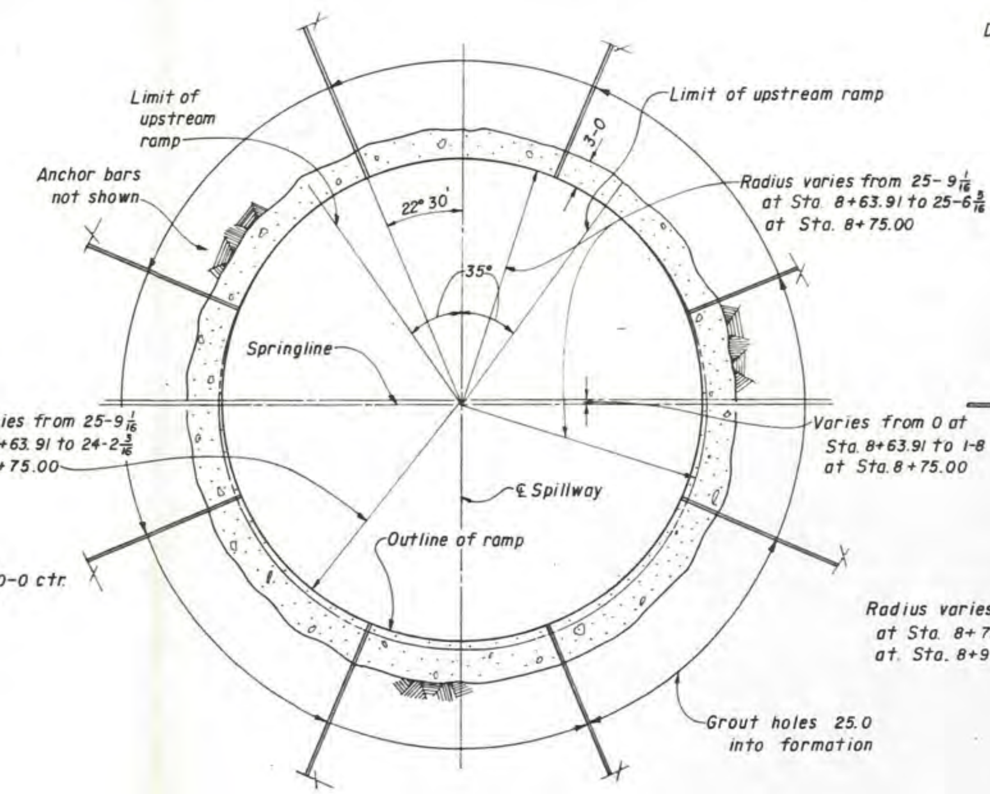


Figure 13. — Second aerator design modification - flow at 20,000 ft^3/s

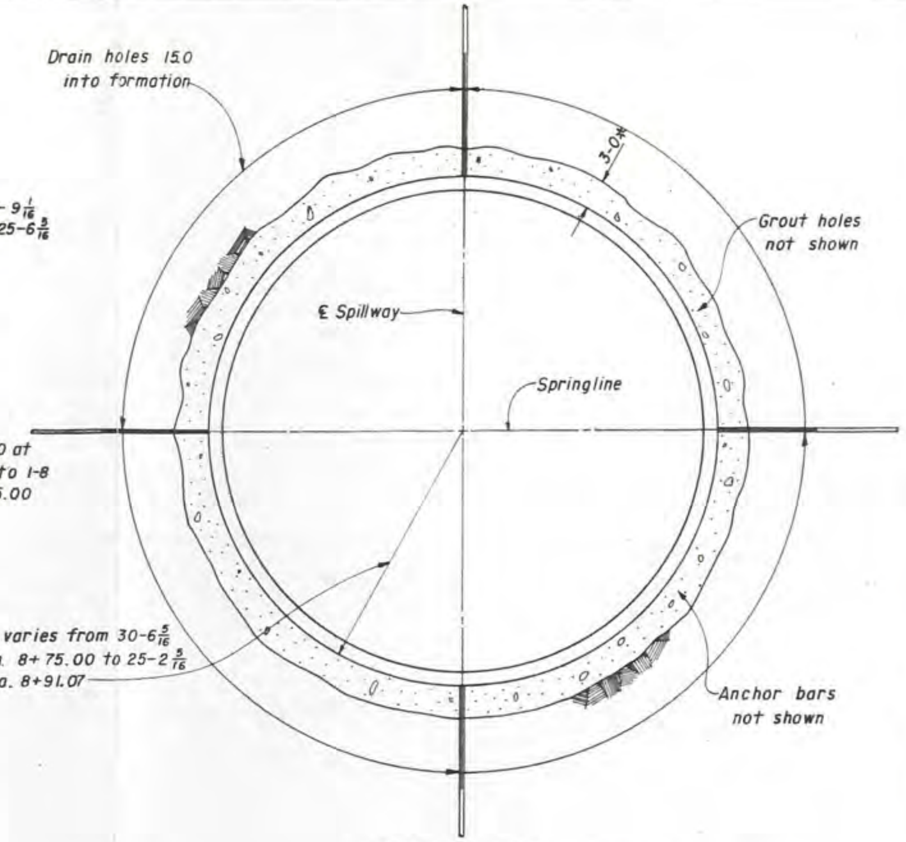


PROFILE ALONG ℄ SPILLWAY TUNNEL

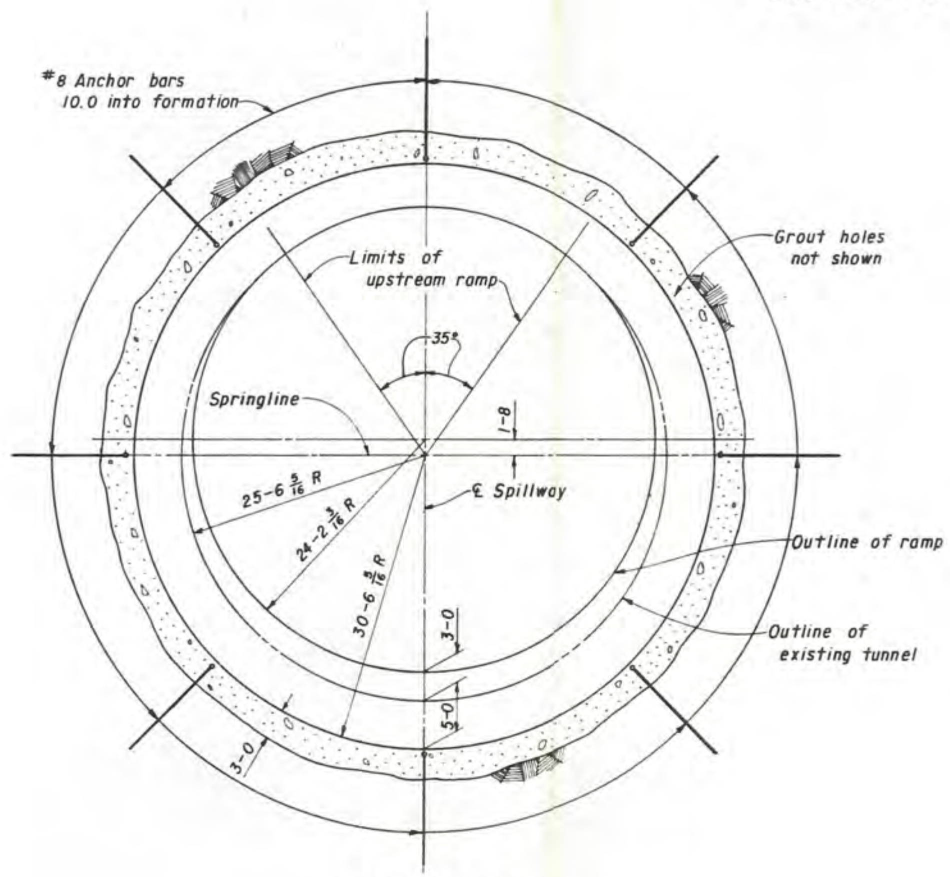
10 0 10 20 30
SCALE OF FEET



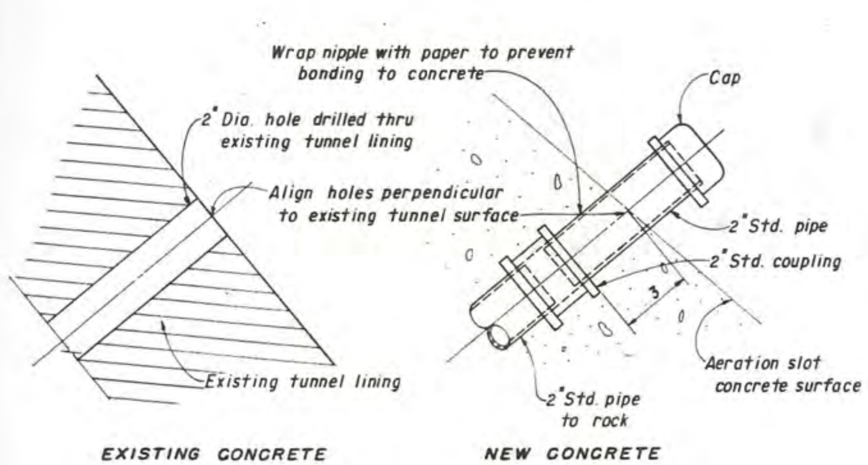
SECTION B-B



SECTION C-C



SECTION A-A



GROUTING DETAILS

CONCRETE REQUIREMENTS

STRENGTH:

Design of concrete is based on concrete having a minimum compressive strength of 4000 psi @ 28 days.

FINISHES:

Flow surfaces of aeration slot and concrete lining repair-around complete circumference- Sta. 8+25.00 to Sta. 8+75.00 ____ U3 or F4

Flow surfaces of aeration slot and concrete lining repair-below springline downstream of Sta. 8+75.00 ____ U2 or F2

Flow surfaces of aeration slot and concrete lining repair-below springline upstream of Sta. 8+25.00 ____ U2 or F2

Construction joint surfaces ____ F1

REFERENCE DRAWINGS

DAM:

DAM AND APPURTENANT WORKS-GENERAL LAYOUT-SHEET 1 OF 4 ____ 45-D-13856
NEVADA SPILLWAY-GENERAL PLAN ____ 45-D-1437
NEVADA SPILLWAY-LINING ANCHORAGE-REINFORCEMENT AND DRAINAGE ____ 45-D-1438
ARIZONA SPILLWAY-GENERAL PLAN ____ 45-D-1442
ARIZONA SPILLWAY-LINING ANCHORAGE-REINFORCEMENT AND DRAINAGE ____ 45-D-1443
IECO-GENERAL PLAN ____ 45-D-16591

ARIZONA AND NEVADA SPILLWAY MODIFICATION AND REPAIR:

LOCATION MAP ____ 45-D-16583
NEVADA SPILLWAY-TUNNEL DAMAGE SHEET 1 OF 2 ____ 45-D-16586
ARIZONA SPILLWAY-TUNNEL DAMAGE SHEET 1 OF 2 ____ 45-D-16588
RAMP AND AERATION SLOT-REINFORCEMENT ____ 45-
NEVADA SPILLWAY-INSTRUMENTATION ____ 45-

NOTES

For general concrete outline notes and details, see Dwg. 40-D-7006.
For general notes and minimum reinforcement requirements, see Dwg. 40-D-6263 (Table 4-60).
Stations, elevations, and diameters were calculated, from Dwgs. (1437) and (1442), assuming a 52-0 Dia. at Sta. 8+52, invert El. 935.55 and varying linearly to a 50-0 Dia. at Sta. 9+00.40, invert El. 877.87. As built stations, elevations and diameters to be determined in the field.
Stationing is measured horizontally.
All stations and elevations are located on the existing tunnel invert.
Information on this drawing applies to both the Arizona and Nevada spillways, unless otherwise noted.
*- Indicates dimension measured normal to slope.
Edges of new and existing concrete should match. Offsets due to inaccurate forming shall be ground flush.
Existing drain holes in tunnel crown to be redrilled, after grouting operations, from Sta. 8+00 to Sta. 12+00. New drainage holes in the aeration slot area shall be drilled after grouting operations are complete.
+- Indicates slope measured with respect to existing tunnel outline.
Backfill grouting is required but not shown. Location to be determined by the contracting officer.

ALWAYS THINK SAFETY

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT
ARIZONA AND NEVADA

HOOVER DAM
SPILLWAY MODIFICATION AND REPAIR
RAMP AND AERATION SLOT
PROFILE, SECTIONS, AND DETAILS

DESIGNED ____ TECHNICAL APPROVAL ____
DRAWN ____ SUBMITTED ____

Figure 14.—Final aerator design

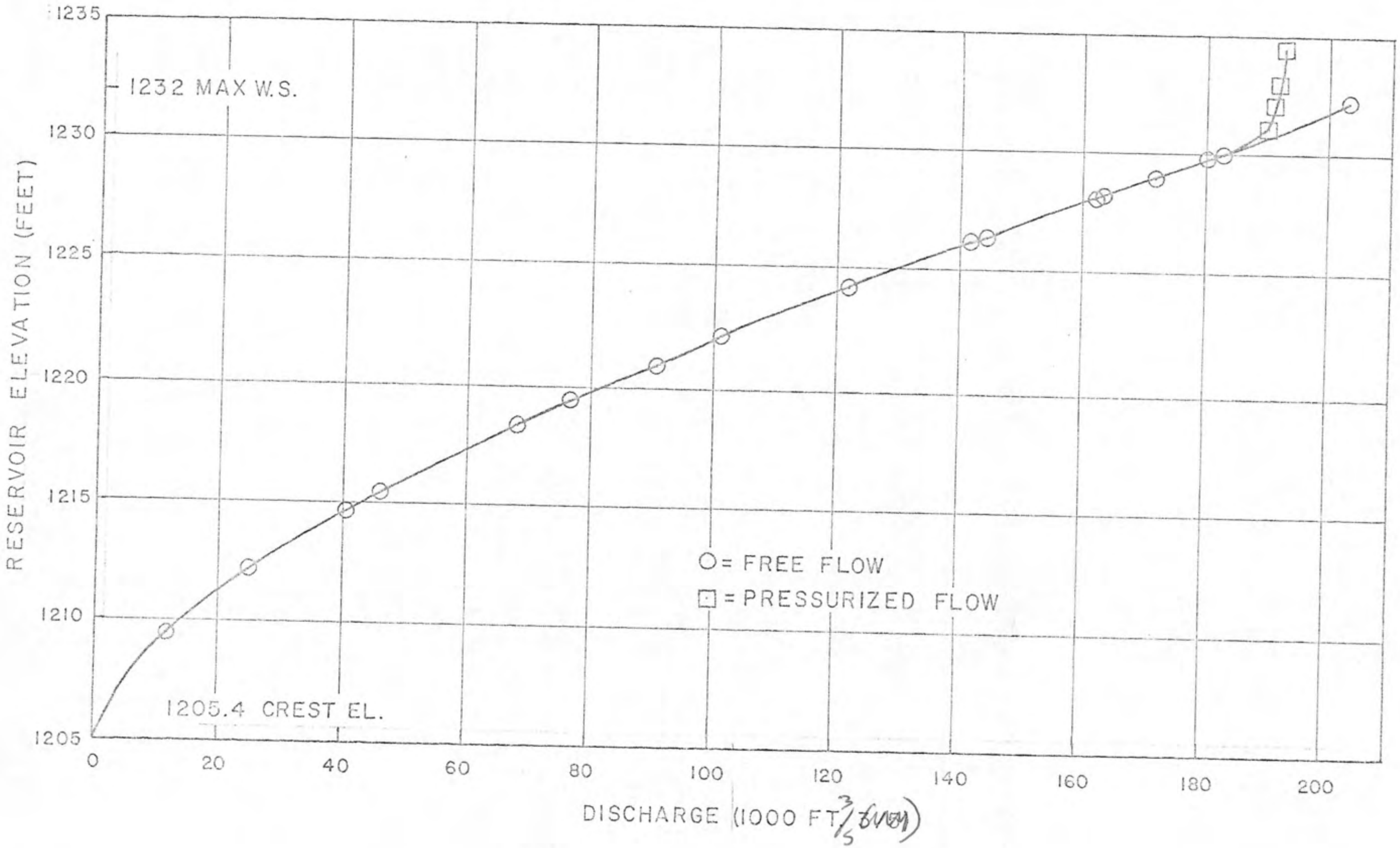


Figure 15. – Discharge curve for Hoover Dam Arizona Spillway.

Figure 16 ~~15~~ - Final aerator design - jet impacting upstream of the vertical bend for a discharge of 20,000 ft^3/s

17 Final aerator design - fins impinging on the tunnel crown for a dishcarge of 100,000 ft^3/s

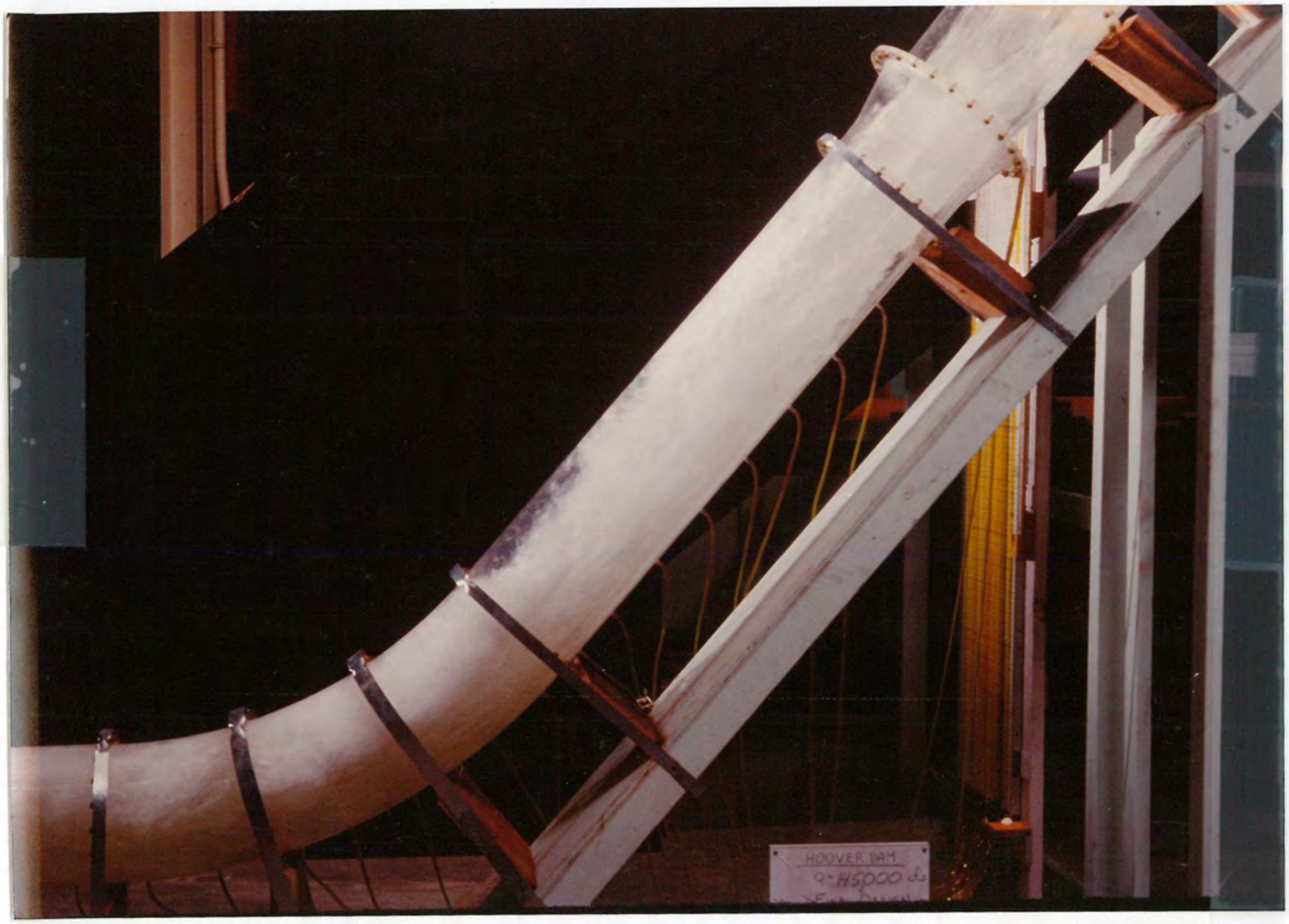


Figure 18.- Final aerator design - transient hydraulic jump down stream of the aerator for a discharge of 145,000 ft^3/s

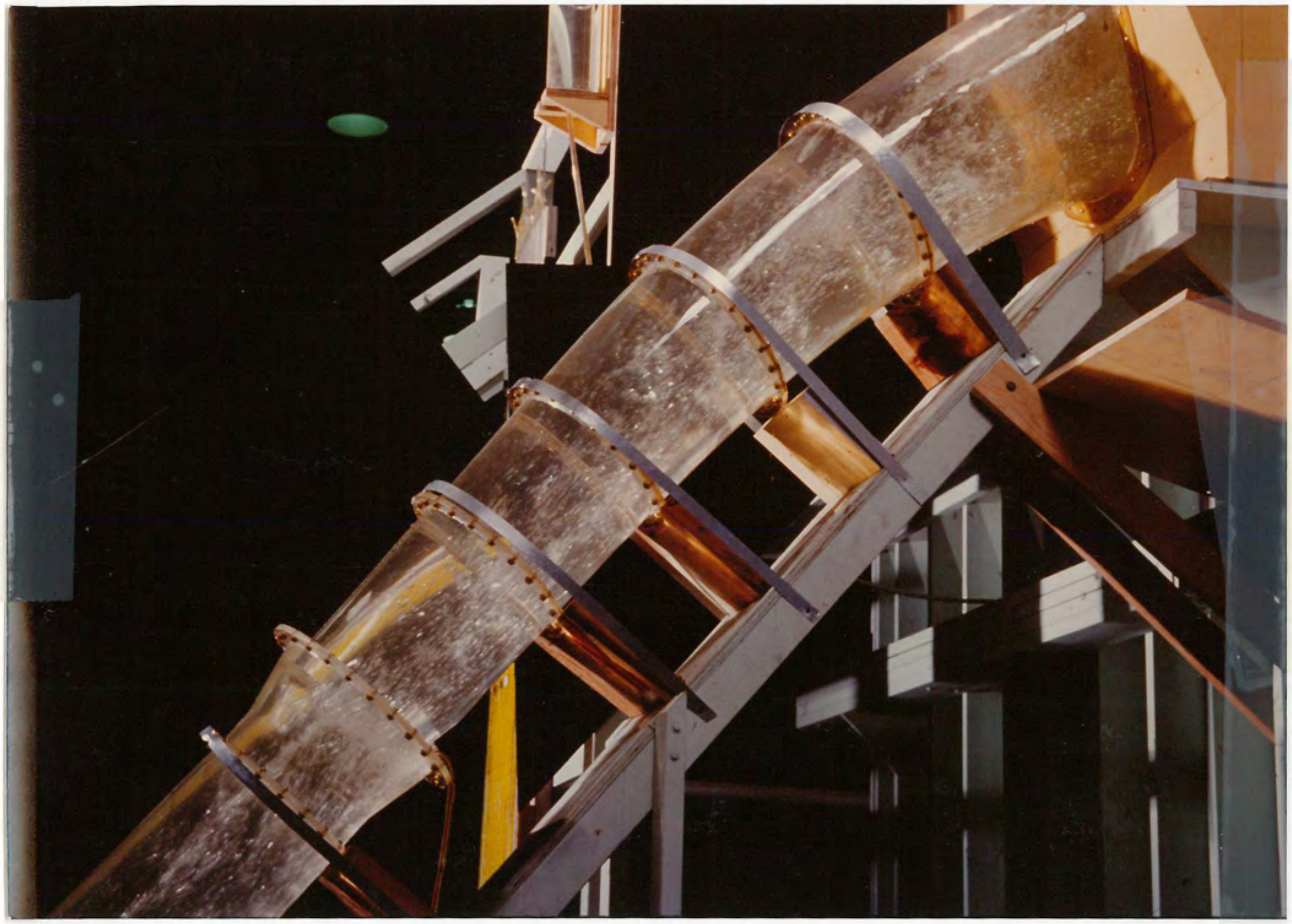


Figure 18. - Final aerator design - fully submerged aerator and pressure flow in the tunnel for a discharge of ~~200~~ 191,000 ft^3/s

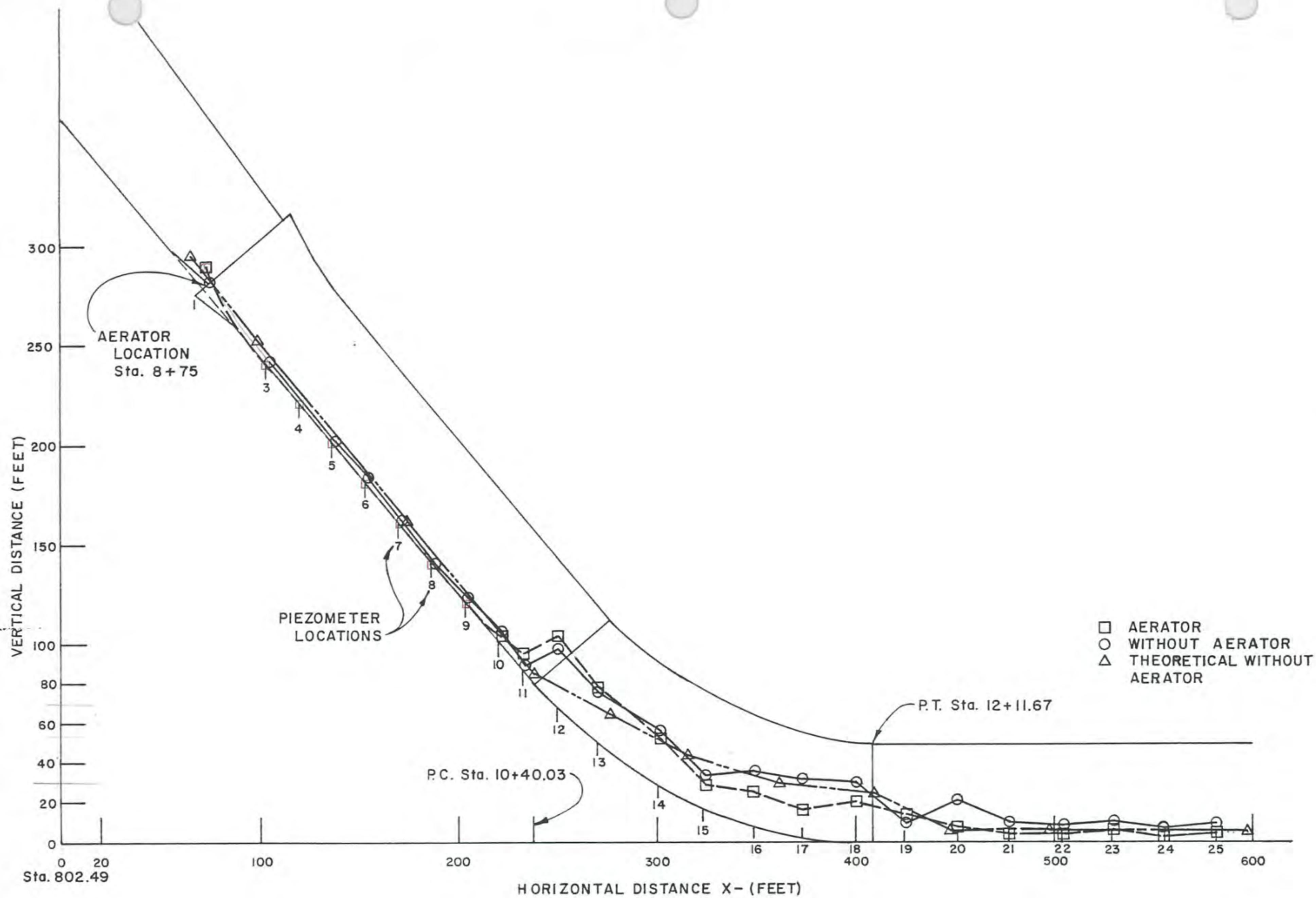


Figure 20.—Pressure profiles downstream of the air slot for 20,000 ft³/s.

7-1654 (7-73)
Bureau of Reclamation

COMPUTATION SHEET

BY	DATE	PROJECT	SHEET ___ OF ___
CHKD BY	DATE	FEATURE	
DETAILS			

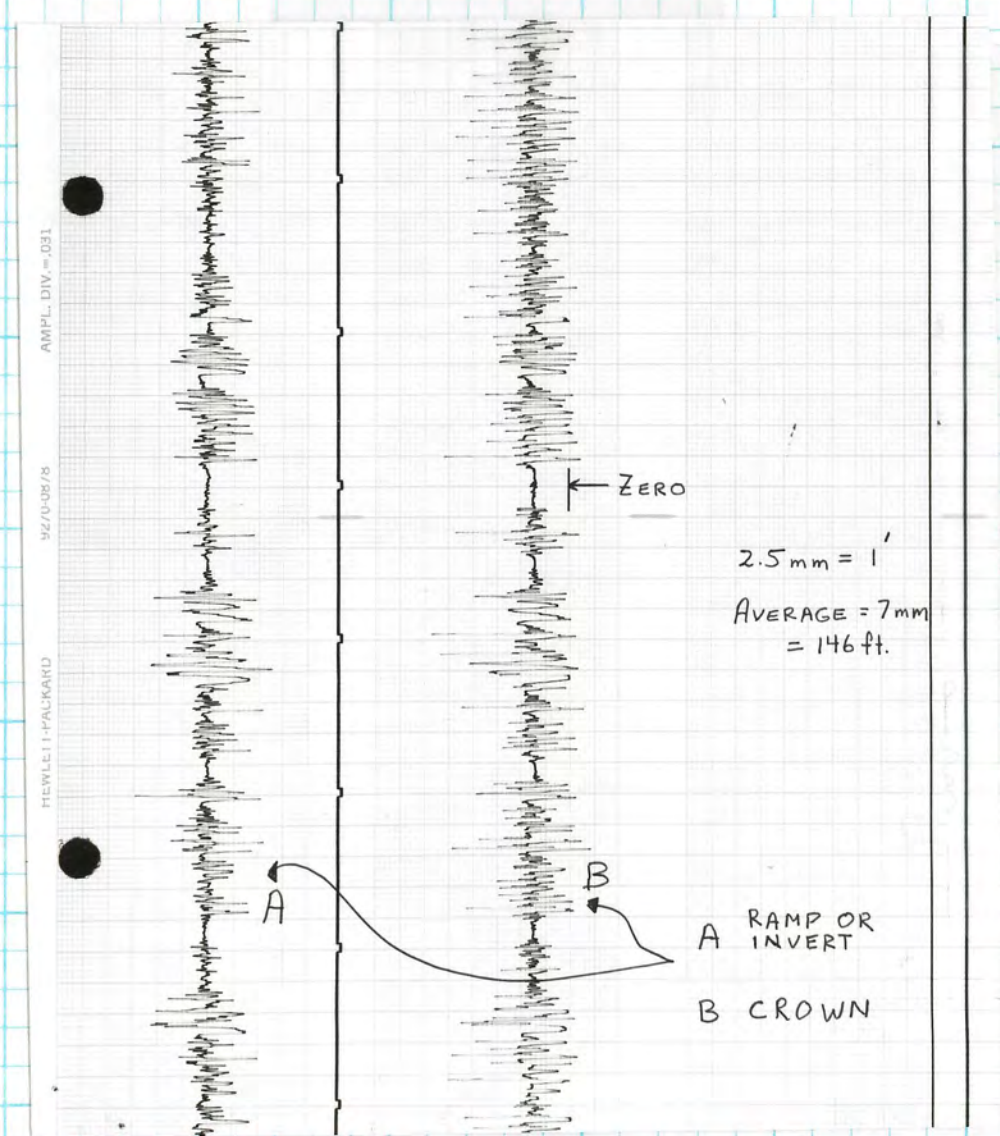


Figure 21. – Typical strip chart recording of pressures at the flip bucket for 125,000 ft³/s.

7-1654 (7-73)
Bureau of Reclamation

BY

CHKD BY

DETAILS

OF

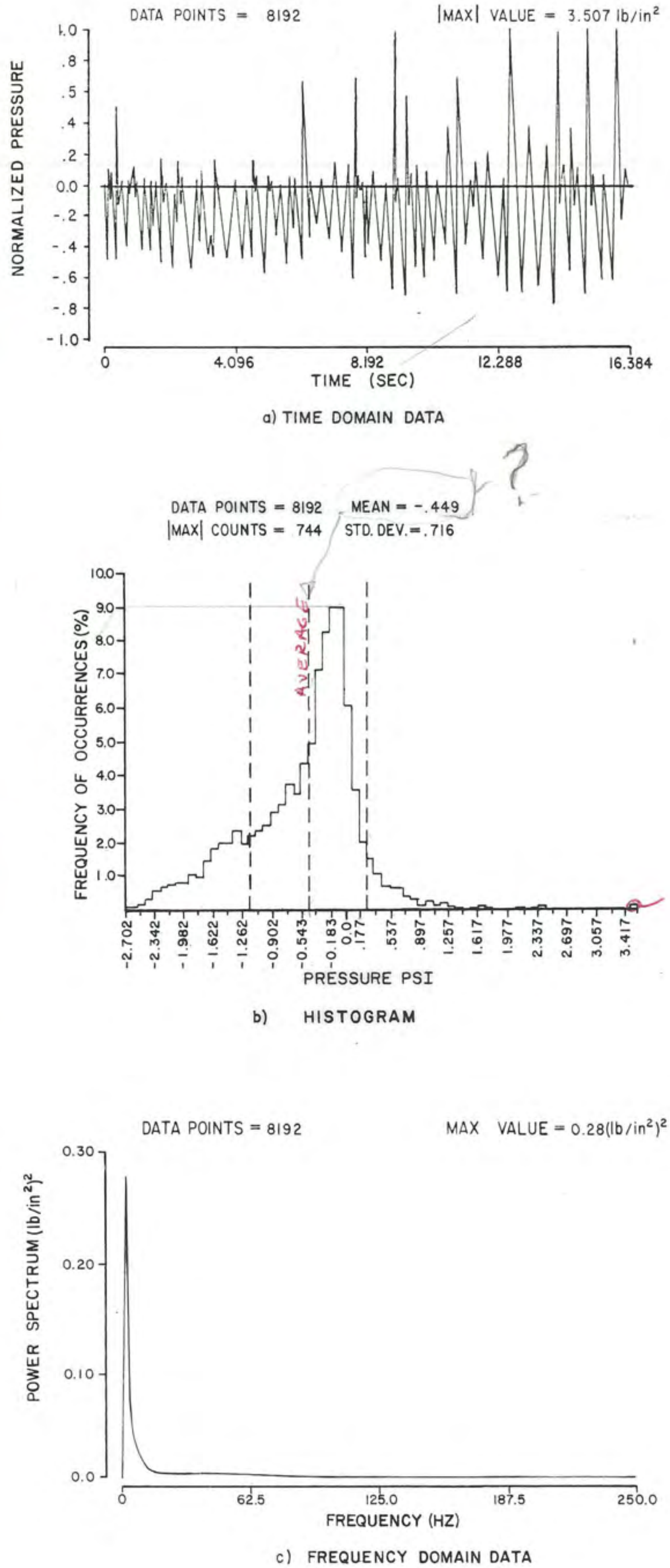


Figure 22. - Model dynamic pressures at the flip bucket crown for a

FLOW

Figure 23 — Modified flip bucket passing a discharge of 200,000 ft^3/s.

LOCATION OF INSTRUMENTATION BOXES

(NO)	STATION	ELEVATION
1	SEE SECTION A-A	
2	8+84.75	894.05
3	10+15	741.30
4	10+80	675.08
5	20+05*	633.41

*Indicates diversion tunnel stationing.
Stationing is located along the tunnel invert.
Instrumentation boxes No. 2 thru No. 5 are located on the tunnel invert.

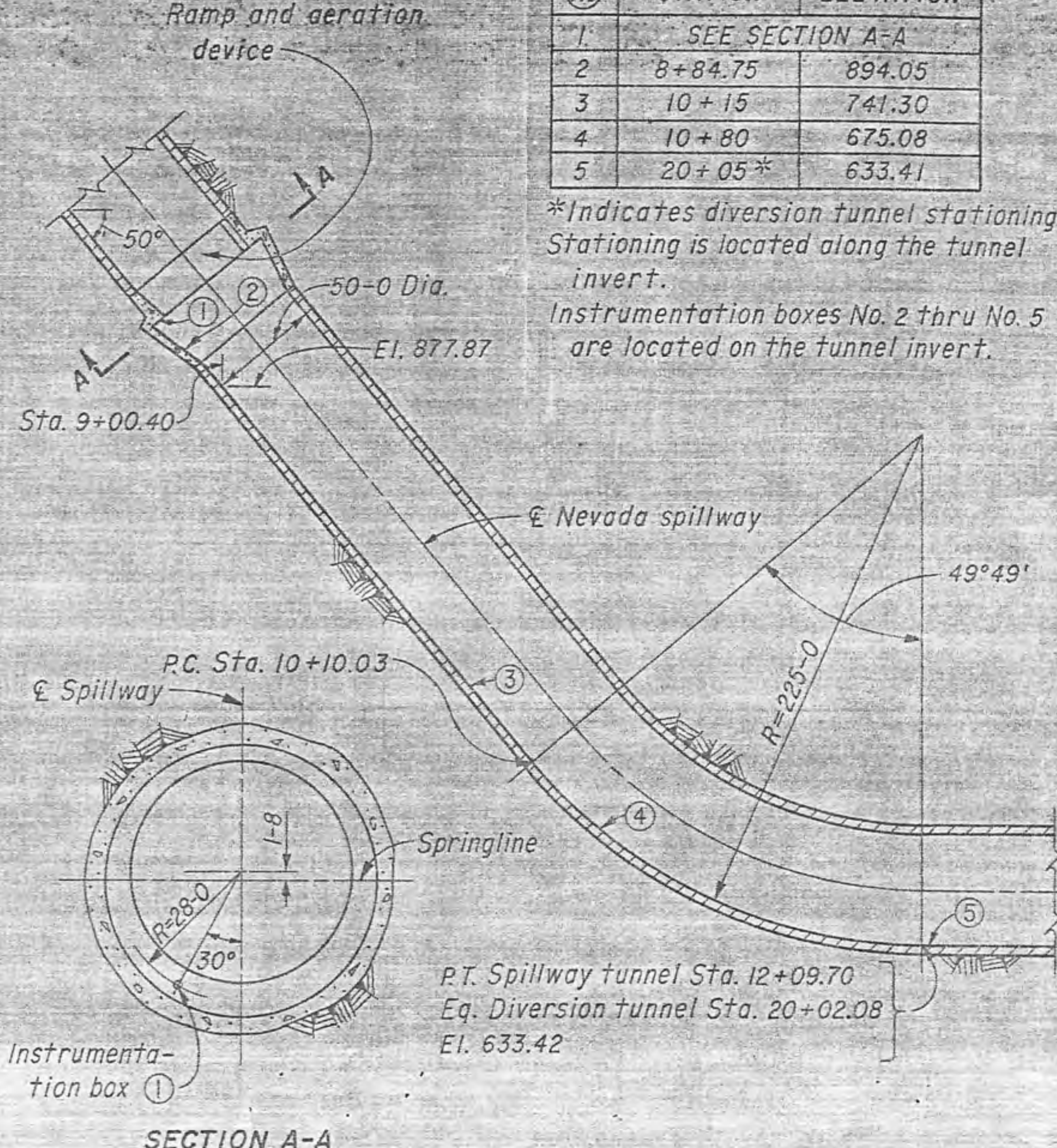


Figure 24. - Locations of prototype instrument boxes.

APPENDIX 1

HOOVER DAM - ARIZONA SPILLWAY

Q = 5000.0 CFS INITIAL DEPTH = 2.80 FT RUGOSITY = .001000 FT N = .0121

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
660.0	1116.44	.5190	2.800	34.843	2.134	1137.602	0.000	S2	1.087	7.054	.858
725.0	1072.73	.6725	2.552	59.769	1.174	1129.897	0.000	S2	1.371	9.489	1.446
763.0	1037.93	.9158	3.611	71.862	1.673	1122.367	0.000	S2	2.322	11.446	1.782
802.5	994.55	1.0985	3.309	84.768	2.228	1111.073	0.000	S2	2.311	12.018	2.126
825.0	967.73	1.1915	3.172	90.676	2.039	1102.714	0.000	S2	2.297	12.190	2.322
867.8	916.77	1.1918	3.043	100.521	1.956	1084.036	0.000	S2	2.344	12.468	2.668
875.1	907.99	1.1913	3.040	100.992	1.954	1080.495	0.000	S2	2.348	12.489	2.727
900.4	877.87	1.1919	2.964	105.825	1.905	1067.672	0.000	S2	2.359	12.555	2.923
975.0	788.97	1.1917	2.758	117.734	1.773	1026.916	0.000	S2	2.359	12.554	2.758
1040.0	711.47	1.1918	2.642	125.497	1.698	982.180	0.000	S2	2.359	12.555	2.642
1078.5	675.27	.9410	2.627	126.544	7.662	956.451	0.000	S2	2.423	12.353	2.627
1117.0	652.32	.5966	2.628	126.521	8.643	934.385	0.000	S2	2.599	11.854	2.628
1164.0	636.36	.3394	2.654	124.627	8.774	910.431	0.000	S3	2.910	11.557	2.654
1211.7	631.08	.1108	2.712	120.730	8.697	888.743	0.000	S3	3.775	11.412	2.712
1250.0	630.95	.0034	2.750	118.274	2.750	872.638	1.584	S3	8.956	11.210	2.750
1300.0	630.79	.0032	2.829	113.422	2.829	853.356	1.321	S3	9.090	11.207	2.829
1400.0	630.46	.0033	2.986	104.695	2.986	820.668	.916	S3	9.019	11.209	2.986
1500.0	630.13	.0033	3.141	97.112	3.141	794.353	.672	S3	9.019	11.210	3.141
1711.9	629.43	.0033	3.471	83.790	3.471	752.819	.367	S3	9.016	11.210	3.471
2212.1	627.79	.0033	4.272	61.664	4.272	697.011	.045	S3	9.033	11.210	4.272
2601.3	626.36	.0037	4.840	51.330	4.840	676.203	0.000	S3	8.776	11.210	4.840
2622.9	626.98	-.0286	4.771	49.631	6.021	675.076	0.000	A3	-1000.000	11.146	4.771
2644.6	628.87	-.0873	4.146	48.414	5.166	674.072	0.000	A3	-1000.000	10.237	4.146
2666.3	632.03	-.1458	3.730	46.135	4.538	672.923	0.000	A3	-1000.000	9.504	3.730
2687.9	636.50	-.2063	3.658	42.525	4.288	671.677	0.000	A3	-1000.000	9.119	3.658
2707.3	644.40	-.4087	4.018	35.569	4.261	670.271	0.000	A3	-1000.000	9.143	3.747

ERROR IN DEPTH EXCEEDS 2. PERCENT PLEASE ADD INTERMEDIATE STATIONS AT 2698.4

ENERGY GRADE LINE AT BEGINNING OF BOUNDARY LAYER
1150.643

HOOVER DAM - ARIZONA SPILLWAY

Q = 5000.0 CFS INITIAL DEPTH = 2.80 FT RUGOSITY = .001000 FT N = .0121

CAVITATION CHARACTERISTICS

STATION	FLOW SIGMA	SIGMA OF UNIFORM ROUGHNESS	REQUIRED CHAMFER TO STOP CAVITATION	DAMAGE POTENTIAL CIRCULAR ARC 1/4-IN 5-MM	CIRCULAR ARC 1/2-IN 10-MM	CIRCULAR ARC 1-IN 25-MM	90-DEGREE OFFSET 1/4-IN 5-MM	90-DEGREE OFFSET 1/2-IN 10-MM	90-DEGREE OFFSET 1-IN 25-MM
660.00	1.819	.050	1 TO 1	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01
725.00	.602	.051	1 TO 5	.358E-01	.766E+00	.335E+01	.304E+00	.191E+01	.746E+01
763.00	.423	.051	1 TO 8	.207E+01	.764E+01	.243E+02	.360E+01	.131E+02	.424E+02
802.49	.310	.052	1 TO 13	.134E+02	.416E+02	.121E+03	.188E+02	.601E+02	.182E+03
825.00	.269	.052	1 TO 16	.271E+02	.808E+02	.230E+03	.353E+02	.110E+03	.325E+03
867.76	.219	.053	1 TO 21	.747E+02	.214E+03	.595E+03	.883E+02	.265E+03	.771E+03
875.13	.217	.053	1 TO 21	.777E+02	.223E+03	.618E+03	.908E+02	.272E+03	.792E+03
→ 900.40	.198	.053	1 TO 24	.121E+03	.343E+03	.943E+03	.135E+03	.402E+03	.116E+04
975.00	.159	.054	1 TO 32	.350E+03	.967E+03	.262E+04	.386E+03	.112E+04	.318E+04
1040.03	.140	.054	1 TO 39	.652E+03	.178E+04	.480E+04	.717E+03	.206E+04	.581E+04
1078.50	.162	.054	1 TO 32	.575E+03	.159E+04	.430E+04	.632E+03	.183E+04	.521E+04
1116.97	.166	.054	1 TO 31	.554E+03	.154E+04	.417E+04	.610E+03	.177E+04	.504E+04
1164.00	.172	.054	1 TO 29	.474E+03	.132E+04	.358E+04	.522E+03	.152E+04	.434E+04
1211.67	.183	.054	1 TO 27	.345E+03	.964E+03	.263E+04	.381E+03	.112E+04	.320E+04
1250.00	.163	.054	1 TO 31	.345E+03	.955E+03	.259E+04	.380E+03	.111E+04	.314E+04
1300.00	.178	.053	1 TO 28	.226E+03	.631E+03	.172E+04	.250E+03	.733E+03	.210E+04
1400.00	.210	.053	1 TO 22	.993E+02	.283E+03	.783E+03	.111E+03	.331E+03	.960E+03
1500.00	.245	.052	1 TO 18	.449E+02	.132E+03	.370E+03	.504E+02	.155E+03	.457E+03
1711.86	.332	.051	1 TO 12	.854E+01	.274E+02	.817E+02	.979E+01	.329E+02	.102E+03
2212.06	.627	.049	1 TO 5	.100E-01	.376E+00	.223E+01	.100E-01	.557E+00	.307E+01
2601.25	.919	.048	1 TO 3	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01	.921E-02
2622.92	1.014	.048	1 TO 3	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01
2644.58	1.042	.049	1 TO 3	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01
2666.25	1.128	.049	1 TO 2	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01
2687.92	1.319	.049	1 TO 2	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01
2707.25	1.883	.048	1 TO 1	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01

HOOVER DAM - ARIZONA SPILLWAY

Q = 10000.0 CFS   INITIAL DEPTH = 4.40 FT   RUGOSITY = .001000 FT   N = .0125

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
660.0	1116.44	.5190	4.400	43.664	3.043	1149.191	0.000	S2	1.680	10.986	.821
725.0	1072.73	.6725	4.487	66.023	1.712	1142.365	0.000	S2	2.126	14.533	1.396
763.0	1037.93	.9158	5.453	78.200	2.290	1136.096	0.000	S2	3.243	16.279	1.727
802.5	994.55	1.0985	5.055	90.691	3.403	1126.949	0.000	S2	3.230	17.158	2.067
825.0	967.73	1.1915	4.834	97.304	3.108	1120.316	0.000	S2	3.210	17.408	2.260
867.8	916.77	1.1918	4.628	108.247	2.975	1105.669	0.000	S2	3.278	17.824	2.601
875.1	907.99	1.1913	4.602	109.465	2.959	1102.888	0.000	S2	3.283	17.851	2.659
900.4	877.87	1.1919	4.481	114.950	2.880	1092.776	0.000	S2	3.298	17.949	2.851
975.0	788.97	1.1917	4.134	129.444	2.657	1062.348	0.000	S2	3.298	17.952	3.375
1040.0	711.47	1.1918	3.962	137.808	2.547	1028.566	0.000	S2	3.298	17.952	3.809
1078.5	675.27	.9410	3.967	137.584	13.078	1009.442	0.000	S2	3.389	17.773	3.967
1117.0	652.32	.5966	3.956	138.149	14.859	993.168	0.000	S2	3.638	17.055	3.956
1164.0	636.36	.3394	3.965	137.641	15.161	975.115	0.000	S3	4.076	16.620	3.965
1211.7	631.08	.1108	4.015	135.151	15.125	958.199	0.000	S3	5.302	16.409	4.015
1250.0	630.95	.0034	4.023	134.741	4.023	945.077	.904	S3	12.789	16.009	4.023
1300.0	630.79	.0032	4.098	131.143	4.098	928.649	.820	S3	12.986	16.009	4.098
1400.0	630.46	.0033	4.246	124.432	4.246	899.172	.630	S3	12.881	16.010	4.246
1500.0	630.13	.0033	4.394	118.314	4.394	873.623	.496	S3	12.881	16.011	4.394
1711.9	629.43	.0033	4.707	106.927	4.707	829.429	.297	S3	12.877	16.011	4.707
2212.1	627.79	.0033	5.456	86.101	5.456	759.871	.039	S3	12.903	16.011	5.456
2601.3	626.36	.0037	6.012	74.715	6.012	727.722	0.000	S3	12.523	16.010	6.012
2622.9	626.98	-.0286	5.959	72.381	9.284	725.751	0.000	A3	-1000.000	16.100	5.959
2644.6	628.87	-.0873	5.229	71.475	8.057	724.186	0.000	A3	-1000.000	15.051	5.229
2666.3	632.03	-.1458	4.687	69.846	7.076	722.433	0.000	A3	-1000.000	14.213	4.687
2687.9	636.50	-.2063	4.468	67.354	6.536	720.525	0.000	A3	-1000.000	13.810	4.468
2707.3	644.40	-.4087	4.477	63.109	6.045	718.472	0.000	A3	-1000.000	14.109	4.477

ENERGY GRADE LINE AT BEGINNING OF BOUNDARY LAYER
1160.743

HOOVER DAM - ARIZONA SPILLWAY

Q = 10000.0 CFS   INITIAL DEPTH = 4.40 FT   RUGOSITY = .001000 FT   N = .0125

CAVITATION CHARACTERISTICS

				DAMAGE POTENTIAL					
				CIRCULAR ARC			90-DEGREE OFFSET		
STATION	FLOW SIGMA	SIGMA OF UNIFORM ROUGHNESS	REQUIRED CHAMFER TO STOP CAVITATION	1/4-IN 5-MM	1/2-IN 10-MM	1-IN 25-MM	1/4-IN 5-MM	1/2-IN 10-MM	1-IN 25-MM
660.00	1.189	.046	1 TO 2	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01	.123E-01
725.00	.501	.047	1 TO 7	.658E+00	.305E+01	.106E+02	.154E+01	.633E+01	.217E+02
763.00	.364	.047	1 TO 10	.582E+01	.192E+02	.578E+02	.939E+01	.314E+02	.975E+02
802.49	.280	.048	1 TO 15	.266E+02	.799E+02	.228E+03	.364E+02	.114E+03	.338E+03
825.00	.241	.048	1 TO 18	.545E+02	.158E+03	.444E+03	.696E+02	.211E+03	.619E+03
867.76	.194	.049	1 TO 25	.152E+03	.429E+03	.118E+04	.177E+03	.522E+03	.150E+04
875.13	.190	.049	1 TO 25	.169E+03	.474E+03	.130E+04	.194E+03	.571E+03	.164E+04
900.40	.172	.049	1 TO 29	.266E+03	.742E+03	.202E+04	.293E+03	.856E+03	.244E+04
975.00	.135	.050	1 TO 41	.792E+03	.217E+04	.582E+04	.788E+03	.226E+04	.638E+04
1040.03	.119	.050	1 TO 49	.138E+04	.373E+04	.998E+04	.128E+04	.366E+04	.103E+05
1078.50	.156	.050	1 TO 34	.962E+03	.265E+04	.717E+04	.883E+03	.256E+04	.728E+04
1116.97	.161	.050	1 TO 32	.951E+03	.263E+04	.712E+04	.873E+03	.254E+04	.723E+04
1164.00	.163	.050	1 TO 32	.907E+03	.251E+04	.680E+04	.833E+03	.243E+04	.691E+04
1211.67	.169	.050	1 TO 30	.756E+03	.210E+04	.570E+04	.694E+03	.203E+04	.580E+04
1250.00	.130	.050	1 TO 43	.102E+04	.280E+04	.750E+04	.943E+03	.270E+04	.762E+04
1300.00	.138	.050	1 TO 40	.783E+03	.215E+04	.577E+04	.721E+03	.208E+04	.588E+04
1400.00	.154	.049	1 TO 34	.464E+03	.128E+04	.347E+04	.428E+03	.124E+04	.354E+04
1500.00	.171	.049	1 TO 29	.279E+03	.777E+03	.212E+04	.257E+03	.756E+03	.217E+04
1711.86	.211	.049	1 TO 22	.981E+02	.281E+03	.780E+03	.909E+02	.275E+03	.802E+03
2212.06	.332	.047	1 TO 12	.874E+01	.284E+02	.851E+02	.810E+01	.280E+02	.886E+02
2601.25	.447	.046	1 TO 8	.121E+01	.525E+01	.179E+02	.110E+01	.521E+01	.188E+02
2622.92	.517	.046	1 TO 6	.404E+00	.275E+01	.106E+02	.358E+00	.278E+01	.113E+02
2644.58	.514	.047	1 TO 6	.419E+00	.270E+01	.103E+02	.430E+00	.294E+01	.117E+02
2666.25	.526	.047	1 TO 6	.312E+00	.222E+01	.862E+01	.365E+00	.260E+01	.104E+02
2687.92	.558	.047	1 TO 6	.105E+00	.139E+01	.585E+01	.157E+00	.172E+01	.741E+01
2707.25	.627	.047	1 TO 5	.100E-01	.444E+00	.260E+01	.100E-01	.624E+00	.347E+01

HOOVER DAM - ARIZONA SPILLWAY

Q = 15000.0 CFS INITIAL DEPTH = 6.20 FT RUGOSITY = .001000 FT N = .0128

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
660.0	1116.44	.5190	6.200	45.691	4.174	1153.087	0.000	S2	2.170	14.173	.813
725.0	1072.73	.6725	6.361	67.970	2.261	1146.854	0.000	S2	2.753	18.511	1.385
763.0	1037.93	.9158	7.064	80.261	2.859	1141.292	0.000	S2	3.948	20.029	1.715
802.5	994.55	1.0985	6.563	92.751	4.418	1133.338	0.000	S2	3.933	21.168	2.053
825.0	967.73	1.1915	6.267	99.696	4.029	1127.607	0.000	S2	3.909	21.480	2.245
867.8	916.77	1.1918	5.991	111.199	3.851	1115.093	0.000	S2	3.993	22.010	2.584
875.1	907.99	1.1913	5.948	112.705	3.824	1112.724	0.000	S2	3.999	22.045	2.642
900.4	877.87	1.1919	5.785	118.548	3.718	1104.115	0.000	S2	4.018	22.169	2.833
975.0	788.97	1.1917	5.310	134.401	3.413	1079.604	0.000	S2	4.019	22.168	3.353
1040.0	711.47	1.1918	5.054	144.482	3.249	1051.794	0.000	S2	4.019	22.172	3.783
1078.5	675.27	.9410	5.051	144.628	17.537	1035.802	0.000	S2	4.130	22.049	4.003
1117.0	652.32	.5966	5.028	145.593	19.952	1022.096	0.000	S2	4.434	21.159	4.186
1164.0	636.36	.3394	5.037	145.188	20.443	1006.819	0.000	S2	4.972	20.614	4.387
1211.7	631.08	.1108	5.094	142.844	20.496	992.446	0.000	S3	6.481	20.345	4.579
1250.0	630.95	.0034	5.080	143.402	5.080	981.158	.543	S3	15.858	19.757	4.731
1300.0	630.79	.0032	5.163	140.027	5.163	966.825	.505	S3	16.109	19.757	4.928
1400.0	630.46	.0033	5.317	134.146	5.317	940.656	.393	S3	15.976	19.758	5.316
1500.0	630.13	.0033	5.476	128.452	5.476	917.429	.310	S3	15.976	19.759	5.476
1711.9	629.43	.0033	5.781	118.662	5.781	875.720	.180	S3	15.970	19.759	5.781
2212.1	627.79	.0033	6.507	99.855	6.506	804.609	0.000	S3	16.004	19.759	6.507
2601.3	626.36	.0037	7.053	88.790	7.053	768.073	0.000	S3	15.519	19.756	7.053
2622.9	626.98	-.0286	7.031	85.901	12.558	765.577	0.000	A3	-1000.000	20.003	7.031
2644.6	628.87	-.0873	6.234	85.164	11.029	763.783	0.000	A3	-1000.000	18.871	6.234
2666.3	632.03	-.1458	5.625	83.810	9.777	761.785	0.000	A3	-1000.000	18.015	5.625
2687.9	636.50	-.2063	5.356	81.712	9.057	759.602	0.000	A3	-1000.000	17.679	5.356
2707.3	644.40	-.4087	5.320	78.207	8.393	757.266	0.000	A3	-1000.000	18.162	5.320

ENERGY GRADE LINE AT BEGINNING OF BOUNDARY LAYER
1163.637

HOOVER DAM - ARIZONA SPILLWAY

Q = 15000.0 CFS   INITIAL DEPTH = 6.20 FT   RUGOSITY = .001000 FT   N = .0128

CAVITATION CHARACTERISTICS

STATION	FLOW SIGMA	SIGMA OF UNIFORM ROUGHNESS	REQUIRED CHAMFER TO STOP CAVITATION	DAMAGE POTENTIAL: CIRCULAR ARC 1/4-IN 5-MM	CIRCULAR ARC 1/2-IN 10-MM	CIRCULAR ARC 1-IN 25-MM	90-DEGREE OFFSET 1/4-IN 5-MM	90-DEGREE OFFSET 1/2-IN 10-MM	90-DEGREE OFFSET 1-IN 25-MM
660.00	1.121	.044	1 TO 2	.100E-01	.100E-01	.100E-01	.100E-01	.100E-01	.149E+00
725.00	.481	.044	1 TO 7	.997E+00	.423E+01	.143E+02	.218E+01	.854E+01	.286E+02
763.00	.351	.045	1 TO 11	.764E+01	.247E+02	.737E+02	.121E+02	.401E+02	.123E+03
802.49	.275	.046	1 TO 15	.324E+02	.965E+02	.275E+03	.440E+02	.136E+03	.405E+03
825.00	.236	.046	1 TO 19	.674E+02	.195E+03	.545E+03	.855E+02	.259E+03	.755E+03
867.76	.189	.046	1 TO 26	.193E+03	.541E+03	.148E+04	.222E+03	.655E+03	.188E+04
875.13	.184	.047	1 TO 27	.218E+03	.611E+03	.167E+04	.249E+03	.730E+03	.209E+04
900.40	.166	.047	1 TO 31	.350E+03	.971E+03	.264E+04	.382E+03	.111E+04	.316E+04
975.00	.128	.047	1 TO 44	.111E+04	.302E+04	.810E+04	.109E+04	.313E+04	.880E+04
1040.03	.111	.048	1 TO 54	.211E+04	.570E+04	.152E+05	.195E+04	.553E+04	.155E+05
1078.50	.155	.048	1 TO 34	.138E+04	.381E+04	.103E+05	.125E+04	.361E+04	.103E+05
1116.97	.160	.048	1 TO 32	.136E+04	.376E+04	.102E+05	.121E+04	.351E+04	.998E+04
1164.00	.162	.048	1 TO 32	.129E+04	.356E+04	.965E+04	.112E+04	.326E+04	.930E+04
1211.67	.168	.048	1 TO 30	.108E+04	.300E+04	.815E+04	.929E+03	.272E+04	.776E+04
1250.00	.118	.048	1 TO 49	.170E+04	.462E+04	.124E+05	.145E+04	.414E+04	.116E+05
1300.00	.125	.048	1 TO 46	.134E+04	.363E+04	.974E+04	.113E+04	.323E+04	.909E+04
1400.00	.136	.047	1 TO 41	.859E+03	.235E+04	.633E+04	.713E+03	.206E+04	.582E+04
1500.00	.149	.047	1 TO 36	.557E+03	.154E+04	.415E+04	.462E+03	.134E+04	.382E+04
1711.86	.176	.047	1 TO 28	.249E+03	.698E+03	.191E+04	.207E+03	.612E+03	.176E+04
2212.06	.254	.046	1 TO 17	.401E+02	.119E+03	.339E+03	.331E+02	.105E+03	.315E+03
2601.25	.325	.045	1 TO 12	.104E+02	.335E+02	.100E+03	.843E+01	.294E+02	.933E+02
2622.92	.395	.045	1 TO 9	.500E+01	.183E+02	.580E+02	.401E+01	.161E+02	.545E+02
2644.58	.389	.045	1 TO 9	.519E+01	.186E+02	.585E+02	.447E+01	.173E+02	.580E+02
2666.25	.390	.046	1 TO 9	.478E+01	.171E+02	.538E+02	.437E+01	.168E+02	.559E+02
2687.92	.403	.046	1 TO 9	.366E+01	.135E+02	.431E+02	.347E+01	.137E+02	.461E+02
2707.25	.433	.045	1 TO 8	.209E+01	.839E+01	.278E+02	.201E+01	.867E+01	.302E+02

HOOVER DAM - ARIZONA SPILLWAY

Q = 20000.0 CFS   INITIAL DEPTH = 7.40 FT   RUGOSITY = .001000 FT   N = .0129

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
660.0	1116.44	.5190	7.400	50.471	4.634	1160.674	0.000	S2	2.604	16.934	.797
725.0	1072.73	.6725	7.893	71.460	2.414	1154.530	0.000	S2	3.308	21.890	1.364
763.0	1037.93	.9158	8.387	83.320	3.182	1149.233	0.000	S2	4.542	23.215	1.691
802.5	994.55	1.0985	7.839	95.436	5.277	1141.832	0.000	S2	4.525	24.590	2.027
825.0	967.73	1.1915	7.493	102.421	4.817	1136.526	0.000	S2	4.497	24.956	2.218
867.8	916.77	1.1918	7.173	114.038	4.611	1125.084	0.000	S2	4.596	25.583	2.555
875.1	907.99	1.1913	7.118	115.662	4.577	1122.931	0.000	S2	4.603	25.625	2.612
900.4	877.87	1.1919	6.924	121.628	4.450	1115.124	0.000	S2	4.626	25.771	2.803
975.0	788.97	1.1917	6.346	138.077	4.079	1093.950	0.000	S2	4.626	25.770	3.320
1040.0	711.47	1.1918	6.022	149.050	3.871	1069.753	0.000	S2	4.626	25.773	3.747
1078.5	675.27	.9410	6.019	149.159	21.663	1055.777	0.000	S2	4.754	25.721	3.966
1117.0	652.32	.5966	5.983	150.464	24.647	1043.769	0.000	S2	5.107	24.687	4.148
1164.0	636.36	.3394	5.982	150.509	25.268	1030.289	0.000	S2	5.730	24.042	4.348
1211.7	631.08	.1108	6.034	148.610	25.364	1017.491	0.000	S3	7.481	23.733	4.538
1250.0	630.95	.0034	5.989	150.245	5.989	1007.288	.338	S3	18.558	22.956	4.689
1300.0	630.79	.0032	6.073	147.242	6.073	994.143	.320	S3	18.862	22.956	4.883
1400.0	630.46	.0033	6.227	141.952	6.227	969.815	.241	S3	18.700	22.957	5.267
1500.0	630.13	.0033	6.387	136.786	6.387	947.837	.182	S3	18.700	22.957	5.646
1711.9	629.43	.0033	6.709	127.341	6.708	907.609	.084	S3	18.694	22.958	6.430
2212.1	627.79	.0033	7.464	109.044	7.464	836.854	0.000	S3	18.735	22.958	7.464
2601.3	626.36	.0037	8.028	98.126	8.028	798.854	0.000	S3	18.151	22.956	8.028
2622.9	626.98	-.0286	8.044	94.735	15.735	796.011	0.000	A3	-1000.000	23.355	8.044
2644.6	628.87	-.0873	7.193	94.125	13.958	794.153	0.000	A3	-1000.000	22.200	7.193
2666.3	632.03	-.1458	6.537	92.949	12.488	792.088	0.000	A3	-1000.000	21.397	6.537
2687.9	636.50	-.2063	6.241	91.079	11.630	789.821	0.000	A3	-1000.000	21.045	6.241
2707.3	644.40	-.4087	6.208	87.950	10.865	787.389	0.000	A3	-1000.000	21.508	6.208

ENERGY GRADE LINE AT BEGINNING OF BOUNDARY LAYER
1171.071

HOOVER DAM - ARIZONA SPILLWAY

Q = 20000.0 CFS   INITIAL DEPTH = 7.40 FT   RUGOSITY = .001000 FT   N = .0129

CAVITATION CHARACTERISTICS

STATION	FLOW SIGMA	SIGMA OF UNIFORM ROUGHNESS	REQUIRED CHAMFER TO STOP CAVITATION	DAMAGE POTENTIAL CIRCULAR ARC 1/4-IN 5-MM	CIRCULAR ARC 1/2-IN 10-MM	CIRCULAR ARC 1-IN 25-MM	90-DEGREE OFFSET 1/4-IN 5-MM	90-DEGREE OFFSET 1/2-IN 10-MM	90-DEGREE OFFSET 1-IN 25-MM
660.00	.930	.043	1 TO 3	.100E-01	.100E-01	.138E+00	.100E-01	.649E-01	.118E+01
725.00	.437	.043	1 TO 8	.205E+01	.765E+01	.245E+02	.409E+01	.148E+02	.477E+02
763.00	.329	.044	1 TO 12	.116E+02	.363E+02	.107E+03	.180E+02	.581E+02	.177E+03
802.49	.266	.044	1 TO 16	.423E+02	.125E+03	.354E+03	.571E+02	.176E+03	.519E+03
825.00	.228	.045	1 TO 20	.863E+02	.248E+03	.691E+03	.109E+03	.328E+03	.953E+03
867.76	.183	.045	1 TO 27	.241E+03	.675E+03	.184E+04	.277E+03	.813E+03	.233E+04
875.13	.178	.045	1 TO 28	.275E+03	.768E+03	.209E+04	.312E+03	.913E+03	.261E+04
900.40	.161	.045	1 TO 32	.439E+03	.121E+04	.329E+04	.477E+03	.139E+04	.394E+04
975.00	.124	.046	1 TO 46	.141E+04	.383E+04	.102E+05	.138E+04	.394E+04	.111E+05
1040.03	.106	.046	1 TO 58	.278E+04	.751E+04	.200E+05	.255E+04	.724E+04	.202E+05
1078.50	.157	.046	1 TO 33	.169E+04	.466E+04	.126E+05	.151E+04	.439E+04	.125E+05
1116.97	.163	.046	1 TO 31	.169E+04	.466E+04	.126E+05	.148E+04	.431E+04	.123E+05
1164.00	.165	.046	1 TO 31	.164E+04	.453E+04	.123E+05	.141E+04	.412E+04	.117E+05
1211.67	.169	.046	1 TO 30	.142E+04	.395E+04	.107E+05	.121E+04	.355E+04	.101E+05
1250.00	.111	.046	1 TO 55	.258E+04	.699E+04	.186E+05	.218E+04	.619E+04	.174E+05
1300.00	.115	.046	1 TO 51	.210E+04	.569E+04	.152E+05	.175E+04	.500E+04	.140E+05
1400.00	.125	.046	1 TO 46	.144E+04	.392E+04	.105E+05	.118E+04	.338E+04	.953E+04
1500.00	.135	.046	1 TO 41	.982E+03	.269E+04	.723E+04	.792E+03	.228E+04	.646E+04
1711.86	.157	.046	1 TO 33	.466E+03	.129E+04	.350E+04	.364E+03	.107E+04	.305E+04
2212.06	.218	.045	1 TO 21	.919E+02	.265E+03	.741E+03	.703E+02	.216E+03	.637E+03
2601.25	.273	.044	1 TO 15	.289E+02	.877E+02	.253E+03	.218E+02	.711E+02	.217E+03
2622.92	.348	.044	1 TO 11	.136E+02	.454E+02	.138E+03	.101E+02	.367E+02	.119E+03
2644.58	.340	.044	1 TO 11	.144E+02	.472E+02	.142E+03	.113E+02	.402E+02	.129E+03
2666.25	.337	.044	1 TO 11	.138E+02	.452E+02	.136E+03	.115E+02	.402E+02	.128E+03
2687.92	.344	.044	1 TO 11	.116E+02	.382E+02	.115E+03	.985E+01	.349E+02	.112E+03
2707.25	.363	.044	1 TO 10	.792E+01	.270E+02	.828E+02	.681E+01	.250E+02	.813E+02

HOOVER DAM - ARIZONA SPILLWAY

Q = 50000.0 CFS   INITIAL DEPTH = 14.80 FT   RUGOSITY = .001000 FT   N = .0135

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
660.0	1116.44	.5190	14.800	59.011	7.852	1178.380	0.000	S2	4.670	29.291	.773
725.0	1072.73	.6725	16.024	78.953	3.056	1172.607	0.000	S2	5.959	36.400	1.328
763.0	1037.93	.9158	15.073	89.833	4.858	1168.184	0.000	S2	7.125	37.234	1.650
802.5	994.55	1.0985	14.288	100.905	9.618	1162.460	0.000	S2	7.106	39.614	1.982
825.0	967.73	1.1915	13.659	108.089	8.781	1158.276	0.000	S2	7.062	40.166	2.171
867.8	916.77	1.1918	13.113	120.069	8.429	1149.623	0.000	S2	7.230	40.847	2.505
875.1	907.99	1.1913	13.000	121.925	8.358	1148.025	0.000	S2	7.242	40.877	2.562
900.4	877.87	1.1919	12.640	128.225	8.124	1142.293	0.000	S2	7.281	40.974	2.751
975.0	788.97	1.1917	11.520	146.190	7.405	1129.803	0.000	S2	7.281	40.972	3.262
1040.0	711.47	1.1918	10.848	159.233	6.973	1115.315	0.000	S2	7.281	40.978	3.683
1078.5	675.27	.9410	10.931	157.512	42.039	1106.997	0.000	S2	7.487	41.098	3.899
1117.0	652.32	.5966	10.838	159.445	47.822	1099.930	0.000	S2	8.054	39.755	4.080
1164.0	636.36	.3394	10.781	160.638	49.154	1091.883	0.000	S2	9.062	38.865	4.277
1211.7	631.08	.1108	10.814	159.940	49.533	1084.079	0.000	S3	11.929	38.421	4.465
1250.0	630.95	.0034	10.528	166.168	10.528	1077.539	0.000	S3	32.457	36.915	4.612
1300.0	630.79	.0032	10.611	164.316	10.611	1068.698	0.000	S3	33.151	36.915	4.802
1400.0	630.46	.0033	10.766	160.960	10.766	1051.764	0.000	S3	32.780	36.915	5.176
1500.0	630.13	.0033	10.926	157.623	10.926	1035.764	0.000	S3	32.780	36.915	5.545
1711.9	629.43	.0033	11.252	151.157	11.252	1004.610	0.000	S3	32.765	36.916	6.302
2212.1	627.79	.0033	12.023	137.607	12.023	943.071	0.000	S3	32.857	36.916	8.007
2601.3	626.36	.0037	12.651	128.067	12.651	904.979	0.000	S3	31.548	36.913	9.300
2622.9	626.98	-.0286	13.004	121.388	32.570	900.719	0.000	A3	-1000.000	37.995	9.372
2644.6	628.87	-.0873	11.966	121.273	29.859	898.965	0.000	A3	-1000.000	36.766	9.445
2666.3	632.03	-.1458	11.241	119.916	27.762	896.996	0.000	A3	-1000.000	35.581	9.518
2687.9	636.50	-.2063	10.985	117.988	26.639	894.808	0.000	A3	-1000.000	26.274	9.592
2707.3	644.40	-.4087	11.332	115.202	26.173	892.365	0.000	A3	-1000.000	29.478	9.663

ENERGY GRADE LINE AT BEGINNING OF BOUNDARY LAYER
1188.150

HOOVER DAM - ARIZONA SPILLWAY

Q = 50000.0 CFS INITIAL DEPTH = 14.80 FT RUGOSITY = .001000 FT N = .0135

CAVITATION CHARACTERISTICS

				DAMAGE POTENTIAL					
				CIRCULAR ARC			90-DEGREE OFFSET		
STATION	FLOW SIGMA	SIGMA OF UNIFORM ROUGHNESS	REQUIRED CHAMFER TO STOP CAVITATION	1/4-IN 5-MM	1/2-IN 10-MM	1-IN 25-MM	1/4-IN 5-MM	1/2-IN 10-MM	1-IN 25-MM
660.00	.740	.039	1 TO 4	.100E-01	.298E+00	.223E+01	.119E+00	.169E+01	.745E+01
725.00	.364	.039	1 TO 10	.694E+01	.226E+02	.679E+02	.125E+02	.411E+02	.126E+03
763.00	.296	.040	1 TO 14	.246E+02	.743E+02	.214E+03	.371E+02	.116E+03	.346E+03
802.49	.265	.040	1 TO 16	.640E+02	.189E+03	.533E+03	.855E+02	.262E+03	.773E+03
825.00	.227	.041	1 TO 20	.129E+03	.371E+03	.103E+04	.162E+03	.485E+03	.141E+04
867.76	.182	.041	1 TO 27	.353E+03	.987E+03	.269E+04	.403E+03	.118E+04	.337E+04
875.13	.177	.041	1 TO 28	.408E+03	.114E+04	.310E+04	.459E+03	.134E+04	.383E+04
900.40	.159	.041	1 TO 33	.654E+03	.180E+04	.488E+04	.704E+03	.204E+04	.579E+04
975.00	.120	.042	1 TO 48	.220E+04	.596E+04	.159E+05	.213E+04	.608E+04	.170E+05
1040.03	.101	.042	1 TO 62	.475E+04	.128E+05	.339E+05	.430E+04	.122E+05	.339E+05
1078.50	.194	.042	1 TO 25	.191E+04	.534E+04	.146E+05	.169E+04	.498E+04	.143E+05
1116.97	.204	.042	1 TO 23	.191E+04	.537E+04	.147E+05	.165E+04	.491E+04	.142E+05
1164.00	.204	.042	1 TO 23	.197E+04	.555E+04	.152E+05	.167E+04	.497E+04	.144E+05
1211.67	.207	.042	1 TO 23	.185E+04	.521E+04	.143E+05	.154E+04	.460E+04	.133E+05
1250.00	.101	.042	1 TO 62	.591E+04	.159E+05	.423E+05	.487E+04	.138E+05	.385E+05
1300.00	.103	.042	1 TO 60	.524E+04	.141E+05	.375E+05	.427E+04	.121E+05	.338E+05
1400.00	.108	.042	1 TO 56	.419E+04	.113E+05	.301E+05	.334E+04	.949E+04	.265E+05
1500.00	.113	.042	1 TO 53	.335E+04	.906E+04	.242E+05	.261E+04	.745E+04	.209E+05
1711.86	.124	.042	1 TO 46	.214E+04	.581E+04	.156E+05	.161E+04	.461E+04	.130E+05
2212.06	.152	.041	1 TO 35	.782E+03	.216E+04	.586E+04	.550E+03	.161E+04	.460E+04
2601.25	.178	.041	1 TO 28	.361E+03	.101E+04	.278E+04	.243E+03	.726E+03	.210E+04
2622.92	.285	.041	1 TO 14	.118E+03	.359E+03	.104E+04	.776E+02	.255E+03	.785E+03
2644.58	.274	.041	1 TO 15	.126E+03	.378E+03	.108E+04	.827E+02	.269E+03	.821E+03
2666.25	.271	.041	1 TO 15	.118E+03	.354E+03	.101E+04	.777E+02	.252E+03	.768E+03
2687.92	.275	.041	1 TO 15	.102E+03	.308E+03	.884E+03	.673E+02	.219E+03	.671E+03
2707.25	.286	.041	1 TO 14	.798E+02	.244E+03	.705E+03	.525E+02	.174E+03	.536E+03

HOOVER DAM - ARIZONA SPILLWAY

Q = 60000.0 CFS   INITIAL DEPTH = 16.10 FT   RUGOSITY = .001000 FT   N = .0135

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
660.0	1116.44	.5190	16.100	64.365	7.452	1188.236	0.000	S2	5.249	32.528	.759
725.0	1072.73	.6725	17.841	83.184	2.149	1182.349	0.000	S2	6.701	40.072	1.309
763.0	1037.93	.9158	16.707	93.302	4.839	1178.016	0.000	S2	7.801	40.867	1.628
802.5	994.55	1.0985	15.957	103.717	10.742	1172.488	0.000	S2	7.781	43.340	1.959
825.0	967.73	1.1915	15.281	110.777	9.824	1168.393	0.000	S2	7.734	43.884	2.147
867.8	916.77	1.1918	14.717	122.578	9.460	1160.003	0.000	S2	7.921	44.178	2.480
875.1	907.99	1.1913	14.594	124.427	9.383	1158.461	0.000	S2	7.935	44.169	2.536
900.4	877.87	1.1919	14.203	130.673	9.128	1152.945	0.000	S2	7.978	44.110	2.724
975.0	788.97	1.1917	12.957	148.600	8.329	1141.449	0.000	S2	7.978	44.115	3.234
1040.0	711.47	1.1918	12.200	161.766	7.842	1128.180	0.000	S2	7.978	44.122	3.653
1078.5	675.27	.9410	12.337	159.217	48.185	1120.620	0.000	S2	8.205	44.065	3.869
1117.0	652.32	.5966	12.233	161.136	54.779	1114.244	0.000	S2	8.831	42.901	4.049
1164.0	636.36	.3394	12.163	162.457	56.310	1106.979	0.000	S2	9.943	42.094	4.246
1211.7	631.08	.1108	12.191	161.918	56.772	1099.917	0.000	S3	13.120	41.682	4.433
1250.0	630.95	.0034	11.811	169.341	11.811	1093.935	0.000	S3	37.413	40.264	4.580
1300.0	630.79	.0032	11.894	167.666	11.894	1085.766	0.000	M3	50.000	40.273	4.770
1400.0	630.46	.0033	12.050	164.613	12.050	1070.044	0.000	M3	50.000	40.273	5.142
1500.0	630.13	.0033	12.210	161.573	12.210	1055.092	0.000	M3	50.000	40.273	5.508
1711.9	629.43	.0033	12.539	155.628	12.538	1025.712	0.000	S3	37.847	40.266	6.262
2212.1	627.79	.0033	13.315	143.014	13.315	966.616	0.000	S3	37.978	40.268	7.953
2601.3	626.36	.0037	13.947	134.021	13.947	929.164	0.000	S3	36.170	40.272	9.234
2622.9	626.98	-.0286	14.413	126.590	37.769	924.490	0.000	A3	-1000.000	41.213	9.306
2644.6	628.87	-.0873	13.342	126.553	34.859	922.788	0.000	A3	-1000.000	39.171	9.378
2666.3	632.03	-.1458	12.605	125.391	32.626	920.864	0.000	A3	-1000.000	31.952	9.451
2687.9	636.50	-.2063	12.376	123.640	31.483	918.700	0.000	A3	-1000.000	38.904	9.525
2707.3	644.40	-.4087	12.918	120.918	31.345	916.227	0.000	A3	-1000.000	30.803	9.594

ENERGY GRADE LINE AT BEGINNING OF BOUNDARY LAYER
1198.198

HOOVER DAM - ARIZONA SPILLWAY

Q = 60000.0 CFS INITIAL DEPTH = 16.10 FT RUGOSITY = .001000 FT N = .0135

CAVITATION CHARACTERISTICS

STATION	FLOW SIGMA	SIGMA OF UNIFORM ROUGHNESS	REQUIRED CHAMFER TO STOP CAVITATION	DAMAGE POTENTIAL: CIRCULAR ARC 1/4-IN 5-MM	CIRCULAR ARC 1/2-IN 10-MM	CIRCULAR ARC 1-IN 25-MM	90-DEGREE OFFSET 1/4-IN 5-MM	90-DEGREE OFFSET 1/2-IN 10-MM	90-DEGREE OFFSET 1-IN 25-MM
660.00	.616	.039	1 TO 5	.184E+00	.178E+01	.725E+01	.117E+01	.562E+01	.204E+02
725.00	.320	.039	1 TO 12	.133E+02	.412E+02	.120E+03	.230E+02	.727E+02	.219E+03
763.00	.274	.039	1 TO 15	.370E+02	.110E+03	.312E+03	.550E+02	.169E+03	.500E+03
802.49	.258	.040	1 TO 17	.821E+02	.240E+03	.676E+03	.109E+03	.332E+03	.976E+03
825.00	.221	.040	1 TO 21	.160E+03	.458E+03	.127E+04	.200E+03	.597E+03	.173E+04
867.76	.179	.040	1 TO 28	.420E+03	.117E+04	.319E+04	.478E+03	.140E+04	.399E+04
875.13	.174	.040	1 TO 29	.484E+03	.134E+04	.366E+04	.542E+03	.158E+04	.451E+04
900.40	.157	.040	1 TO 33	.764E+03	.210E+04	.569E+04	.820E+03	.237E+04	.673E+04
975.00	.119	.041	1 TO 49	.250E+04	.679E+04	.181E+05	.243E+04	.691E+04	.194E+05
1040.03	.100	.041	1 TO 63	.539E+04	.145E+05	.385E+05	.487E+04	.138E+05	.384E+05
1078.50	.205	.041	1 TO 23	.191E+04	.537E+04	.147E+05	.169E+04	.501E+04	.145E+05
1116.97	.217	.041	1 TO 21	.189E+04	.536E+04	.148E+05	.164E+04	.490E+04	.142E+05
1164.00	.217	.041	1 TO 21	.197E+04	.558E+04	.154E+05	.167E+04	.499E+04	.145E+05
1211.67	.220	.041	1 TO 21	.186E+04	.528E+04	.146E+05	.155E+04	.465E+04	.135E+05
1250.00	.100	.042	1 TO 63	.685E+04	.184E+05	.489E+05	.562E+04	.159E+05	.444E+05
1300.00	.102	.041	1 TO 61	.614E+04	.165E+05	.439E+05	.498E+04	.141E+05	.394E+05
1400.00	.106	.041	1 TO 58	.502E+04	.135E+05	.360E+05	.398E+04	.113E+05	.316E+05
1500.00	.111	.041	1 TO 54	.410E+04	.111E+05	.295E+05	.318E+04	.907E+04	.254E+05
1711.86	.120	.041	1 TO 48	.273E+04	.741E+04	.198E+05	.204E+04	.585E+04	.165E+05
2212.06	.145	.041	1 TO 37	.110E+04	.302E+04	.817E+04	.767E+03	.223E+04	.635E+04
2601.25	.167	.041	1 TO 30	.545E+03	.152E+04	.415E+04	.364E+03	.108E+04	.311E+04
2622.92	.283	.040	1 TO 15	.163E+03	.493E+03	.142E+04	.106E+03	.347E+03	.106E+04
2644.58	.272	.040	1 TO 15	.174E+03	.522E+03	.149E+04	.114E+03	.367E+03	.112E+04
2666.25	.268	.040	1 TO 16	.167E+03	.498E+03	.142E+04	.109E+03	.351E+03	.107E+04
2687.92	.271	.040	1 TO 16	.148E+03	.443E+03	.127E+04	.964E+02	.312E+03	.949E+03
2707.25	.282	.040	1 TO 15	.116E+03	.353E+03	.102E+04	.759E+02	.249E+03	.765E+03

HOOVER DAM - ARIZONA SPILLWAY

Q =100000.0 CFS   INITIAL DEPTH = 23.00 FT   RUGOSITY = .001000 FT   N = .0138

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
660.0	1116.44	.5190	23.000	70.869	8.573	1203.010	0.000	S2	7.290	43.245	.745
725.0	1072.73	.6725	25.334	89.353	.289	1197.008	0.000	S2	9.306	51.942	1.287
763.0	1037.93	.9158	23.369	98.126	5.662	1193.144	0.000	S2	10.076	51.995	1.603
802.5	994.55	1.0985	22.630	107.225	15.234	1188.397	0.000	S2	10.061	52.482	1.931
825.0	967.73	1.1915	21.672	114.287	13.932	1184.628	0.000	S2	10.000	52.524	2.118
867.8	916.77	1.1918	20.966	126.026	13.477	1177.106	0.000	S2	10.260	49.904	2.449
875.1	907.99	1.1913	20.792	127.905	13.367	1175.736	0.000	S2	10.278	49.698	2.505
900.4	877.87	1.1919	20.241	134.183	13.010	1170.869	0.000	S2	10.339	48.995	2.692
975.0	788.97	1.1917	18.410	152.420	11.834	1162.186	0.000	S2	10.339	48.996	3.199
1040.0	711.47	1.1918	17.283	166.087	11.109	1152.211	0.000	S2	10.339	48.995	3.617
1078.5	675.27	.9410	17.725	160.459	69.849	1146.664	0.000	S2	10.639	48.522	3.832
1117.0	652.32	.5966	17.584	162.218	79.266	1142.110	0.000	S2	11.468	48.149	4.012
1164.0	636.36	.3394	17.456	163.844	81.545	1136.919	0.000	S2	12.949	47.889	4.208
1211.7	631.08	.1108	17.468	163.681	82.334	1131.845	0.000	S2	17.246	47.746	4.395
1250.0	630.95	.0034	16.619	175.232	16.619	1127.391	0.000	M3	1000.000	47.675	4.541
1300.0	630.79	.0032	16.705	173.997	16.705	1121.110	0.000	M3	1000.000	47.675	4.729
1400.0	630.46	.0033	16.866	171.721	16.866	1108.884	0.000	M3	1000.000	47.675	5.099
1500.0	630.13	.0033	17.031	169.448	17.031	1097.084	0.000	M3	1000.000	47.675	5.461
1711.9	629.43	.0033	17.373	164.903	17.373	1073.392	0.000	M3	1000.000	47.675	6.206
2212.1	627.79	.0033	18.186	154.962	18.186	1023.610	0.000	M3	1000.000	47.675	7.871
2601.3	626.36	.0037	18.845	147.683	18.845	990.219	0.000	M3	1000.000	47.675	9.127
2622.9	626.98	-.0286	19.890	137.402	57.120	984.134	0.000	A3	-1000.000	48.914	9.198
2644.6	628.87	-.0873	18.761	137.535	53.814	982.692	0.000	A3	-1000.000	40.810	9.269
2666.3	632.03	-.1458	18.123	136.731	51.564	980.982	0.000	A3	-1000.000	43.898	9.340
2687.9	636.50	-.2063	18.126	135.282	50.750	978.974	0.000	A3	-1000.000	37.088	9.412
2707.3	644.40	-.4087	20.315	131.991	54.025	976.240	0.000	A3	-1000.000	30.254	9.481

ENERGY GRADE LINE AT BEGINNING OF BOUNDARY LAYER
1213.168

HOOVER DAM - ARIZONA SPILLWAY

Q =100000.0 CFS INITIAL DEPTH = 23.00 FT RUGOSITY = .001000 FT N = .0138

CAVITATION CHARACTERISTICS

				DAMAGE POTENTIAL					
				CIRCULAR ARC			90-DEGREE OFFSET		
STATION	FLOW SIGMA	SIGMA OF UNIFORM ROUGHNESS	REQUIRED CHAMFER TO STOP CAVITATION	1/4-IN 5-MM	1/2-IN 10-MM	1-IN 25-MM	1/4-IN 5-MM	1/2-IN 10-MM	1-IN 25-MM
660.00	.522	.037	1 TO 6	.139E+01	.613E+01	.210E+02	.425E+01	.162E+02	.538E+02
725.00	.262	.038	1 TO 16	.318E+02	.935E+02	.264E+03	.525E+02	.159E+03	.467E+03
763.00	.254	.038	1 TO 17	.608E+02	.177E+03	.499E+03	.889E+02	.270E+03	.789E+03
802.49	.266	.038	1 TO 16	.996E+02	.292E+03	.825E+03	.132E+03	.403E+03	.119E+04
825.00	.228	.038	1 TO 20	.193E+03	.552E+03	.153E+04	.239E+03	.717E+03	.208E+04
867.76	.186	.038	1 TO 26	.490E+03	.137E+04	.374E+04	.555E+03	.163E+04	.466E+04
875.13	.180	.038	1 TO 27	.564E+03	.157E+04	.428E+04	.630E+03	.184E+04	.526E+04
900.40	.163	.039	1 TO 32	.884E+03	.244E+04	.661E+04	.947E+03	.275E+04	.779E+04
975.00	.123	.039	1 TO 47	.290E+04	.787E+04	.210E+05	.280E+04	.798E+04	.224E+05
1040.03	.102	.039	1 TO 61	.634E+04	.170E+05	.453E+05	.571E+04	.161E+05	.450E+05
1078.50	.256	.039	1 TO 17	.147E+04	.425E+04	.119E+05	.130E+04	.397E+04	.117E+05
1116.97	.274	.039	1 TO 15	.141E+04	.412E+04	.116E+05	.121E+04	.376E+04	.111E+05
1164.00	.274	.039	1 TO 15	.148E+04	.434E+04	.122E+05	.125E+04	.388E+04	.115E+05
1211.67	.277	.039	1 TO 15	.143E+04	.419E+04	.118E+05	.118E+04	.368E+04	.110E+05
1250.00	.104	.040	1 TO 60	.842E+04	.227E+05	.602E+05	.686E+04	.194E+05	.543E+05
1300.00	.105	.039	1 TO 59	.776E+04	.209E+05	.556E+05	.624E+04	.177E+05	.494E+05
1400.00	.108	.039	1 TO 56	.666E+04	.180E+05	.478E+05	.523E+04	.149E+05	.416E+05
1500.00	.112	.039	1 TO 54	.572E+04	.155E+05	.412E+05	.440E+04	.125E+05	.351E+05
1711.86	.119	.039	1 TO 49	.421E+04	.114E+05	.305E+05	.310E+04	.888E+04	.250E+05
2212.06	.137	.039	1 TO 40	.211E+04	.577E+04	.155E+05	.144E+04	.418E+04	.119E+05
2601.25	.152	.039	1 TO 35	.124E+04	.343E+04	.927E+04	.812E+03	.238E+04	.679E+04
2622.92	.307	.039	1 TO 13	.258E+03	.792E+03	.230E+04	.163E+03	.543E+03	.168E+04
2644.58	.295	.039	1 TO 14	.278E+03	.845E+03	.244E+04	.176E+03	.579E+03	.178E+04
2666.25	.290	.039	1 TO 14	.273E+03	.827E+03	.238E+04	.173E+03	.566E+03	.174E+04
2687.92	.294	.039	1 TO 14	.247E+03	.751E+03	.216E+04	.156E+03	.514E+03	.158E+04
2707.25	.321	.039	1 TO 12	.175E+03	.547E+03	.160E+04	.109E+03	.373E+03	.117E+04

HOOVER DAM - ARIZONA SPILLWAY

Q =150000.0 CFS   INITIAL DEPTH = 29.50 FT   RUGOSITY = .001000 FT   N = .0140

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
660.0	1116.44	.5190	29.500	78.711	7.450	1220.099	0.000	S2	9.467	53.657	.729
725.0	1072.73	.6725	32.479	96.719	-4.191	1213.806	0.000	S2	12.059	63.163	1.263
763.0	1037.93	.9158	30.558	103.650	5.653	1210.430	0.000	S2	12.385	58.211	1.575
802.5	994.55	1.0985	30.133	111.043	20.285	1206.352	0.000	S2	12.379	55.238	1.901
825.0	967.73	1.1915	28.852	118.040	18.548	1202.723	0.000	S2	12.304	54.869	2.087
867.8	916.77	1.1918	28.110	129.564	18.068	1195.640	0.000	S2	12.648	50.940	2.416
875.1	907.99	1.1913	27.880	131.434	17.925	1194.356	0.000	S2	12.673	50.675	2.472
900.4	877.87	1.1919	27.161	137.660	17.457	1189.817	0.000	S2	12.754	49.800	2.658
975.0	788.97	1.1917	24.606	155.916	15.817	1182.628	0.000	S2	12.754	49.799	3.163
1040.0	711.47	1.1918	23.036	169.753	14.807	1174.469	0.000	S2	12.754	49.799	3.579
1078.5	675.27	.9410	24.075	160.344	94.608	1170.066	0.000	S2	13.132	49.418	3.794
1117.0	652.32	.5966	23.914	161.729	107.088	1166.570	0.000	S2	14.180	49.284	3.974
1164.0	636.36	.3394	23.717	163.464	110.173	1162.595	0.000	S2	16.065	49.210	4.170
1211.7	631.08	.1108	23.715	163.484	111.326	1158.703	0.000	S2	21.652	49.168	4.357
1250.0	630.95	.0034	22.069	179.525	22.069	1155.161	0.000	M3	1000.000	49.516	4.502
1300.0	630.79	.0032	22.161	178.545	22.161	1150.016	0.000	M3	1000.000	49.516	4.690
1400.0	630.46	.0033	22.335	176.725	22.335	1139.934	0.000	M3	1000.000	49.515	5.057
1500.0	630.13	.0033	22.513	174.908	22.513	1130.121	0.000	M3	1000.000	49.515	5.417
1711.9	629.43	.0033	22.884	171.219	22.884	1110.167	0.000	M3	1000.000	49.516	6.157
2212.1	627.79	.0033	23.769	163.003	23.769	1067.124	0.000	M3	1000.000	49.515	7.804
2601.3	626.36	.0037	24.485	156.905	24.485	1037.253	0.000	M3	1000.000	49.515	9.046
2622.9	626.98	-.0286	26.576	143.124	80.037	1029.438	0.000	A3	-1000.000	47.217	9.116
2644.6	628.87	-.0873	25.514	143.280	76.770	1028.169	0.000	A3	-1000.000	45.631	9.186
2666.3	632.03	-.1458	25.185	142.506	75.124	1026.587	0.000	A3	-1000.000	43.675	9.257
2687.9	636.50	-.2063	25.957	140.822	75.975	1024.565	0.000	A3	-1000.000	38.849	9.329
				ERROR IN TOTAL HEAD EXCEEDS 27.1 PERCENT							
2707.3	644.40	-.4087	27.706	161.374	98.931	1013.073	0.000	A3	-1000.000	29.832	9.394

ENERGY BALANCE WAS NOT REACHED
SEVERAL CONDITIONS CAN CAUSE THIS PROBLEM

TOO RAPID DIVERGENCE OF BOUNDARY
TOO SMALL A VALUE FOR THE VERTICAL RADIUS OF CURVATURE OF INVERT,
AND PASSING THRU AN HYDRAULIC JUMP ARE A FEW CAUSES.

PLEASE REVIEW YOUR NORMAL DEPTH AND CRITICAL DEPTH
COMPUTATIONS AS WELL AS THE PROFILE TYPE.

ALSO, CHECK INPUT DATA FILE FOR MISSING OR INCORRECT ENTRIES.

IF NONE OF THE ABOVE, ADD AN INTERMEDIATE STATION AT 2698.4

STA = 2707.25 ELEV = 644.400 DEPTH = 27.706 VEL HEAD = 409.593 PIEZ HEAD = 98.931 LOSS = 11.493
CRITICAL DEPTH = 29.832
NORMAL DEPTH =-1000.000

HOOVER DAM - ARIZONA SPILLWAY

Q =200000.0 CFS INITIAL DEPTH = 35.90 FT RUGOSITY = .001000 FT N = .0141

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
660.0	1116.44	.5190	35.900	82.169	7.020	1228.304	0.000	S2	11.397	62.139	.723
725.0	1072.73	.6725	38.984	100.589	-8.081	1221.771	0.000	S2	14.470	72.141	1.252
763.0	1037.93	.9158	37.939	106.133	6.004	1218.861	0.000	S2	14.368	59.635	1.564
802.5	994.55	1.0985	38.089	112.108	25.640	1215.382	0.000	S2	14.375	55.758	1.889
825.0	967.73	1.1915	36.322	119.214	23.350	1211.817	0.000	S2	14.288	55.300	2.074
867.8	916.77	1.1918	35.646	130.695	22.913	1205.001	0.000	S2	14.715	51.118	2.403
875.1	907.99	1.1913	35.344	132.576	22.724	1203.763	0.000	S2	14.746	50.842	2.459
900.4	877.87	1.1919	34.404	138.828	22.113	1199.401	0.000	S2	14.847	49.937	2.644
975.0	788.97	1.1917	30.854	157.263	19.833	1193.060	0.000	S2	14.848	49.937	3.148
1040.0	711.47	1.1918	28.733	171.279	18.469	1185.950	0.000	S2	14.847	49.937	3.563
1078.5	675.27	.9410	30.706	158.160	117.924	1182.214	0.000	S2	15.297	49.881	3.779
1117.0	652.32	.5966	30.546	159.140	133.170	1179.338	0.000	S2	16.546	49.560	3.960
1164.0	636.36	.3394	30.263	160.911	136.992	1176.080	0.000	S2	18.811	49.996	4.157
1211.7	631.08	.1108	30.247	161.010	138.498	1172.889	0.000	S2	25.692	49.510	4.344
1250.0	630.95	.0034	27.430	181.311	27.430	1169.892	0.000	M3	1000.000	49.846	4.489
1300.0	630.79	.0032	27.533	180.473	27.533	1165.429	0.000	M3	1000.000	49.846	4.676
1400.0	630.46	.0033	27.728	178.910	27.728	1156.653	0.000	M3	1000.000	49.847	5.042
1500.0	630.13	.0033	27.926	177.349	27.926	1148.069	0.000	M3	1000.000	49.846	5.402
1711.9	629.43	.0033	28.343	174.154	28:343	1130.489	0.000	M3	1000.000	49.847	6.138
2212.1	627.79	.0033	29.346	166.953	29.346	1091.981	0.000	M3	1000.000	49.846	7.778
2601.3	626.36	.0037	30.159	161.570	30.159	1064.723	0.000	M3	1000.000	49.847	9.012
2622.9	626.98	-.0286	33.897	144.132	102.725	1055.162	0.000	A3	-1000.000	49.257	9.082
BISTABLE FLOW POSSIBLE IN CONDUIT											
2644.6	628.87	-.0873	33.026	144.203	99.925	1054.012	0.000	A3	-1000.000	45.417	9.153
2666.3	632.03	-.1458	33.610	142.994	100.362	1052.334	0.000	A3	-1000.000	43.665	9.223

THE DEPTH OVER RADIUS RATIO IS TOO SMALL FOR AN ENERGY BALANCE
INCREASE STARTING DEPTH

STATION GEOMETRY FOR WATER SURFACE PROFILE PROGRAM
HOOVER DAM - ARIZONA SPILLWAY

STA	INVERT ELEV	WIDTH OR R2	SIDE SLOPE	RADIUS	UPPER RADIUS	CL HEIGHT	LOWER RADIUS	WALL OR C2	RAD CURV
660.00	1116.44	49.85	.50						-303.0
725.00	1072.73	31.51	.50						-303.0
763.00	1037.93			30.00					-604.0
802.49	994.55			28.00					0.0
825.00	967.73			27.75					0.0
867.76	916.77			25.60					0.0
875.13	907.99			25.46					0.0
900.40	877.87			25.00					0.0
975.00	788.97			25.00					0.0
1040.03	711.47			25.00					0.0
1078.50	675.27			25.00					250.0
1116.97	652.32			25.00					225.0
1164.00	636.36			25.00					225.0
1211.67	631.08			25.00					225.0
1250.00	630.95			25.00					0.0
1300.00	630.79			25.00					0.0
1400.00	630.46			25.00					0.0
1500.00	630.13			25.00					0.0
1711.86	629.43			25.00					0.0
2212.06	627.79			25.00					0.0
2601.25	626.36			25.00					0.0
2622.92	626.98	48.00			25.00	24.38	23.00	0.00	320.5
2644.58	628.87	47.60			25.00	22.49	19.50	0.00	320.5
2666.25	632.03	46.40			25.00	19.33	15.40	0.00	320.5
2687.92	636.50	45.20			25.00	14.86	12.20	0.00	320.5
2707.25	644.40	44.00			25.00	6.96	8.04	0.00	320.5