OFFICE MEMORANDUM

TO: J.W. Hayden

FROM: G. Krishnan

SUBJECT: Susitna Hydroelectric Project
Nitrogen Supersaturation Studies

Date: September 13, 1982

File: P5700.14.53

Enclosed is a copy of the final draft of the report on Gas Concentration and Temperature of Spill Discharges Below Watana and Devil Canyon Dams.

Please note that no graphics efforts have been spent on getting the figures in the Acres standard format. This has been postponed until after your review of the material and advice on the inclusion of any field measurements of natural supersaturation in the river. Messers M. Bell and J. Douma had expressed an interest to receive copies of this report. Please advise if this can be done at this time.

G. Krishnan

GK:ccv
Enclosure

cc: J.D. Lawrence
A.F. Coniglio
K.R. Young
W. Dyok/D. Crawford

GAS CONCENTRATION AND TEMPERATURE OF
SPILL DISCHARGES BELOW
WATANA AND DEVIL CANYON DAMS

1 - INTRODUCTION

Supersaturation of atmospheric gases (especially nitrogen) in hatchery and
aquarium facilities was first noted in the 1900's (1) and was ascribed as
causing the condition in fish known as gas bubble disease. Supersaturation
caused by entrainment of air in waters spilled over dams on the Columbia
River was recognized as a problem for anadromous fisheries in the river in
1965. A comprehensive study (2) of dissolved gas levels in the Columbia River
showed that waters plunging below spillways was the main cause of super-
saturation in the river waters. Several later studies have confirmed the
harmful effects of nitrogen supersaturation to fisheries. The tolerence of
fish to levels of nitrogen supersaturation depends on the time of exposure,
age, and species of the fish; dissolved nitrogen levels referenced to surface
pressure above 110 percent are generally considered harmful (3). The state
of Alaska water quality criterion is set of 110% for total gas saturation in
its waters.

With this background, the potential problem of supersaturation of spill waters
from the proposed Watana and Devil Canyon developments on the Susitna River
was recognized early during the feasibility studies. Alternative spillway
facilities were studied to minimize such a potential problem, and a scheme
comprising fixed cone valves and overflow spillway was selected for each
development based on detailed discussions with environmental study groups.

This report describes the selected spillway schemes briefly and presents the
analyses and field investigations carried out to assess the performance of
the proposed schemes with respect to gas supersaturation in spill waters.
A related concern on temperature of spill waters is also discussed.

A summary of the studies undertaken and the important conclusions are
presented in Section 2. A short description of the proposed schemes is given

in Section 3.   Section 4 details the engineering analyses carried out.   Results
of these analyses, field investigations, and their interpretation are presented
in Section 5.   The next section presents the major conclusions drawn from
these studies.   Appendix A comprises the field study report and Appendix B
deals with the temperature of spill waters, its impacts downstream, and possible
reservoir operation scenarios to minimize such impacts.

2 - SUMMARY

Relatively little information is available in the literature on the performance of fixed-cone valves to reduce gas supersaturation in their discharges. Published studies (4) on the aeration efficiency of Howell Bunger valves (the more commonly known type of fixed-cone valves) were reviewed, and a theoretical assessment of the performance of the proposed valve layouts was made based on the physical and geometric characteristics of diffused jets discharging freely into the atmosphere. Results of a companion study on assessment of scour hole development below high-head spillways (5) were used to estimate the potential plunging of the valve discharges into tailwater pools at the proposed developments, and the resulting supersaturation in the releases was calculated. Specific field tests were conducted at the Lake Comanche Dam on the Mokelumne River in California (6) to study jet characteristics and the efficiency of the existing Howell Bunger valves in reducing supersaturation level in the reservoir releases.

The analyses indicate that no serious supersaturation of nitrogen is likely to occur in the releases from the proposed Watana and Devil Canyon developments for spills up to 1:50 year recurrence interval. Field test results tend to confirm some of the assumptions made in the theoretical analysis with respect to jet shape, diffusion, and gas concentration in the valve discharges. Several assumptions and approximations, albeit conservative, have been made in the analyses which should be confirmed in later study phases, perhaps in a physical model. For the purpose of feasibility studies, however, it is felt that the analyses adequately support the proposed schemes for their intended purpose.

A related question of the temperature of spill waters and its effects on the downstream water temperature has been analyzed and detailed in Appendix E. Simulation studies of the two-reservoir operations indicate that continuous (24 hour) spills would occur in the month of August in 30 out of 32 years of simulation and in 18 out of 32 years in September for the Case "C" operation which maintains a minimum instantaneous flow of 12,000 cfs in August at Gold Creek. This spill frequency is simulated for a system energy demand in the year 2010 (Bettelle forecast) and assumes that the entire demand is met by

Watana and Devil Canyon developments where possible. The spills will be greater and more frequent in the years between 2002 (Devil Canyon commissioning) and 2010. When Watana alone is operational (between 1993 and 2002), less frequent spills are simulated to occur. Reservoir operation studies are currently being refined to finalize acceptable downstream flows.

Temperature of spill waters at Watana is expected to be close to that of power flow, and hence, it is not expected to create temperature problems downstream when Watana is operating alone (1993-2002) or when it spills into Devil Canyon. At Devil Canyon, however, spill temperature is expected to be close to 39°F compared to a power flow temperature of 48-49°F in August and 45°F in September. This is based on the conservative assumption that the temperature of spill water does not increase significantly while in contact with the atmosphere despite the highly diffused valve discharge. It is, therefore, considered necessary to keep the spill from Devil Canyon to a minimum to avoid unacceptably low downstream temperatures. The analyses indicate that by operating Devil Canyon to meet most or all of the base load demand and with Watana generating essentially to meet peak demands and spilling continuously when necessary, it would be possible to maintain downstream flow temperatures below Devil Canyon close to that of power flow while reducing spill frequency considerably.

During major floods (1:10 year or rarer), there will be significant spills from Devil Canyon in addition to the power flow resulting in cold slugs of water downstream for a few days. It will be necessary to establish criteria for acceptability of lower temperatures for short durations in August and September in consultation with fisheries study groups and concerned agencies. Currently, downstream water temperature analyses are being refined, and when the results are available, the above spill temperatures and duration should be reviewed to confirm downstream temperatures during normal power operation as well as flood events. If the projected temperature regime downstream is unacceptable, alternative means to remedy the situation should be considered. These may include provision of higher level intakes to several or all fixed-cone valve discharges at Devil Canyon, multilevel power intake at Devil Canyon, limited operation of main overflow spillway (for floods 1:50 year or more frequent) to improve temperature without serious increase in nitrogen supersaturation, etc.

3 - SCOPE OF ANALYSES

The objective of the analyses presented in the following sections is to
provide an assessment of the performance of the fixed-cone valves in their
proposed configuration with respect to their potential in reducing gas con-
centration in spill waters from the Watana and Devil Canyon developments. The
analysis is a theoretical study supplemented by available field information on
performance of these valves for aeration. Field measurements were conducted
on the Howell Bunger valves at the Lake Comanche dam on the Mokelumne River
in California. Results of the tests are interpreted to confirm some of the
study assumptions.

A related question of temperature of spill waters is analyzed in Appendix B.
The data for the analyses has been drawn from the Feasibility Report (7).

4 - SCHEME DESCRIPTION

This section presents a short description of the selected spillway and outlet facilities for the proposed Watana and Devil Canyon developments.

4.1 - Scheme Description

Selection of the discharge capacity and the type of spillway and outlet facilities has been based on project safety, environmental, and economic considerations. At each development, a set of fixed-cone valves is provided in the outlet works to discharge spills up to 1:50 year recurrence interval. The main spillway comprises a gated control structure and a chute with a flip bucket at its end. This facility has a capacity to discharge, in combination with the outlet works, the routed design flood which has a return period of 1:10,000 years. A fuse plug with an associated rock-cut channel is provided to discharge flows above the design flood and up to the estimated probable maximum flood at the dam. Detailed descriptions of the facilities are presented in the Feasibility Report (7).

The primary purpose of the outlet facility is to discharge the spill waters up to 1:50 year recurrence in such a manner as to reduce potential super-saturation of the spill with atmospheric gases, particularly nitrogen. This frequency was adopted after discussions with environmental study groups as an acceptable level of protection of the downstream fisheries against the gas bubble disease. A set of fixed-cone valves were selected to discharge the spills in highly diffused jets to achieve significant energy dissipation without provision of a stilling basin or a plunge pool where potentially large supersaturation develops. The valves have been selected to be within current world experience with respect to their size and operating heads. At Watana, six 78 inch diameter valves are provided and are located about 125 ft above average tailwater level in the river. The design capacity of each valve is 6,000 cfs. At Devil Canyon, seven fixed cone valves with a total design capacity of 38,500 cfs are provided at two levels within the arch dam, four 102 inch valves at the high level some 170 ft above average tailwater level, and three 90 inch valves about 50 ft above average tailwater level. The lower

valves have a capacity of 5,100 cfs each and the higher ones 5,800 cfs each. In sizing these valves, it has been assumed that the valve gate opening will be restricted to 80% of full stroke to reduce vibration.

5 - ENGINEERING ANALYSES

This section details the analyses carried out to estimate potential super-saturation in the releases from the Watana and Devil Canyon developments when the reservoirs spill.

5.1 - Available Data

Fixed cone valves have been used in several water resource projects for water control, energy dissipation, and aeration of discharge waters, and data on their performance for such operations is readily available. However, no precedence has been reported on the use of such valves for reducing or eliminating gas supersaturation in spill waters. Manufacturer's catalog information on Howell Bunger valves and Boving Sleeve type discharge regulators (both particular types of fixed cone valves) and the Tennessee Valley Authority Study (4) on aeration efficiency of Howell Bunger valves form the specific data available. Theoretical analyses are carried out based on the geometric and physical characteristics of diffused jets discharging freely into the atmosphere.

5.2 - Field Data Collection

A review of existing facilities where a potential for spilling during the spring of 1982 existed was made, and the Lake Comanche dam, on the Mokelumne River in California, was selected as a feasible site for specific testing.

The Comanche Lake dam is of the rockfill type with outlet facilities fitted with four Howell Bunger valves. These valves are located at the toe of the dam and spray the discharge into confined concrete conduits before releasing the water to the stream.

Outflow through the valves was around 4,000 cfs during the test on May 28, 1982. Water samples were collected at several depths in the reservoir near the valves and at downstream locations and analyzed for nitrogen and oxygen concentrations. Details of the test procedure and results are presented in Appendix 1.

5.3 - Method of Analysis

(a) Flow from the fixed cone valves leaves the structure as a free-discharging jet diffusing radially at the cone angle. The path of the jet depends on the energy of flow available at the valve and the angle at which the jet leaves the valve (assumed as 45°). Referring to Figure 5.1, the path of the trajectory is given by the following equation (8):

$$y = x \tan \theta - \frac{x^2}{k(4 H_n \cos^2 \theta)} \tag{1}$$

where:

θ = angle of the jet to the horizontal;

k = a factor to take account of loss of energy and velocity reduction due to the effect of air resistance, internal turbulences, and disintegration of the jet (assumed at 0.9);

H_n = net energy of the jet, ft.

The proposed valve operation restricts the opening of the valve gate to 80% of full stroke. This may be interpreted as equivalent to producing an additional head loss in the system, thereby reducing the discharge to 80% of the theoretical capacity. The general discharge equation for the valve:

$$Q_T = CA \sqrt{2g\ h_n} \tag{2}$$

may then be written as:

$$Q_D = 0.8\ Q_T = CA \sqrt{2g\ (.8)^2\ h_n} \tag{2a}$$

$$= CA \sqrt{2g \times .64 \times h_n} \tag{3}$$

where:

Q_T = theoretical capacity of valve, cfs;

A = area of valve, ft;

C = coefficient of discharge ($\sim$ .85 for fixed-cone valves);

h_n = net head upstream of valve, cfs;

Q_D = design capacity of valve, cfs.

Equation (1) may be rewritten now as:

$$y = x \tan \theta - \frac{x^2}{k \quad 4 \times (0.64 \times h_n) \times \cos^2 \theta} \tag{4}$$

Referring to Figure 5.1, the longitudinal throw of the jet is calculated with $\theta=45°$ and $-45°$ while its lateral throw calculated when $\theta=0°$.

Vertical rise of the jet above the valve is calculated as a simple projectile subject to gravity and neglecting air friction to yield a conservative value.

(b) <u>Potential Plunging Depth of Jet(s) Into Tailwater Pool</u>

As part of the feasibility studies of the Watana and Devil Canyon developments, a study was made by Acres on the scour hole development below high head spillways, and the results therefrom have been used to estimate the potential plunging of the jets from the fixed cone valves into tailwater. Figure 5.2 presents a definition sketch for the study carried out for a typical flip bucket spillway configuration. It may be readily observed that significant differences exist between a "solid" jet leaving a flip bucket and the diffused discharge jet from the fixed-cone valves in the available energy and its concentration in the jet for scouring downstream or plunging into the tailwater pool. Equation (5) was developed in the above mentioned studies to estimate scour depth for a solid jet:

$$y = 0.24 \, q^{0.65} \, H^{0.32} \tag{5}$$

where:

y = estimated scour depth, ft;
q = unit discharge, cfs/ft;
H = net fall of the jet, ft.

This equation was modified to take account of the maximum discharge intensity, q^1 in cfs/ft^2 of the fixed cone valves assuming the longitudinal spread of the solid jet as equal to its flow depth at the toe of the flip bucket (Figure 5.2). This assumpation is expected to yield a conservative estimate of the scour depth for diffused jets. The fall height H was taken as the drop of the diffused jet from the highest point of its rise to the tailwater pool (Figure 5.1). With these modifications, equations (6) and (7) were developed to estimate the scour depth due to the valve discharges at Watana and Devil Canyon, respectively.

$$y_W = .24 \ (q^1 {}_W)^{0.92} \ H_W{}^{0.32} \tag{6}$$

$$y_{DC} = .24 \ (q^1 {}_{DC})^{0.98} \ H_{DC}{}^{0.32} \tag{7}$$

W and DC represent Watana and Devil Canyon, respectively.

Scour depths, as calculated by equations (6) and (7), give an estimate of the depth to which water may plunge should the jet fall into a tailwater pool instead of on solid ground. The values y_W and y_{DC} are calculated for the highest intensity $q^1{}_W$ or $q^1{}_{DC}$ when all the jets are operating at each of the developments and taken as the plunge depth of the jets.

5.4 - Supersaturation of Spills

(a) Gas Concentration in Valve Discharges

Results of the Lake Comanche dam tests indicate that the Howell Bunger valves have been successful in preventing supersaturat on of the spills

and, to some extent, have reduced the gas concentration in the spill
waters.

The Tennessee Valley Authority studies which were conducted to assess
aeration efficiency of the Howell Bunger valves, suggest that the dis-
charge from the valves are well aerated. The test results indicated
that small supersaturation (101-102%) of oxygen may be found in the
spills but suggested that this may be due to calculation procedure used.
The report concluded that since saturation concentrations were not
measured in the field, it is not certain whether supersaturation acually
occurred in the runoff downstream.

Based on the above test results, it has been conservatively assumed
that a 100% saturation level of atmospheric gas is likely to exist in
the valve discharges at Watana and Devil Canyon.

(b) Supersaturation Due to Plunging

Each component of gas in the atmosphere will dissolve in water independ-
ently of all other gases and, when at equilibrium (i.e. saturation
condition) with the air, the pressure of a specific dissolved gas is
equivalent to its partial pressure in the air. Approximating one
atmospheric pressure to 34 ft head of water, the above relationship
translates roughly to 3% saturation per foot of hydrostatic head. Thus,
it may be extended that fully saturated water mass when plunging into a
pool would develop a supersaturation of gas at the rate of 3% per foot of
plunge provided that adequate supply of air is entrained.

(c) Gas Concentration in Downstream Discharges

Average power flows at the two developments during spills have been
estimated in the reservoir simulation studies. For the current analyses,
it is conservatively assumed that these powerhouse discharges will be
fully saturated. Estimates of final gas concentrations in the total
downstream discharges is calculated assuming the laws of dilution to
hold for mixing discharges at different gas concentrations.

It is assumed that spills from Watana will get completely mixed in the
Devil Canyon storage during their passage through 26 miles of reservoir
and that no supersaturation would build up in the reservoir due to
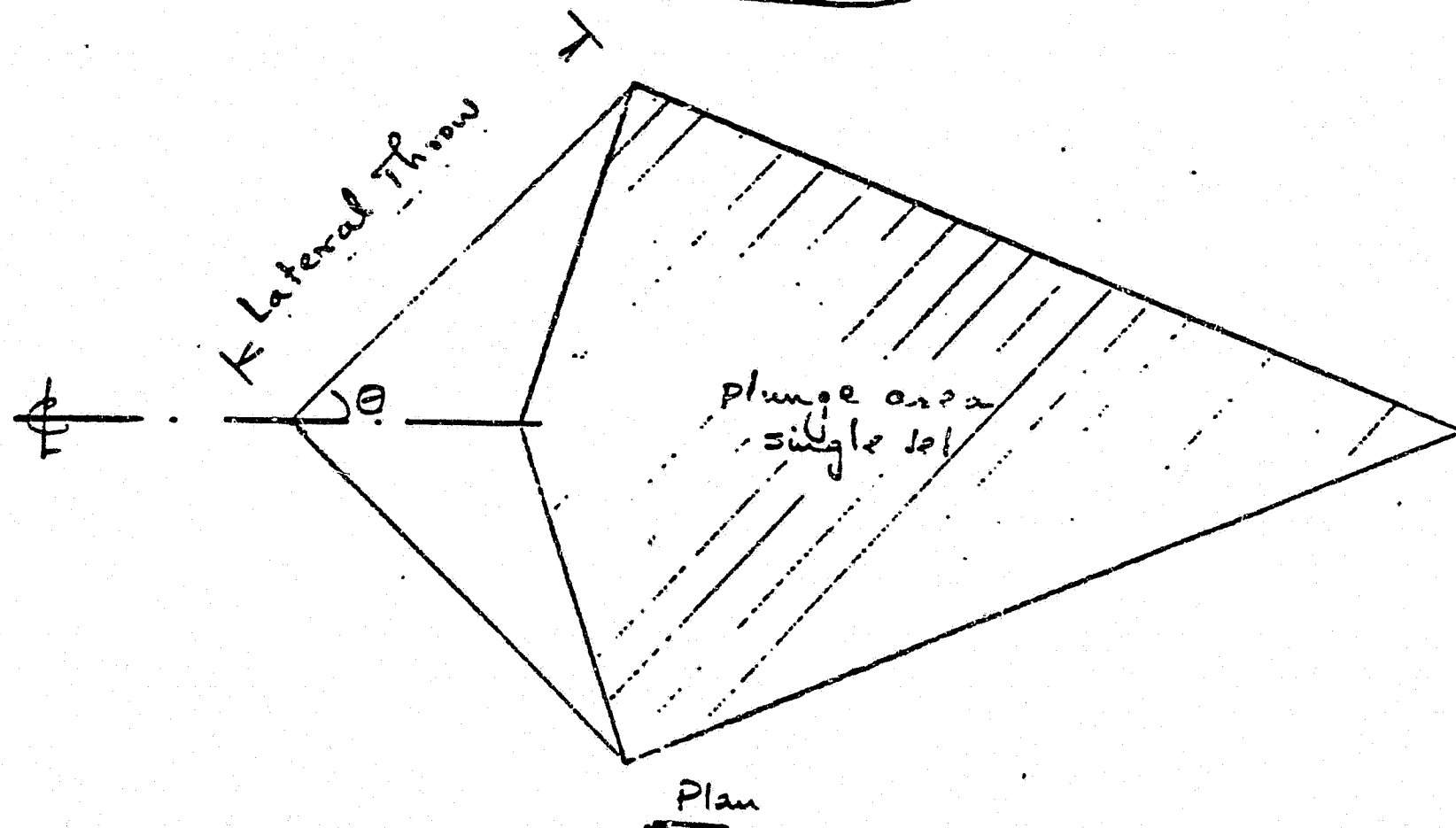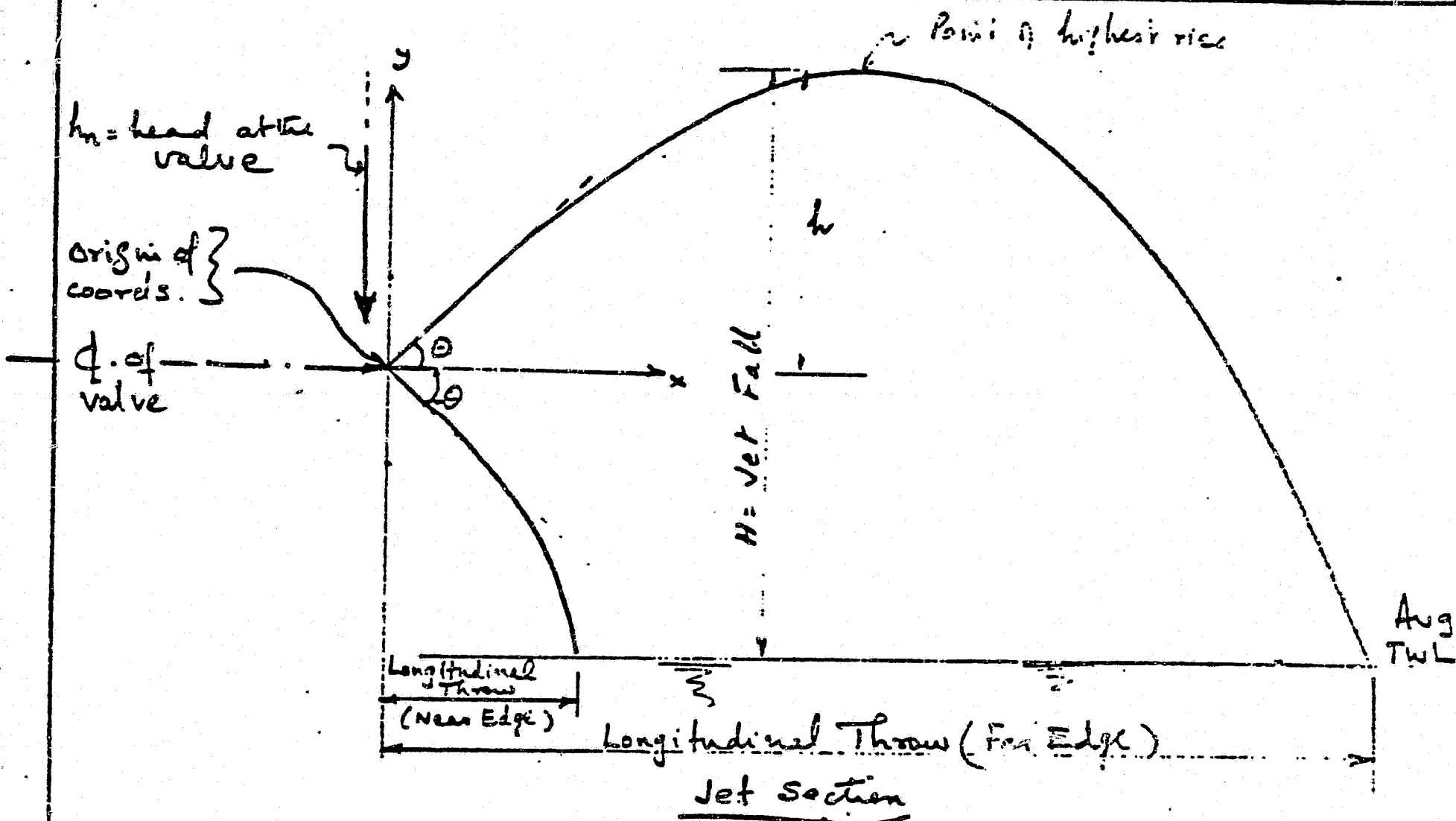Watana spills.

Calculations

ACRES

SUBJECT:

JOB NUMBER_____
FILE NUMBER_____
SHEET_____ OF_____
BY _____ DATE_____
APP _____ DATE_____

~ Point of highest rise

h_o = head at the valve

Origin of coords.

¢ of valve

θ

θ

h

H = Jet Fall

Avg TWL

Longitudinal Throw (Near Edge)

Longitudinal Throw (Far Edge)

Jet Section

Lateral Throw

θ

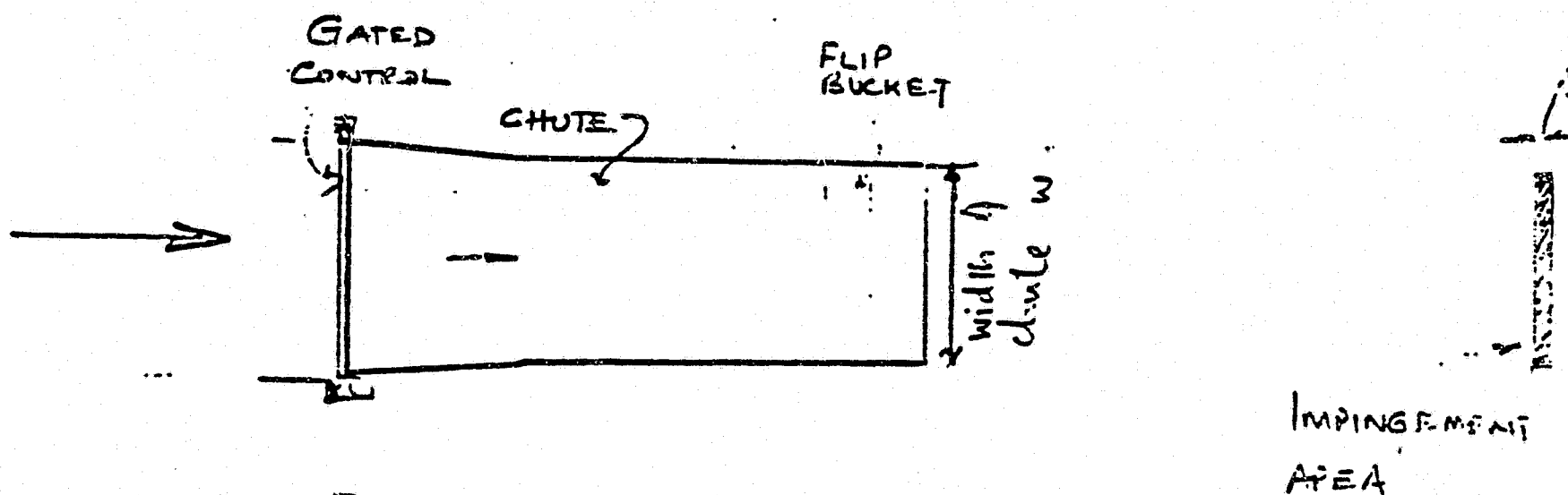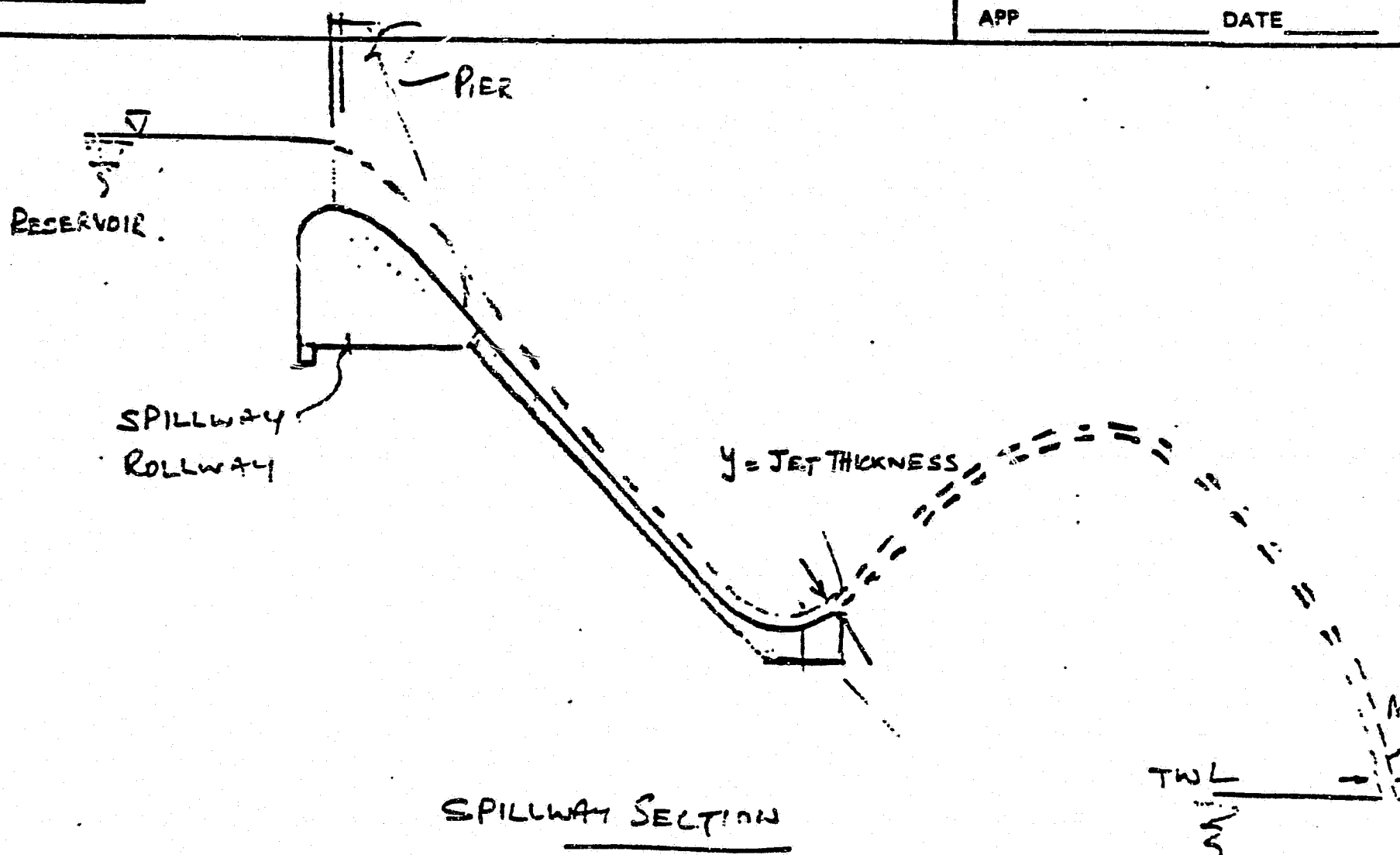Plunge area single jet

Plan

DEFINITION SKETCH FOR SUBMERGED JET

FIGURE 5.1

Calculations

SUBJECT:

ACRES

JOB NUMBER _____
FILE NUMBER _____
SHEET _____ OF _____
BY _____ DATE _____
APP _____ DATE _____

PIER

RESERVOIR

SPILLWAY
ROLLWAY

y = JET THICKNESS

TWL

SPILLWAY SECTION

GATED
CONTROL

CHUTE

FLIP
BUCKET

width of chute w

IMPINGEMENT
AREA

PLAN

DEFINITION SKETCH FOR SOLID JET
FROM CHUTE-FLIP BUCKET SPILLWAY

FIGURE S·2

6 - <u>RESULTS</u>

Table 6.1 presents the results of the analyses carried out to assess the performance of the fixed cone valves at the proposed Watana and Devil Canyon developments in relation to the potential gas supersaturation of spill waters. Figures 6.1 and 6.2 present the jet interference pattern and the areas of impingement.

Estimated supersaturation in the spill discharges with a recurrence interval of 1 in 50 years is 101% at Watana and 102% at Devil Canyon. For more frequent spills, these concentrations are expected to be somewhat lower due to lower intensity of spill discharge and consequent lower plunge in the tailwater pool. For spills of rarer frequency, the main chute spillway will operate leading to potentially greater supersaturation in the downstream discharges.

Results of spill temperature analysis is presented in Appendix B.

TABLE 6.1 - RESULTS OF ANALYSES

| Description	Watana Valves	Devil Canyon Valves Upper Level	Lower Level
1. Valve Parameters			
Diameter of fixed cone valves-inches	78	102	90
Number of valves	6	4	3
Design capacity-cfs	4,000	5,800	5,100
Elevation of valve centerline-ft	1,560	1,050	930
Elevation above average tailwater-ft	105	170	50
Net head (h_n) at the valve-ft	508	365	450
Angle of valve discharge with horizontal-degrees (assumed)	45	45	45
2. Jet Geometry			
Longitudinal throw-near edge-ft	91	130	46
Longitudinal throw-far edge-ft	676	550	564
Lateral throw-ft	351	378	228
Impingement area of single jet-ft^2	145,200	112,250	83,400
Impingement area of all jets-ft^2	221,300	173,250	
Maximum fall of jet (H)-ft	359	353	275
3. Jet Characteristics			
Average intensity of discharge of single jet cfs/ft^2	0.028	0.052	0.061
Maximum intensity (q^1) when all jets are operating cfs/ft^2	6 x 0.028 = 0.168	4 x •052 + 3 x •061 = 0.391	
Estimated plunge depth-ft	0.3	0.62 (H=353^1)	
4. Supersaturation Estimates (1:50 year flood)			
Design valve discharge-cfs	24,000	38,500	
Assumed simultaneous power flow-cfs	7,000	3,500	
Total downstream discharge-cfs	31,000	42,000	
Assumed gas concentration in power flow-percent and valve discharge at valve-%	100.0	100.0	
Maximum gas concentration in valve discharge below dam-%	100.9	101.9	
Maximum gas concentration in total downstream discharge-%	100.7	101.7	

Calculations

ACRES

SUBJECT:

JOB NUMBER _____

FILE NUMBER _____

SHEET _____ OF _____

BY _____ DATE _____

APP _____ DATE _____

$Area = 221200$ sft

$\mathcal{E}$ of Valve

35'

123'

9'

676
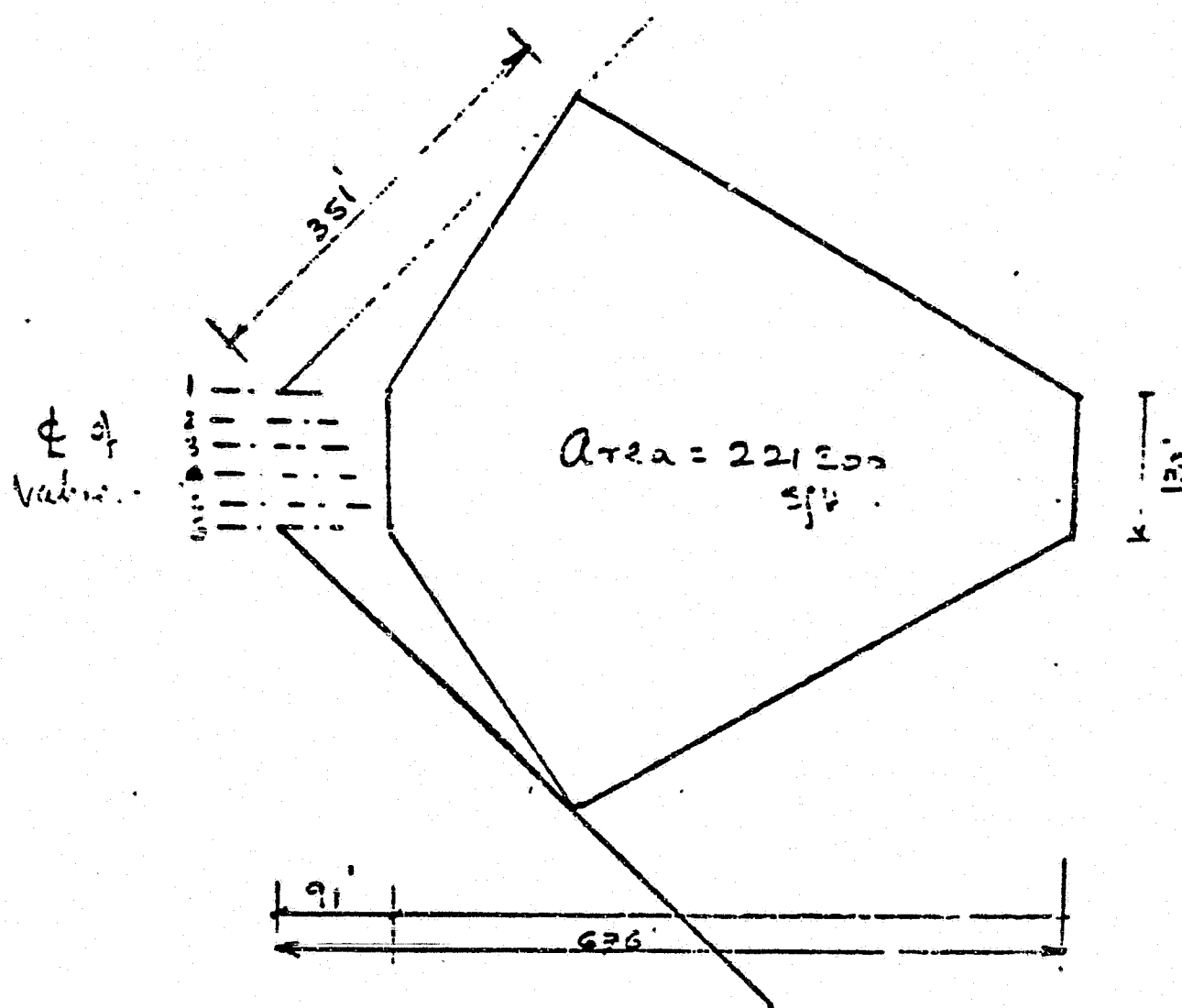
VALVE DISCHARGE PATTERN AND IMPINGEMENT AREA FOR IMPULSE

FIGURE 6·1

Calculations

ACRES

SUBJECT:

JOB NUMBER _____
FILE NUMBER _____
SHEET _____ OF _____
BY _____ DATE _____
APP _____ DATE _____

Approx. outerboundary of
Jet impingement

Value No. 6

approx outline for
calculation of area

Ref. Plate 5.2
vol. 3. Feasibility Report

scale
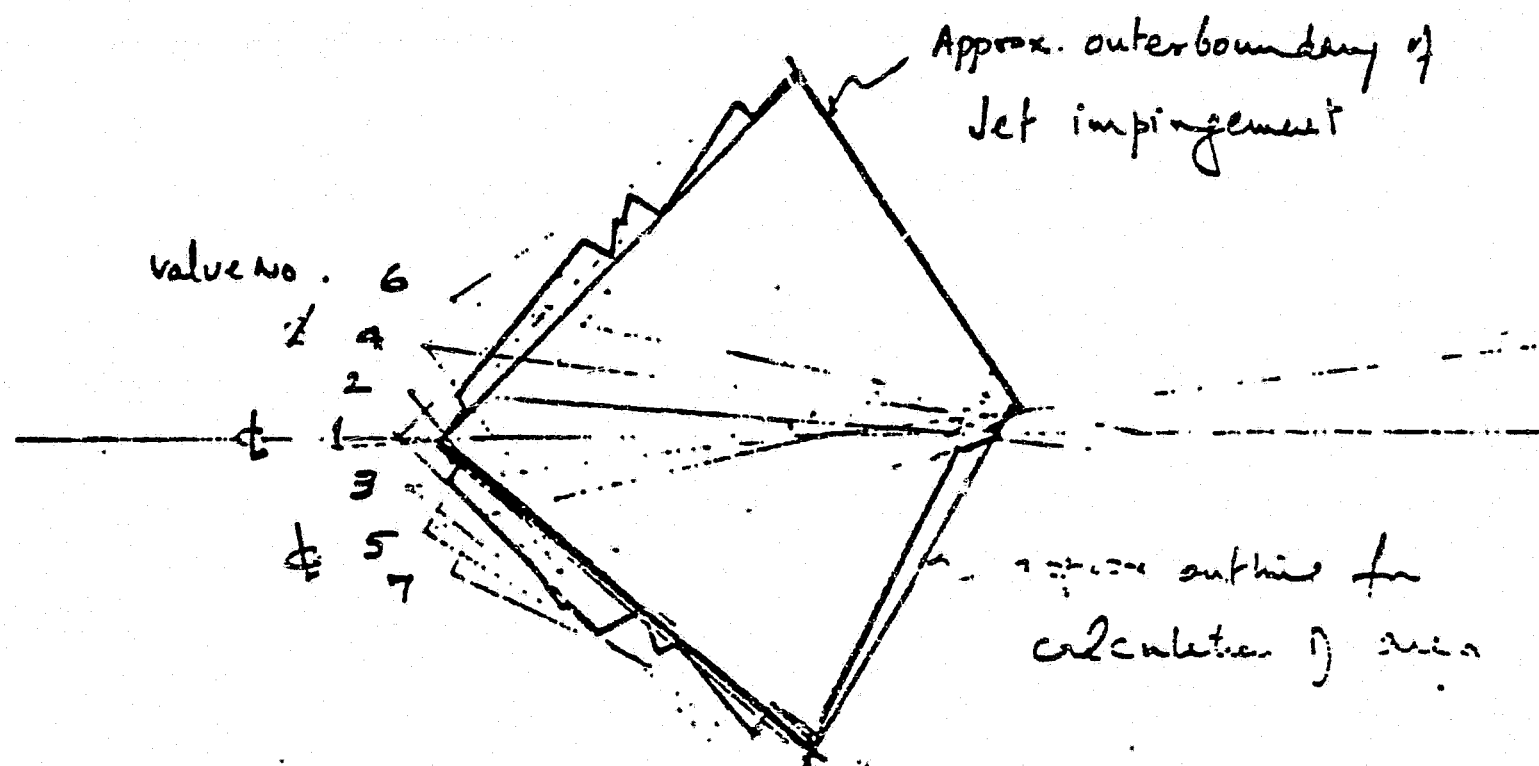
When all 7 valves are operating
total area of impingement $\approx \dfrac{550 \times 630}{2}$ = 173200 sf.

VALUE DISCHARGE PATTERN
IMPINGEMENT AREA FOR
DEVIL CANYON

FIGURE 6·2

.7 - CONCLUSIONS

1. The analyses described above indicate that the proposed fixed-cone valves would adequately prevent serious gas supersaturation in spill waters up to a recurrence interval of 1:50 years.

2. Several assumptions have had to be made in the analyses with respect to jet characteristics and its potential plunge into tailwater pool. Field test results available are only indicative of the valve performance. In particular, the configuration of the proposed valves set high above the tailwater pool and their free discharge with the atmosphere differ signi-ficantly from the Lake Comanche dam arrangement and the TVA test facility. In view of the nature of analyses and lack of precedence for the proposed valve arrangement, it is recommended that a physical model study be carried out to confirm the performance of the valves.

REFERENCES

1. Gorham, F.P., The Gas Bubble Disease of Fish and Its Cause, Bull. U.S. Fish Comm. 19(1899):33-37.

2. Ebel, W.J., Supersaturation of Nitrogen in the Columbia River and Its Effect on Salmon and Steelhead Trout, U.S. Fish and Wildlife Service, Fish Bull. 68:1-11.

3. U.S. Department of the Army, Engineering and Design, Nitrogen Super-saturation, ETL-1110-2-239, September 1978.

4. Tennessee Valley Authority, Progress Report on Aeration Efficiency of Howell Bunger Valves, Report No. O-6728, August 1968.

5. Acres, Susitna Hydroelectric Project, Scour Hole Development Downstream of High Head Dams, March 1982.

6. Ecological Analysts Inc., California, Lake Comanche Dissolved Nitrogen Study, June 1982 (see Appendix A).

7. Acres, Susitna Hydroelectric Project, Feasibility Report, March 1982.

8. U.S. Department of the Interior, Design of Small Dams, Bureau of Reclamation, Water Resources Technical Publication, 1977.