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HYDRO-AESTHETIC IMPROVEMENT OF ST. ANTHONY FALLS SPILLWAY AT LOW FLOW

by

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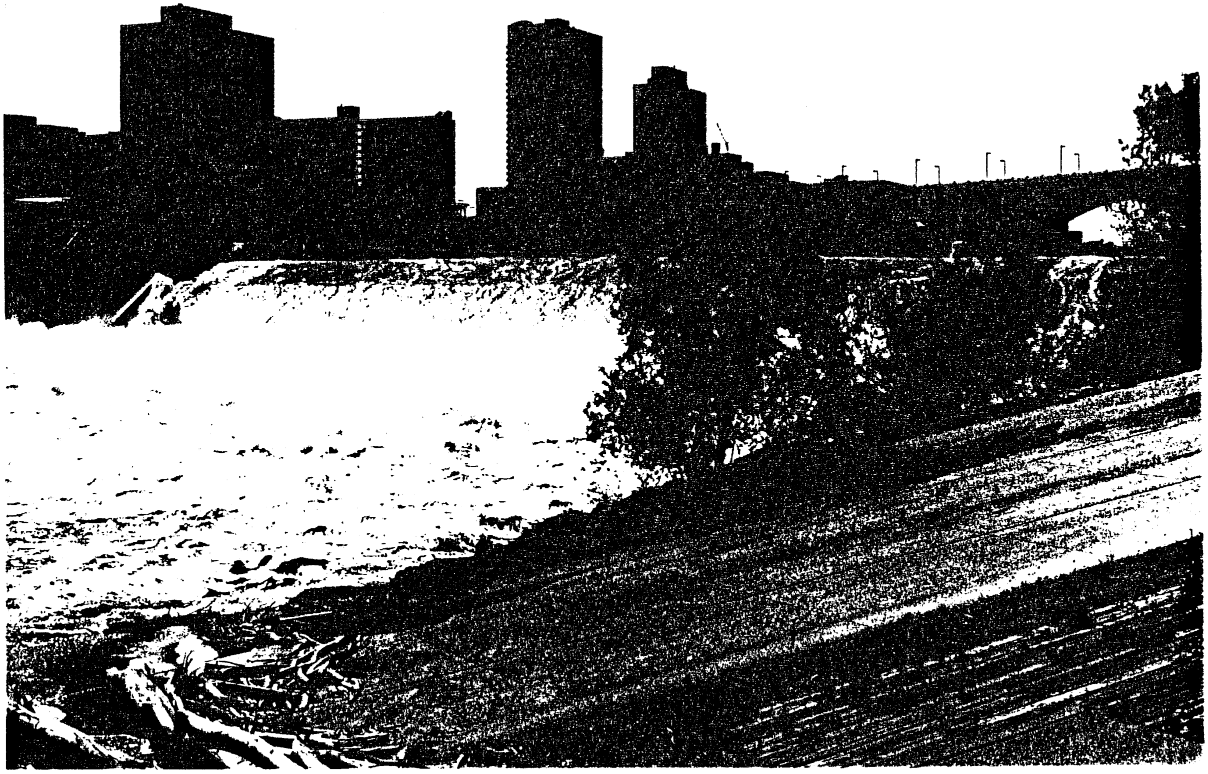

St. Anthony Falls Spillway at 41,000 cfs flow.

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I. INTRODUCTION

The possible expansion of hydropower development at St. Anthony Falls on the Mississippi River within the City of Minneapolis is likely to generate questions on the future appearance of the St. Anthony Falls spillway when most of the riverflow is routed through the existing powerplant and a projected additional power station. In particular, it may be asked how the aesthetics of the St. Anthony Falls spillway can be enhanced when only a small (minimum) flow is discharged over the spillway. It is anticipated that minimum flow spillway discharge will occur for 10 months in an average year when the proposed hydropower facility becomes operational. To study this particular question, an experimental study was conducted at St. Anthony Falls Hydraulic Laboratory and small flow deflectors which can be attached to the spillway surface and generate a "roostertail-like" spray were devised to make the appearance of the spillway more pleasing. The methods used in the study and the recommended design modifications are described in this report. It was not the intent of this study to determine what the minimum flow over the spillway should be, but rather to determine the best aesthetic effects on the spillway that can be accomplished at a low flow.

II. OBJECTIVES AND CRITERIA

The St. Anthony Falls main spillway is a concrete apron drop structure which was built to prevent the Falls of St. Anthony from migrating upstream, as they had for centuries, due to the particular local geology. The currently existing concrete structure profile is shown in Fig. 1. At low flows the water surface appears very smooth near the crest and white in the lower part of the structure. At very low flows roll waves appear on the spillway face, and in summer attached algae can grow on the concrete surface.

It is desired that the low flow appear more interesting to viewers who are attracted to the Falls. This can be achieved by making the flow more tumbling and increasing its air content (whitewater appearance). Any modification must meet a number of criteria: (1) it must not endanger the structural integrity of the spillway, (2) it must be hydraulically acceptable for all flows, (3) it must be inexpensive and easy to install. Experiments were conducted for flows of 100 cfs, 200 cfs and 300 cfs over the spillway.

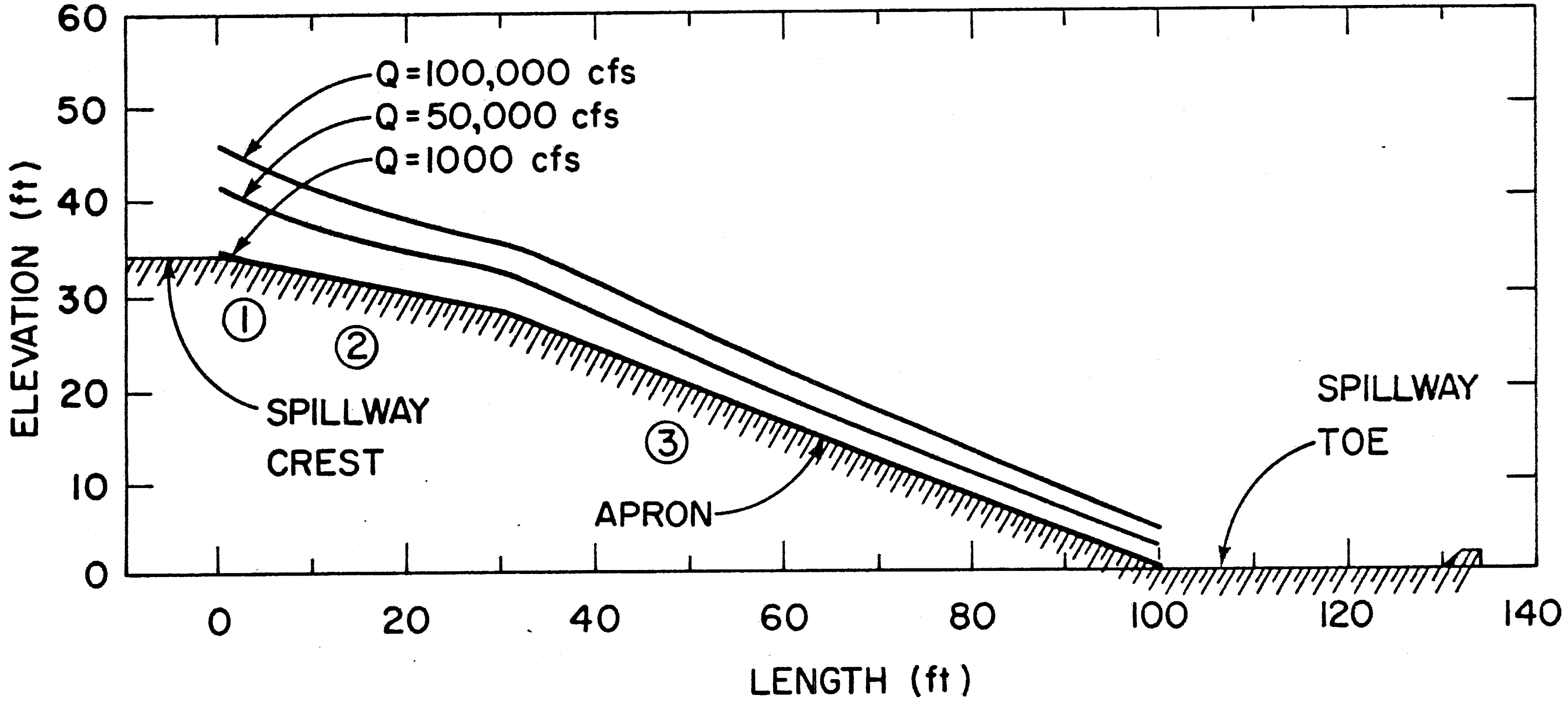


Fig. 1. St. Anthony Falls Spillway cross section and water surface profiles.

III. PROPOSED SOLUTION

After experimentation with several alternatives, the solution that meets the objectives and criteria most closely uses flow deflectors that can be attached to the spillway surface. These deflectors are very small compared to the spillway size and have a shape as shown in Fig. 2. At low flows they disturb the flow sheet very significantly, but at high flows they do not represent any danger to the structure, if placed in the upper portion of the spillway. A cluster distribution of the elements on the spillway face is proposed.

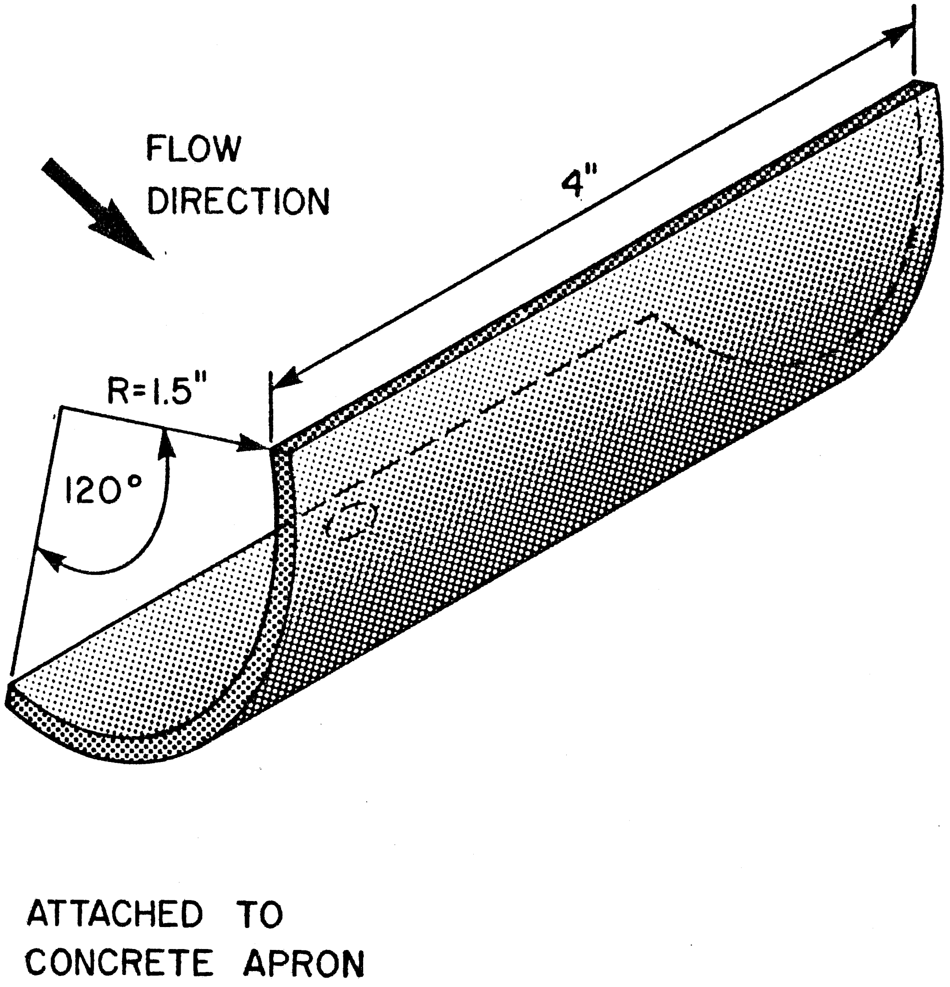


Fig. 2. Proposed prototype flow deflector.

IV. STUDY PROCEDURES

From the beginning it was expected that the more economical solution to the problem would require additions to the existing structure rather than modifications. The second guiding idea was that additions should be as small and as sparse as possible. With this in mind, the shape shown in Fig. 2 was selected.

Experimentation was used to select the most suitable dimensions for the element in Fig. 2. The study proceeded in the following way:

A. Hydraulic Analysis of Various Flows

Water depths and velocities on the spillway were calculated for spillway flows of 300 cfs, 1000 cfs, 3000 cfs, 15,000 cfs, 50,000 cfs and 100,000 cfs. Frequencies of these flows are shown in Fig. 3.

The results of the hydraulic analysis are tabulated in Table 1 and illustrated in Fig. 1.

B. Testing of Single Element

The performance of a single element was tested in a laboratory flume. The length ℓ, height a, and width w of the spray screen ("roostertail") generated were measured. Tests were conducted for 100 cfs, 200 cfs and 300 cfs prototype flow ($q = .235$ cfs/ft, .470 cfs/ft and .706 cfs/ft), and different flow velocities U and flow depths y. In all cases $q = yU$ was fixed. Different values of y and U represent different locations on the spillway. The "roostertail" dimensions, a, ℓ, and w, were measured in a high velocity laboratory flume using a 1/2-scale model element. The data were scaled up to prototype values. For the 300 cfs flow they are reported in Table 2.

To test the validity of "roostertail" scaling, a full-scale element was also tested in a 24-inch wide laboratory flume at a location 4 ft from the spillway crest (x=4 ft). The full-scale spray dimensions were nearly

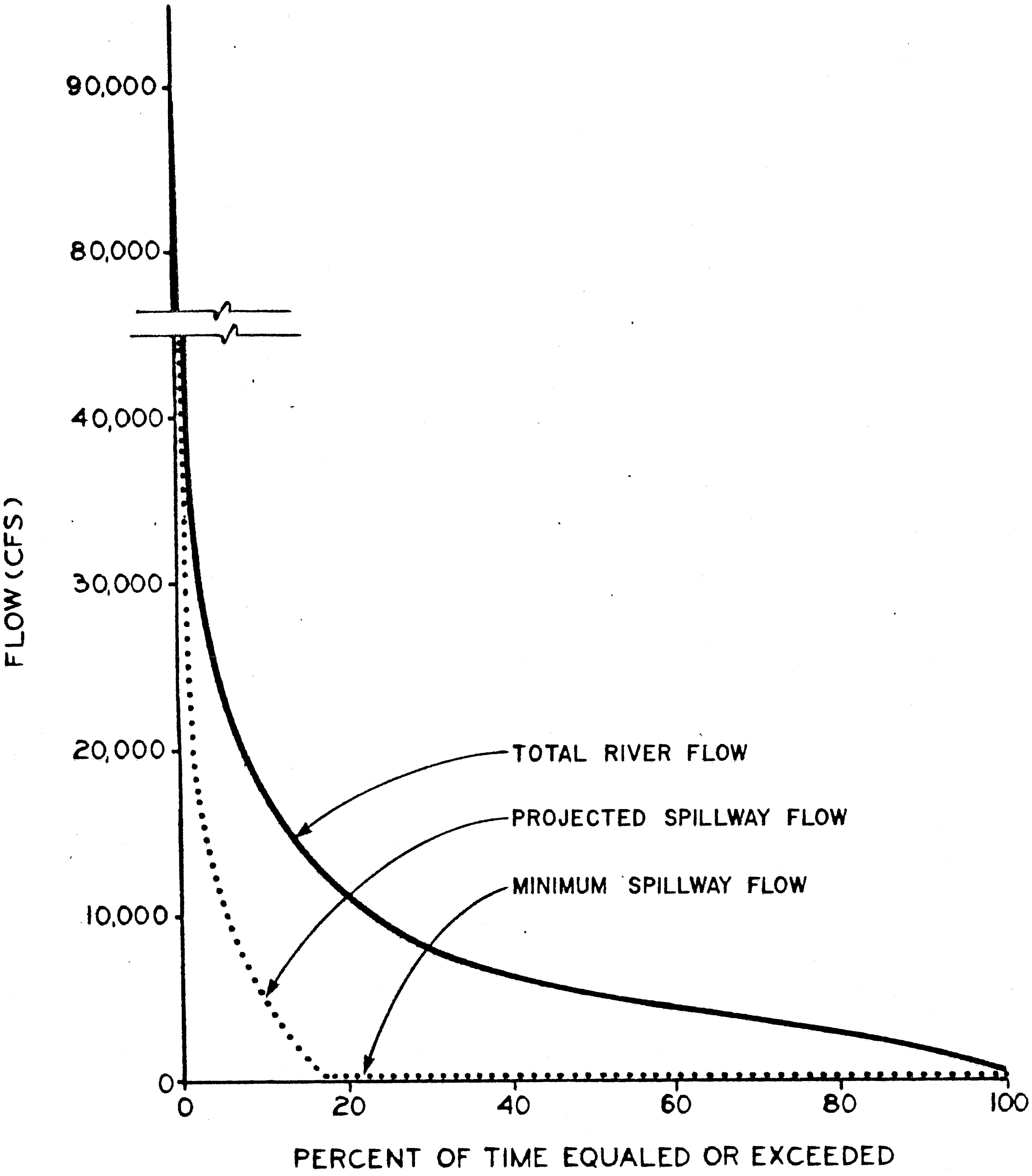


Fig. 3. St. Anthony Falls annual flow duration curve (from NSP-FERC license application-Exhibit B, draft).

TABLE 1. St. Anthony Falls Spillway Water Surface and Velocity Profiles

	Q = 300 cfs		Q = 1000 cfs		Q = 3000 cfs		Q = 15,000 cfs		Q = 50,000 cfs		Q = 100,000 cfs	
X (ft)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)
0	.25	2.84	.56	4.23	1.16	6.1	3.38	10.4	7.55	15.6	11.98	19.6
4	.092	7.67	.26	9.16	.65	10.9	2.35	15.0	5.90	19.9	9.80	24.0
8	.078	9.05	.21	11.2	.54	13.1	2.06	17.1	5.35	22.0	9.06	26.0
12	.074	9.61	.19	12.6	.48	14.7	1.88	18.8	5.00	23.5	8.55	27.5
16	.072	9.81	.17	13.6	.44	16.0	1.75	20.2	4.72	24.9	8.15	28.9
20	.071	9.94	.17	14.3	.41	17.2	1.64	21.5	4.49	26.2	7.82	30.1
24	.071	9.97	.16	14.8	.39	18.1	1.56	22.6	4.31	27.3	7.54	31.2
28	.071	9.97	.16	15.2	.37	19.1	1.49	23.7	4.15	28.4	7.30	32.2
31	.071	9.97	.15	15.4	.36	19.6	1.45	24.4	4.05	29.1	7.14	32.9
35	.061	11.7	.14	17.0	.33	21.4	1.33	26.5	3.79	31.0	6.76	34.8
39	.058	12.2	.13	18.0	.31	22.8	1.25	28.2	3.59	32.8	6.45	36.5
43	.058	12.3	.13	18.7	.29	24.3	1.18	29.9	3.42	34.4	6.18	38.1
47	.057	12.3	.12	19.1	.28	25.2	1.12	31.5	3.28	35.9	5.95	39.6
51	.057	12.3	.12	19.5	.27	26.1	1.07	33.0	3.15	37.4	5.75	41.0
55	.057	12.3	.12	19.6	.26	27.2	1.03	34.3	3.04	38.7	5.57	42.3
59	.057	12.3	.12	19.7	.25	28.2	0.99	35.7	2.94	40.0	5.40	43.6
63	.057	12.3	.12	19.8	.25	28.2	0.96	36.8	2.85	41.3	5.25	44.8
67	.057	12.3	.12	19.8	.25	28.2	0.93	38.0	2.77	42.5	5.12	46.0
71	.057	12.3	.12	19.9	.25	28.2	0.91	38.8	2.70	43.6	4.99	47.2
75	.057	12.3	.12	19.9	.25	28.2	0.89	39.7	2.63	44.7	4.88	48.3
79	.057	12.3	.12	19.9	.25	28.2	0.87	40.6	2.57	45.8	4.77	49.3
83	.057	12.3	.12	19.9	.25	28.2	0.85	41.5	2.52	46.8	4.67	50.4
87	.057	12.3	.12	19.9	.25	28.2	0.83	42.5	2.46	47.8	4.58	51.4
91	.057	12.3	.12	19.9	.25	28.2	0.81	43.6	2.42	48.7	4.50	52.4
95	.057	12.3	.12	19.9	.25	28.2	0.80	44.1	2.37	49.6	4.42	53.3
99	.057	12.3	.12	19.9	.25	28.2	0.79	44.7	2.33	50.6	4.34	54.2
103	.057	12.3	.12	19.9	.25	28.2	0.78	45.3	2.29	51.4	4.27	55.1
106	.057	12.3	.12	19.9	.25	28.2	0.77	45.8	2.25	52.3	4.20	56.0

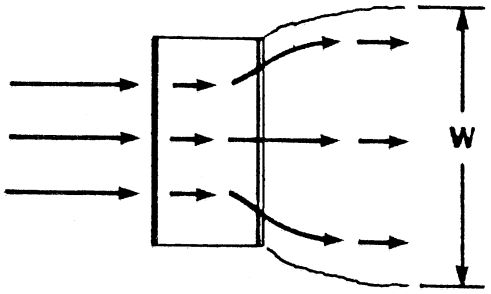
NOTE: X is streamwise distance from spillway crest.
Spillway changes slope at X = 31 ft

TABLE 2 - Prototype "Roostertail" Dimensions for Various Positions on the Spillway for Q = 300 cfs

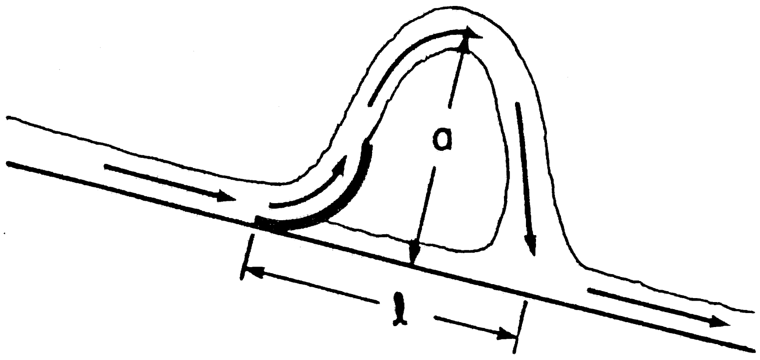
Depth (ft)	Velocity (ft/s)	X* (ft)	ℓ (ft)	w (ft)	a (ft)
.094	7.51	4	2.3	1.5	1.2
.088	8.02	5	2.7	2.0	1.3
.082	8.61	7	2.8	3.3	1.5
.076	9.29	10	3.2	5.3	2.2
.068	10.38	32	3.2	6.0	2.5
.058	12.17	39-106	3.2	7.0	3.2

*Streamwise distance from spillway crest.

PLAN VIEW



SIDE VIEW



identical to the 1/2-scale results. A full-scale test could not be used for distances greater than 4 ft from the spillway crest because of width and head limitations in the 24" flume.

Photographs of the "roostertail" configuration produced by a single full-scale element are shown in Figs. 4, 5, and 6. The photographs show the "roostertails" at three different flow rates at a point four feet from the crest.

C. Testing of Spillway

To determine the possible location and interaction of deflector elements an undistorted 1:8 scale hydraulic model of the spillway operated to Froude similarity was used. Froude scale modeling is appropriate for spillway models because of the predominance of inertial and gravity forces. Because the water depths in the model are extremely small, it is, however, necessary to consider viscous and in particular surface tension effects as well. Flow characteristic scaling is defined in Table 3.

Force scaling ratios in Table 3 indicate that surface tension and, to some extent, viscous effects are far too strong in the model. This became readily apparent when 1:8 scale single elements were tested. The spray configurations which they created had dimensions quite different from those of the prototype. It was therefore necessary to resort to distortion of the model elements to produce an appearance similar to the prototype. This was achieved by increasing the width of the elements to three times the undistorted scale value.

These distorted elements were then installed on the 1:8 scale spillway model and after trying several configurations, cluster placement of the elements proved to give the most appealing appearance. Figures 7, 8, and 9 give photographs of the model e.g. at 300 cfs flow. The exact locations of the elements on the spillway are shown in Fig. 10.

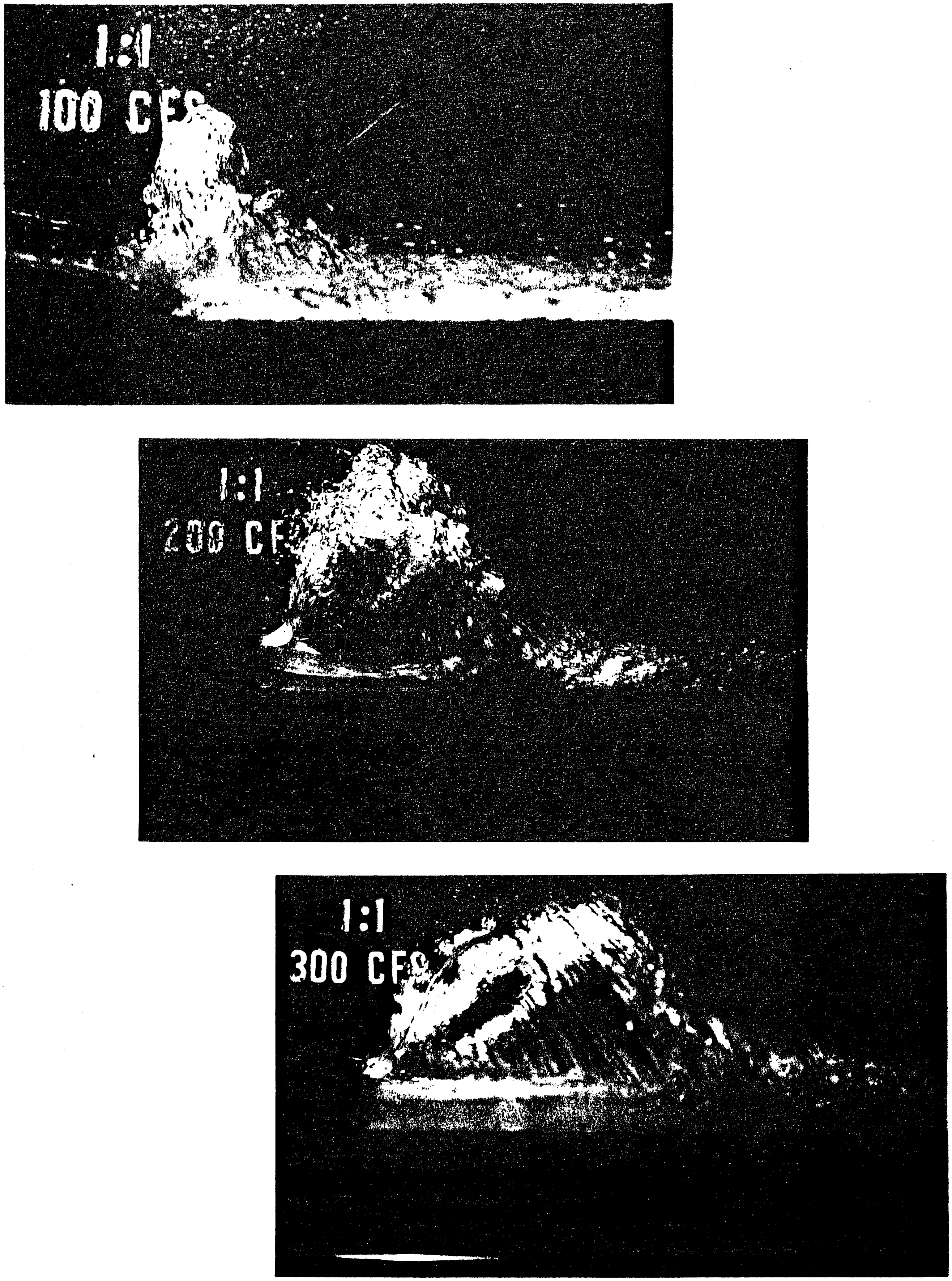


Fig. 4. A single full scale flow deflection element operating at 100, 200, and 300 cfs (prototype) flows; side view.

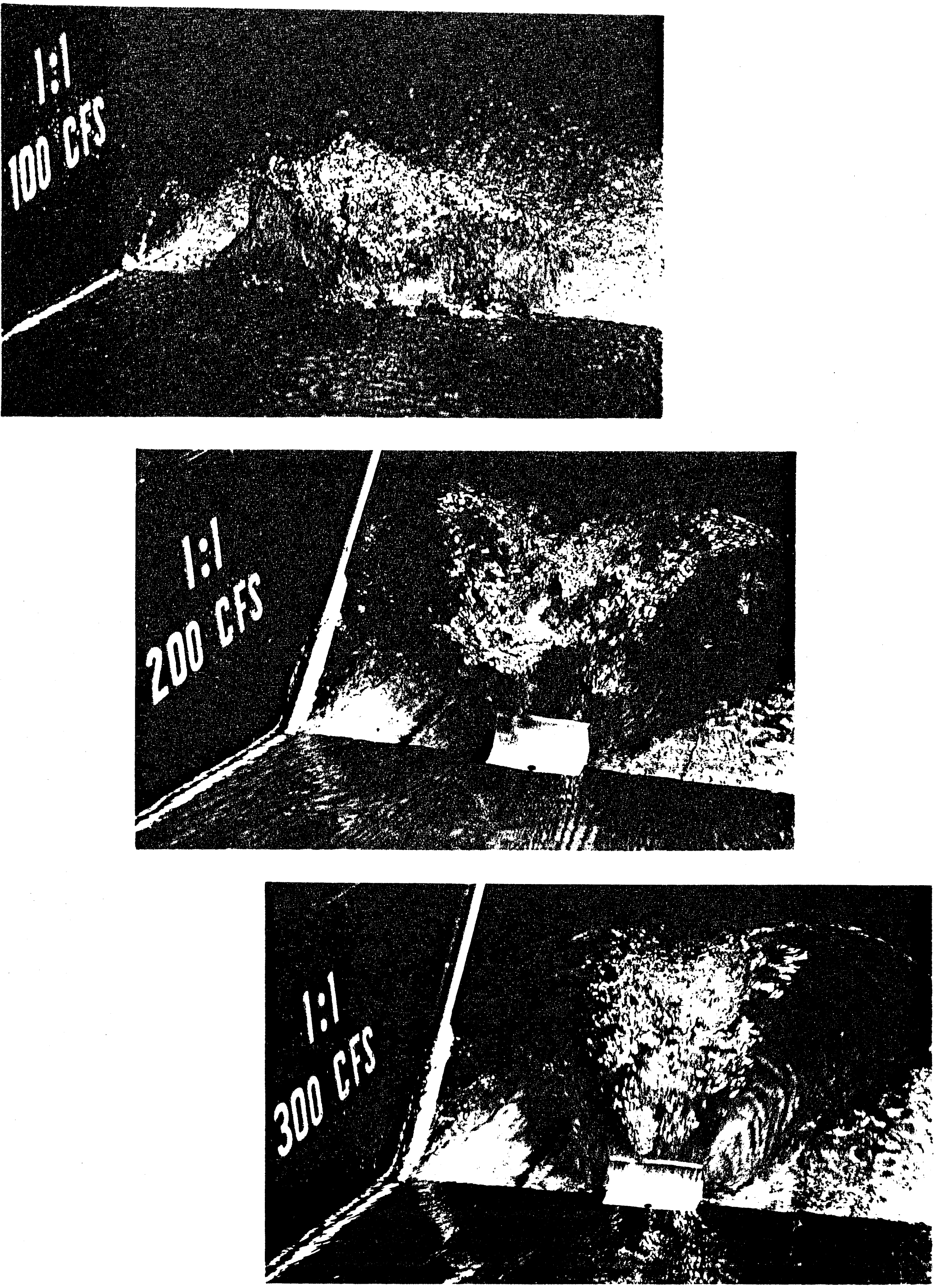


Fig. 5. A single full scale flow deflection element operating at 100, 200, and 300 cfs (prototype) flows; looking downstream.

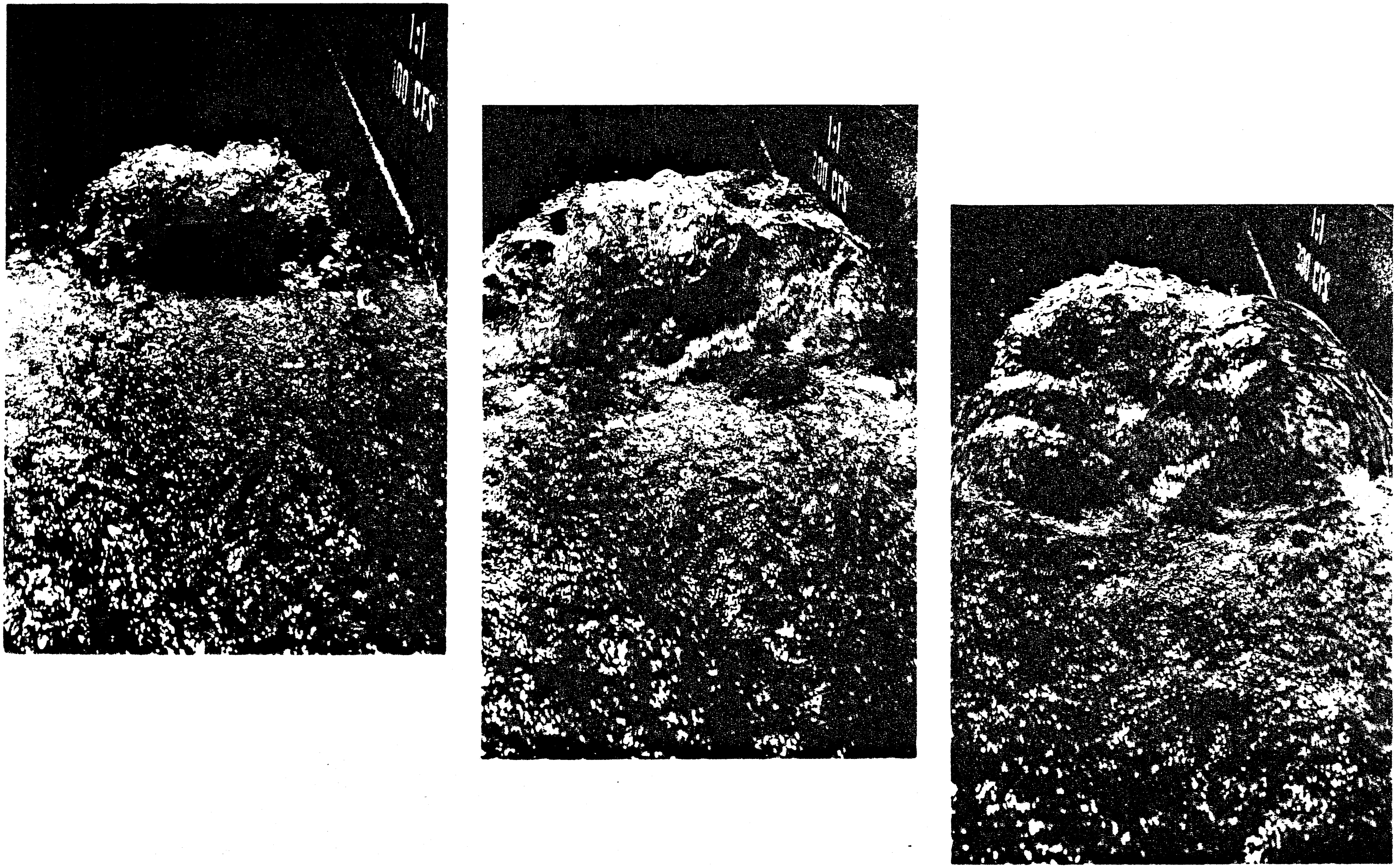


Fig. 6. A single full scale flow deflection element operating at 100, 200, and 300 cfs (prototype) flows; looking upstream.

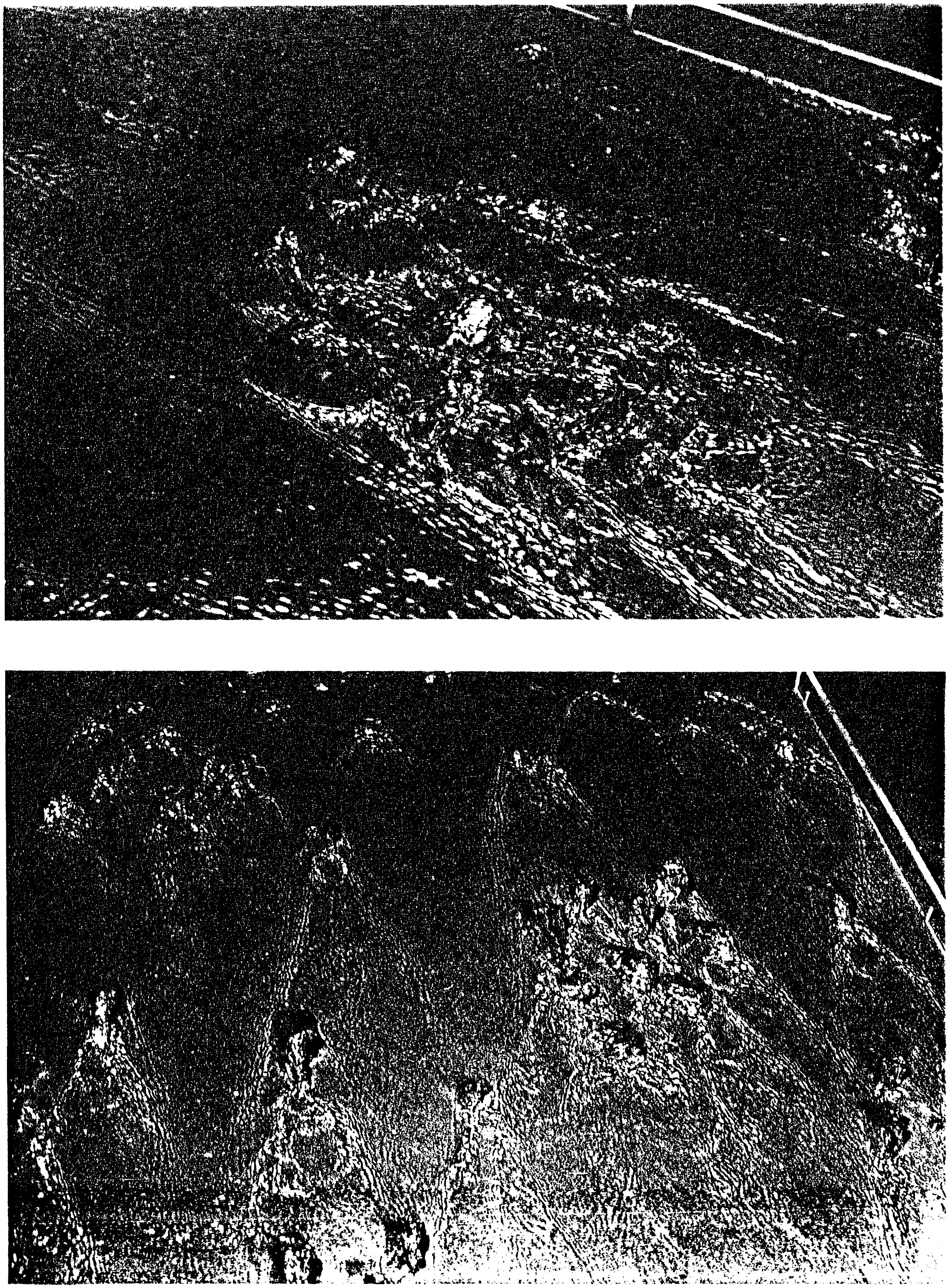


Fig. 7. 1:8 scale clustered arrangement operating at 300 cfs (prototype) flow rate.

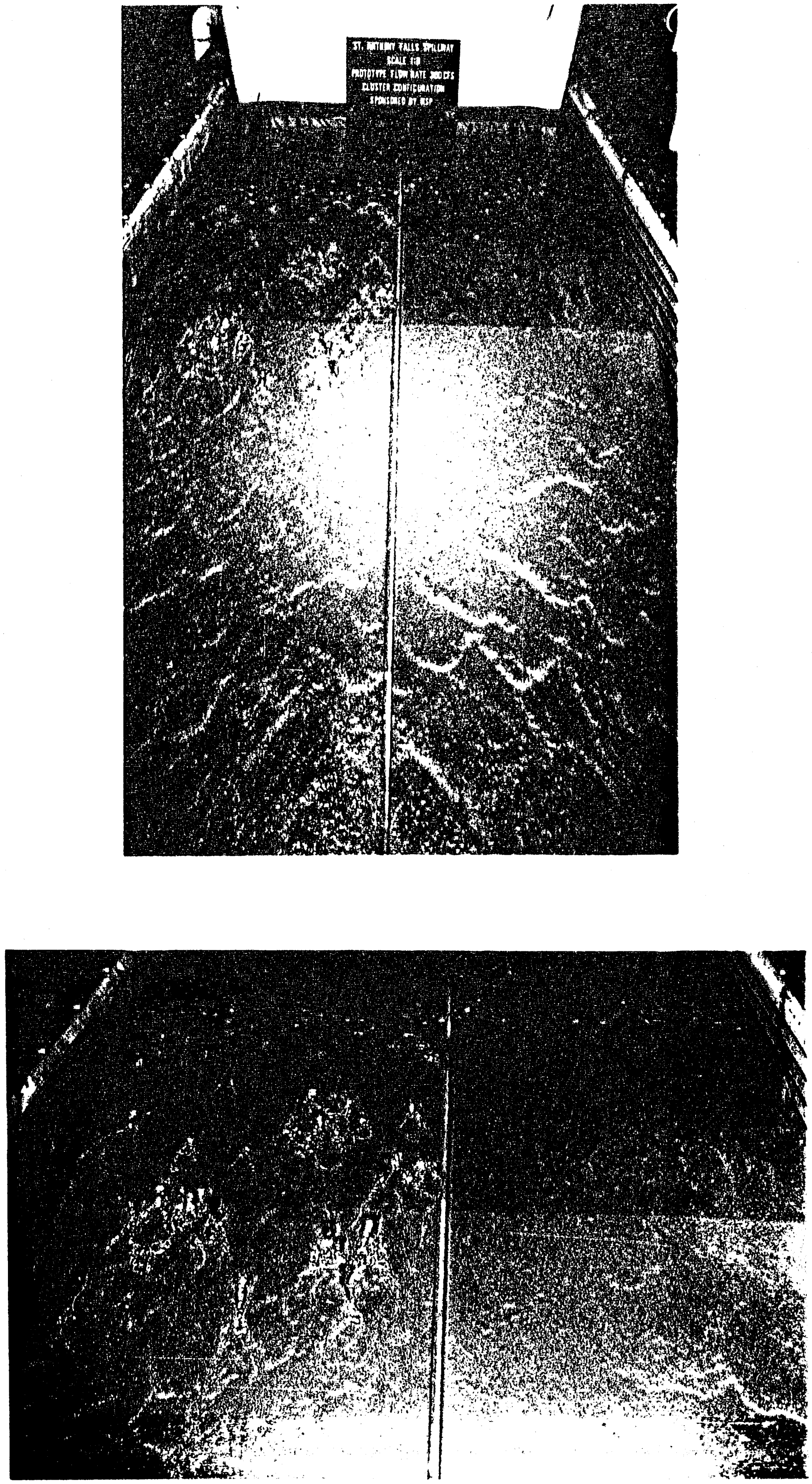


Fig. 8. 1:8 scale spillway section operating at 300 cfs (prototype) discharge with cluster design configuration on left and present condition (no deflectors) on right.

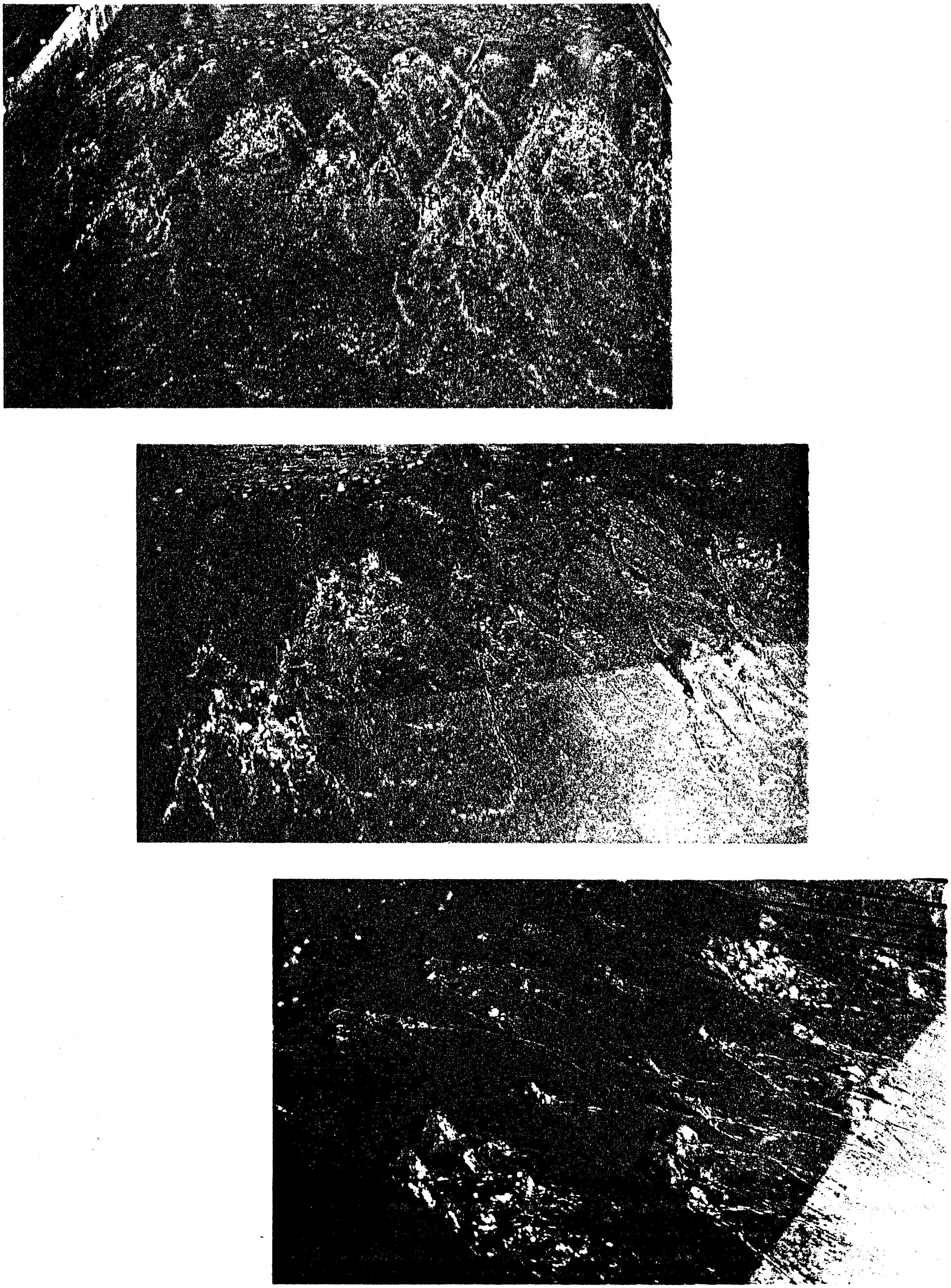


Fig. 9. 1:8 spillway model operating at 300 cfs (prototype) flow.

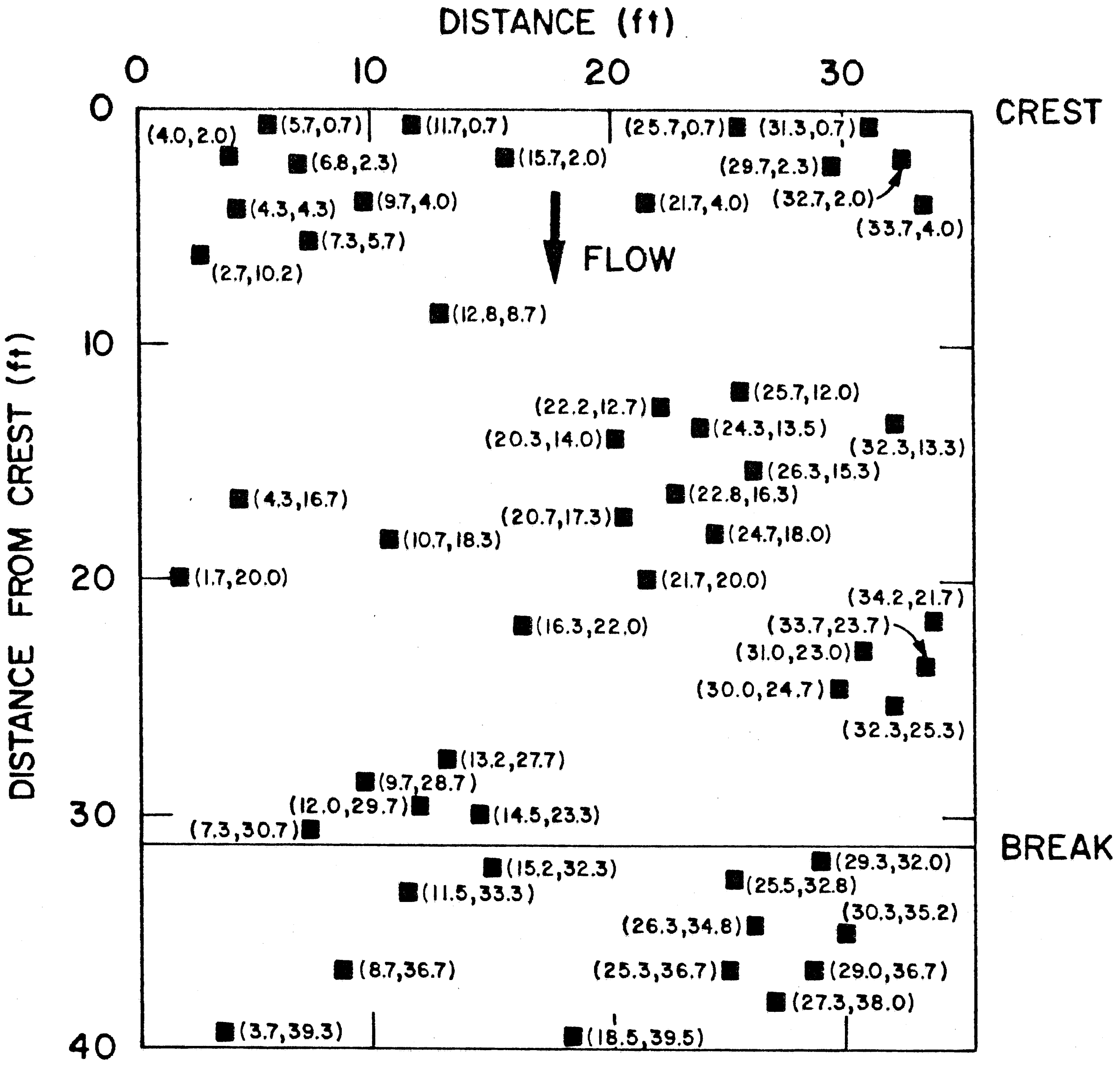


Fig. 10. Locations of elements on spillway.

TABLE 3

	Model:Prototype
Froude No. $U/\sqrt{gH}$	1:1
Height H	1:8
Length L	1:8
Width W	1:8
Velocity U	1:2.83
Flow Rate Q	1:181
Time t	1:2.83
Viscosity ν	1(32°F):0.55(70°F)
Reynolds No. UH/ν	1:41
Surface Tension s	1(32°F):0.96(70°F)
Weber Number $U/\sqrt{\rho H/s}$	1:8.2
Inertial Forces ρQU	1:512
Gravity Forces ρgH^3	1:512
Viscous Forces $\rho \nu UL$	1:12.5
Surface Tension Forces sL	1:7.7

D. Performance at High Flows

Increased abrasion and cavitation damage on the concrete surface are major potential problems which could develop at spillway flows above 3000 cfs. The possible occurrence of cavitation during high flows due to the addition of the proposed elements to the spillway was investigated.

The tendency for a flow field to exhibit cavitation is defined by the cavitation index

$$\sigma = \frac{p - p_v}{\frac{1}{2} \rho U^2} \qquad (1)$$

where p = upstream (reference) pressure
p_v = vapor pressure of water

ρ = density of water
U = upstream (reference) velocity

Assuming a hydrostatic pressure distribution,

$$p = p_{atm} + \gamma y \cos\alpha \tag{2}$$

where p_{atm} = atmospheric pressure
γ = specific weight of water
y = water depth
α = spillway slope

Substituting (2) into (1) and dividing numerator and denominator by γ, gives

$$\sigma = \frac{(p_{atm} - p_v)/\gamma + y \cos\alpha}{U^2/2g} \tag{3}$$

where g = acceleration of gravity = 32.2 ft/sec^2.

$$(p_{atm} - p_v)\gamma \cong 33.1 \text{ ft}$$

and therefore,

$$\sigma = \frac{33.1 \text{ ft} + y \cos\alpha}{U^2/2g} \tag{4}$$

In order to calculate the actual velocity at a flow deflection element, one must take into account the boundary layer adjacent to the spillway face. A boundary layer is the region of velocity deficit caused by the frictional effects of a bounding surface. For a turbulent boundary layer such as the one that exists on the spillway, the boundary layer thickness is

$$\delta = 0.38 \times \left(\frac{u_o x}{\nu} \right)^{-1/5} \tag{5}$$

where

$\delta = \delta(x)$ = boundary layer thickness
x = distance from spillway crest

u_o = velocity outside boundary layer at distance x
ν = kinematic viscosity of water

Once the boundary layer profile has been computed, the actual velocity profile at a position x including the velocity at the elevation of the outer edge of the element (u_{h_o}) can be estimated from

$$u(h) = u_o \left(\frac{h}{\delta} \right)^{1/7} \tag{6}$$

where

$u(h)$ = streamwise velocity
h = distance from spillway surface

and

$$u_{h_o} = u_o \left(\frac{h_o}{\delta} \right)^{1/7} \tag{7}$$

where h_o = element height normal to spillway face = 2.25 in. = .1875 ft. Boundary layer thicknesses and velocities at the element height have been calculated and appear in Table 4 for flows of 15,000 cfs, 50,000 cfs, and 100,000 cfs.

Velocities u_{h_o} serve as the reference velocities U in Eq. 4. Substituting the depths (y) from Table 1 and velocities (u_{h_o}) from Table 4 into Eq. 4 yields the actual cavitation index, σ, as a function of spillway position for the above flows. The results of this computation appear also in Table 4.

To decide at which value of the cavitation index, σ, the flow will begin to cavitate, a critical cavitation index, σ_c, was experimentally determined in the SAFHL free jet water tunnel. In this facility, both a 1/2-scale and a full-scale element of the type proposed for the spillway were mounted and water flows of varying pressures and velocities were generated. Inception of cavitation was defined as the condition when vapor bubbles in the flow could be seen through the lucite walls of the test section. This occurred either in the free shear layer of the flow over the top of the element or in the horseshoe vortex near the bottom of the

TABLE 4. Calculated Boundary Layer Thickness (δ), Velocity at Edge of Element (u_{h_o}), Cavitation Index (σ), and Drag Force Values (D)

	15,000 cfs				50,000 cfs				100,000 cfs			
X (ft)	δ (ft)	u_{h_o} (ft/s)	σ	D (lb)	δ (ft)	u_{h_o} (ft/s)	σ	D (lb)	δ (ft)	u_{h_o} (ft/s)	σ	D (lb)
4	.07	15.0	10.1	16	.07	19.9	6.3	28	.07	24.0	4.8	41
8	.12	17.1	7.7	21	.12	22.0	5.1	34	.11	26.0	4.0	48
12	.17	18.8	6.4	25	.16	23.5	4.4	39	.16	27.5	3.5	54
16	.21	19.9	5.7	28	.20	24.7	4.0	43	.19	28.7	3.2	58
20	.25	20.7	5.2	30	.24	25.4	3.7	46	.23	29.2	3.1	60
24	.28	21.4	4.9	32	.27	25.9	3.6	48	.26	29.7	3.0	63
28	.32	22.0	4.6	34	.30	26.5	3.4	50	.30	30.2	2.9	65
31	.34	22.5	4.4	36	.33	26.9	3.3	51	.32	30.5	2.8	66
35	.37	24.1	3.8	41	.36	28.3	2.9	57	.35	31.9	2.5	72
39	.40	25.4	3.4	46	.38	29.6	2.7	62	.38	33.1	2.3	77
43	.42	26.6	3.1	50	.41	30.8	2.5	67	.40	34.1	2.2	82
47	.45	27.8	2.8	55	.44	31.8	2.3	72	.43	35.1	2.0	87
51	.48	28.9	2.6	59	.46	32.8	2.2	76	.46	36.1	1.9	92
55	.50	29.8	2.5	63	.49	33.7	2.0	81	.48	37.0	1.8	97
59	.53	30.8	2.3	67	.51	34.7	1.9	85	.51	37.8	1.7	101
63	.55	31.5	2.2	70	.54	35.5	1.8	89	.53	38.6	1.6	106
67	.58	32.3	2.1	74	.56	36.3	1.7	93	.55	39.4	1.6	110
71	.60	32.8	2.0	76	.59	37.1	1.7	97	.58	40.2	1.5	114
75	.62	33.4	2.0	79	.61	37.8	1.6	101	.60	40.9	1.5	118
79	.65	34.0	1.9	82	.63	38.5	1.5	105	.62	41.6	1.4	122
83	.67	34.6	1.8	85	.66	39.1	1.5	108	.65	42.2	1.4	126
87	.69	35.3	1.8	88	.68	39.8	1.4	112	.67	42.9	1.3	130
91	.72	36.0	1.7	92	.70	40.4	1.4	115	.69	43.5	1.3	134
95	.74	36.3	1.7	93	.72	41.0	1.4	119	.71	44.1	1.2	137
99	.76	36.6	1.6	95	.74	41.5	1.3	122	.73	44.6	1.2	141
103	.78	36.9	1.6	96	.76	42.1	1.3	125	.75	45.2	1.2	144
106	.77	37.5	1.5	99	.78	42.7	1.2	129	.77	45.8	1.1	148

element. The latter would likely be more dangerous for the concrete spillway surface. σ_c was calculated by substituting the pressure and velocity measured in the free jet tunnel at the inception of cavitation into Eq. (1). Using this procedure, σ_c was found to be 2.3 to 2.5 for both the 1/2-scale and prototype elements.

It needs to be pointed out that in the free jet tunnel a boundary layer was practically non-existent so that these tests examined cavitation inception in a uniform flow rather than a boundary layer flow. Based on element height Reynolds numbers $(u_{h_0} \cdot h_0/\nu)$ in the experiments ranged from 120,000 to 360,000. For cavitation of flow around discs, Reynolds number effects are generally negligible for $Re > 100,000$.

The significance of this analysis lies in the fact that where actual cavitation indices, σ , are greater than the critical cavitation number, σ_c , cavitation is not expected to occur. As can be seen in Table 4, for the 100,000 cfs flood (the worst case under consideration) cavitation is not anticipated in approximately the upper 31 ft of the spillway which corresponds to the area between the crest and the point at which the spillway changes slope. Below this point, cavitation is expected.

For the 300 cfs, 1000 cfs, and 3000 cfs flows, the cavitation indices at the bottom of the spillway are 14.1, 5.4, and 2.7, respectively. Since these are all greater than the critical value of 2.5 and all cavitation indices elsewhere on the spillway at these flows are greater yet, cavitation will not occur anywhere on the spillway for flow rates less than or equal to 3000 cfs.

An alternative consideration is the following. The water depth y in Eq. (4) does not exceed 4 ft if total flow is less than 50,000 cfs and locations are downstream from the spillway break. In that case the term $y \cos \alpha$ in Eq. (4) is small compared to 33.1 ft and the conditions for cavitation inception can be expressed in terms of a velocity U_c not to be exceeded.

$$U < U_{cr} \approx \sqrt{\frac{2g(33.1')}{\sigma_{cr}}} = 29.2 \text{ ft/s} \qquad (8)$$

The approximate location $x = x_{crit}$ where this condition is reached is shown in Fig. 11. It is predicted that cavitation will not occur anywhere on the spillway as long as the total flow Q remains below 3,000 cfs. At flows in excess of that value, the lower portion of the spillway will show velocities in excess of 29.2 ft/s, and thus be susceptible to cavitation. If the lowermost element is placed at x = 39 ft as shown in Fig. 10, cavitation will begin to occur when the total discharge rate is in excess of 50,000 cfs. Since such a flood is a fairly common occurrence, placement of permanent elements downstream from the break is not advisable without further study.

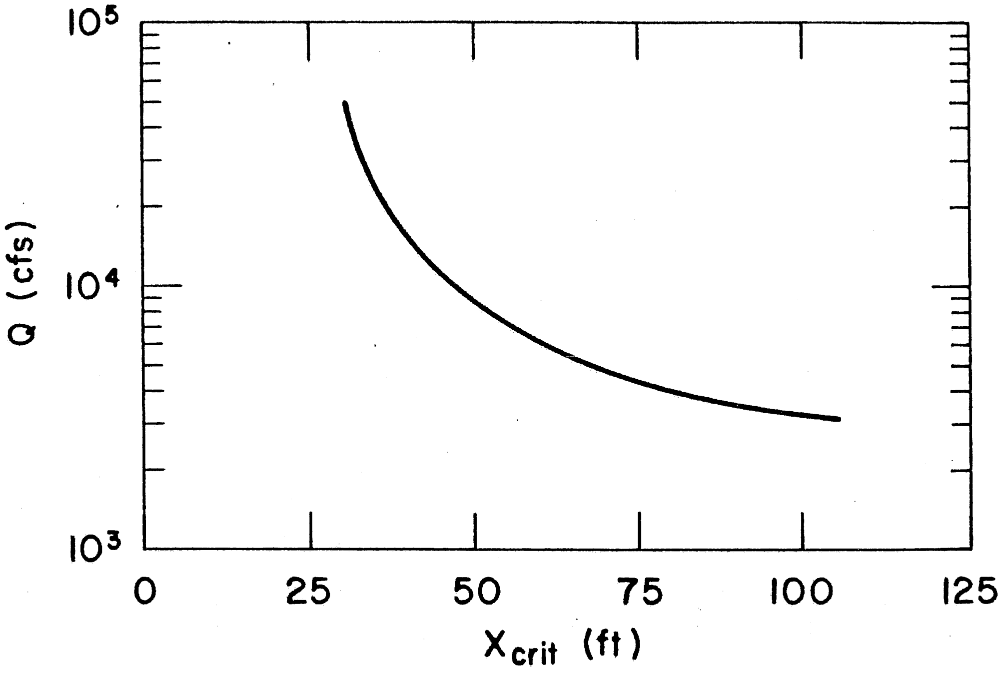


Fig. 11. Prototype flow rate versus location on spillway below which cavitation is expected to occur (using mean flow velocity).

V. CALCULATED LOAD ON AN ELEMENT

The suggested flow deflection elements experience a load or force due to hydrodynamic drag. The magnitude of this force is an important criterion in the design of a fastener as well as in the selection of element material.

Drag is calculated from the equation

$$D = C_D \left(\frac{1}{2} \rho \, \overline{u}^{\,2} \, A \right) \qquad (9)$$

where

D = Drag force
C_D = Coefficient of drag
ρ = Density of water = 1.94 $\mathrm{sl/ft^3}$
$\overline{u}$ = Streamwise velocity
A = Frontal area = Bh_o = .0625 $\mathrm{ft^2}$
h_o = Element height = 2.25 in.
B = Element width = 4.0 in.

At high flow when the drag on the element is important, the element is submerged in a boundary layer type flow. Using the boundary layer velocity profile expressed in Eq. 6,

$$\overline{u}^{\,2} = \frac{7}{9} u_{h_o}^{\;2} \qquad (10)$$

A review of empirically determined drag coefficient for shapes similar to that of the proposed flow enhancement element suggests the use of $C_D \approx 1.5$. Thus,

$$D = 1.5 \left[\frac{1}{2} \left(1.94 \frac{\text{sl}}{\text{ft}^3}\right)\left(\frac{7}{9} u_{h_o}{}^2\right)(.0625 \text{ ft}^2) \right.$$

$$= (.0707 \text{ sl/ft})(u_{h_o}{}^2) \qquad (11)$$

Since u_{h_o} has already been computed for higher flows (Table 4) where drag force is significant, drag can also be calculated. This has been done and appears as a function of spillway position in Table 4. Additionally, a critical drag force, D_{cr}, can be estimated by substituting the value U_{cr} in Eq. 8 into Eq. 11. The drag will exceed this critical value at the same time as cavitation is likely to occur. It should be noted, however, that the calculation of U_{cr} was made neglecting the influence of the water depth, and thus D_{cr} is approximate also.

Making the appropriate substitution,

$$D_{cr} = (.0707 \text{ sl/ft})(29.2 \text{ ft/s})^2 \cong 60 \text{ lb} \qquad (12)$$

If the design option adopted incorporates elements below the change in spillway slope (i.e. in a potentially cavitating region), then the elements and/or fasteners must be designed such that the elements detach before the drag force exceeds D_{cr}. If elements only appear on the upper spillway slope where the velocities will never exceed U_{cr} regardless of flow rate, then anticipated loads will never exceed D_{cr} and elements and fasteners should be design accordingly.

VI. DESIGN RECOMMENDATIONS

Matters of aesthetics, including those of water rushing over a concrete apron are to some extent subject to personal judgement and perception. A hydraulic model study of the St. Anthony Falls main spillway in the Mississippi River near downtown Minneapolis was conducted, and a majority of viewers who saw water flowing over the 1:8 scale model indicated that the attachment of elements (Fig. 2) in clusters, such as shown in Figs. 7 through 10, to the concrete surface will enhance the appearance of the spillway at low flows. The distribution of the elements shown in Fig. 10 was arrived at by experimentation and covers a spillway width of 36 ft. It is to be repeated across the full width of the spillway, but must not be extended to the lower (steeper) portion of the spillway without additional precaution and study. If this is done, 472 elements will be needed to cover the entire width of the spillway. If additional elements are added below the break (Fig. 10), a total of 614 elements will be required.

Individual elements are identical and designed (a) to give a strong "roostertail" effect, (b) to produce a significant fluctuation in the water spray effect, (c) to be easily attachable to the spillway surface, and (d) to be easily replaceable when damaged or destroyed by debris.

The distribution in the downstream direction is limited by concern about cavitation damage to the spillway surface at high flow. For this reason it is recommended that one of two alternative strategies be employed:

1) Place no elements below the line that demarcates the change in spillway slope (x=31 ft), or

2) Design the elements and/or fasteners below that line such that the elements will detach from the spillway face before conditions producing cavitation (i.e., flood flows) are reached.

The preferred (conservative) solution is the first one. The second recommendation may be realized by either designing the element to break away from its fastener during high flows or designing the fasterners to shear away from or pull out of their anchors at these times. Of course, in either case most of the elements would have to be replaced frequently. All elements located at a distance greater than 31 ft from the crest must be attached such that the elements are sheared away before velocities exceed U_{cr} and drag exceeds D_{cr}.

Several materials have been considered for the elements, but no study or selection has been made. The materials include PVC and wire reinforced rubber. The color of the deflector elements should closely match that of the spillway. The final choice of element material and fastening technique will depend on which placement strategy is employed. If permanent elements are decided on, rigid, durable material capable of withstanding the stresses of flood flows should be used. Should break-away elements be the solution of choice, the deflectors would have to be designed in a way that accommodates detachment before water velocities associated with rising flow rates reach the critical velocity U_{cr} discussed above.

The purpose of this study was not to determine what the minimum flow over the spillway should be (over the past 10 years it has often been zero), but to determine what aesthetics can be accomplished at a low flow and at a reasonable cost. The intent was not to recreate the "waterfall" which was highly unstable and migratory in its original form and was therefore replaced by a spillway, but to improve the aesthetics on the existing spillway. The proposed solution meets these criteria and can be tested in a field experiment.

VII. FIELD TESTING

It is recommended that the elements be field tested on the actual spillway by placing them in a 32 ft wide strip at the edge of the spillway. This would represent about one-thirteenth of the total width of the spillway. The field test will (1) show the actual performance of low flow without any distortion due to surface tension and (2) show potential for abrasion or cavitation damage after a period of high flow. Cavitation damage is not anticipated if the foregoing recommendations are followed; abrasion was not studied in the laboratory.

Once the units are installed on a section of the spillway, observation of the actual conditions will allow NSP to obtain more comments, and if the full-scale aesthetics are not acceptable, changes will have to be made. These changes could be addition of deflector, different spacing, or others.