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July 6, 1961

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Model Tests of K-Downcomer Orifice
Plates for General

AUTHOR

Claud C. Lomax

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Leto for	60000	717	NOV 9 '64	
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Research Report No. 61/9-100

MODEL TESTS

OF

X - DOWNCOMER ORIFICE PLATES

FOR

GENERAL ELECTRIC COMPANY

Classification Cancelled and Changed To

By

Claud C. Lomax

July 6, 1961

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By Authority of DS Lewis

CG-PR-2, 4-21-94

By DK Hanson, 5-9-94

Verified By J. E. Savely 5-13-94

Project No. 609

Contract No. 10E-3809-0609

Sponsor Contract No.

Design, Development and Research
Contract DDR-111 Prime Contract
AT(45-1)-1350

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WASHINGTON STATE UNIVERSITY
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DIVISION OF INDUSTRIAL RESEARCH

August 15, 1961

Mr. H. W. Heacock
Supervisor, Reactor Modifications Design
General Electric Company 762 Bldg., 700 Area
Hanford Atomic Products Operation
Richland, Washington

Dear Mr. Heacock;

Mr. Schack, during his visit of July 19, 1961, requested: (1) Additional information on the use of the model data to predict prototype performance and to compare prototype and model results and, (2) An orifice design having specified minimum pressures at the vena contracta for a range of flow rates. In discussing the use of the model data it was apparent that the labeling of the Figures is ambiguous.

It is suggested that our Report HW-WSU-4 will be more readable and the description more accurate if the ordinates of several of the figures are changed to read as follows:

Change in Hydraulic Gradient,
 $p_2/\gamma + z_2 + v_2^2/2g - p_3/\gamma - z_3$ Figure 1

Change in Hydraulic Gradient,
 $p_3/\gamma + z_3 - p_5/\gamma - z_5$ Figures 2-5

Change in Hydraulic Gradient,
 $p_2/\gamma + z_2 + v_2^2/2g - p_5/\gamma - z_5$ Figures 6-9

Change in Hydraulic Gradient,
 $p_2/\gamma + z_2 + v_2^2/2g - p_4/\gamma - z_4$ Figures 10-13

p_4/γ , in feet of water Figures 14-29

$(p_4/\gamma - p_4'/\gamma)$ difference in pressure at P_4
and vena contracta Figure 30

Abscissas for Figures 14-20 should read $p_5/\gamma + z_5$, Elevation of Hydraulic Gradient.

Enclosure 1 gives Instructions for Using the Model Data reported in HW-WSU-1 Rev. 1 and HW-WSU-4 as requested by Mr. Schack.

The sample computations requested by Mr. Schack are being forwarded under separate cover.

Very truly yours,

Claud C. Somay

CCL:mb

Encl. 1 (10 copies)

FIGURE 1 - SAMPLE ENERGY AND HYDRAULIC GRADIENTS

INSTRUCTIONS FOR USING MODEL DATA

As requested we have prepared a sample computation to illustrate how the data included in our reports HW-WSU-1 Rev. 1 and HW-WSU-4 can be used to compare assumed prototype conditions for which some data are available with model results.

After reviewing the reports and the desired usage of the data therein, we believe some clarification is necessary for understanding the results and our treatment of them.

We have used P_2 , P_3 , P_4 , P_4' , and P_5 more as locations than as specific pressures, etc. At P_2 we measured p_2/γ . Since our tank was large $[v_2^2/2g \approx 0]$, p_2/γ measures the actual pressure and the distance to both the hydraulic and energy gradients. At P_3 , P_4 , and P_5 we measured p_3/γ , p_4/γ and p_5/γ respectively; they were the actual pressures at these points. In Figures 1 through 13 where we have used (P_2-P_3) , (P_2-P_4) and (P_4-P_5) , they are not true losses but changes in the hydraulic gradients.

Specifically:

$$(P_2-P_3) = p_2/\gamma + z_2 + v_2^2/2g - p_3/\gamma - z_3$$
$$(P_2-P_4) = p_2/\gamma + z_2 + v_2^2/2g - p_4/\gamma - z_4$$
$$(P_2-P_5) = p_2/\gamma + z_2 + v_2^2/2g - p_5/\gamma - z_5$$

When air enters the channel at the approach tank, the channel does not flow full, and/or the pressure at P_4' is equal to the vapor pressure discontinuities will exist which preclude application of the model data. In some cases part of the model data can be used. For cases where air enters at the approach tank and/or the channel does not flow full no attempt should be made to apply the model data to prototype comparisons.

When separation occurs at P_4' the relationships between P_4' and P_5 become invalid and the equations of flow cannot be applied across this section.

Figure 1 illustrates the hydraulic and energy gradients for the downcomer model and prototype. The channel has been slanted for better understanding.

Flow rates may be limited indirectly by the orifice type and diameter but specific limitations are:

1. The pressure at P_4'
2. The pressure at P_5

One or the other will always control the flow rate through the channel, assuming entrance conditions are not limiting. Understanding of this basic principle is the key to using the model data, Figure 1 may be useful.

The flow history from low flow rates through increasingly higher flow rates is described in the following sequence. Low flows, say 0 to 30,000 gpm, will not fill the first row of channels. Increasing the total flow rate will increase the flow through the first row of channels until their capacity is limited by the orifice size and the pressure at P_4' . Further increases in the total flow rate will cause part of the flow to spill into the second row of channels. This process will continue until the water level in the approach tank reaches the established limit or the effluent back pressure increases sufficiently to limit the flow rates through the channels. After the first row of channels has filled, the flow rate through them will increase only slightly due to the increase in water level in the approach tank.

For each total flow rate there is one set of values of p_2/γ , p_3/γ , p_4'/γ , p_4/γ and p_5/γ for each orifice selected. Determination of these values requires a trial and error approach since model data are for flow rates in the test channel only.

Comparisons of prototype and model results or predictions of prototype performance from the model data given in HW-WSU-4, require different techniques for different flow conditions.

It appears that the following approach is the one most certain of success for all conditions:

Model-Prototype Comparisons

- Given:
- a. Orifice type and diameter
 - b. Total flow rate, Q
 - c. EBP from Q vs EBP curve, $p_5/\gamma + z_5$

Desired: p_2/γ , p_3/γ , p_4'/γ and p_5/γ

Solution:

Step 1: From (P_2-P_4) vs q curve compute and plot a new curve of $(p_2/\gamma + z_2 + v_2^2/2g - p_4'/\gamma - z_4' - v_2^2/2g)$ vs q that is, lower the existing curve by $v_2^2/2g$.

Step 2: Perform the same operation to (P_2-P_5) vs q curve.

- Step 3:
- a. Select maximum permissible elevation of water surface at the entrance to the downcomer channels $(p_2/\gamma + z_2)$.
 - b. Select value of $(p_4'/\gamma + z_4')$.
 - c. Obtain the difference $(p_2/\gamma + z_2) - (p_4'/\gamma + z_4')$.
 - d. Enter curve generated by Step 1 with the value obtained from Step 3c and read the maximum possible q per channel.

Step 4: Compute the total flow rate,

$$Q = q \frac{\text{number of holes in use}}{14}$$

NOTE: If Q from this step is less than the desired Q , it is impossible to obtain the desired Q with this orifice plate.

Step 5: a. Obtain $p_5/\gamma + z_5$ for the q of Step 3d from the curve generated by Step 2.

b. Compare this $p_5/\gamma + z_5$ with the EBP required for the Q obtained in Step 4.

c. If EBP is less than $p_5/\gamma + z_5$ there exists a discontinuity between P_4' and P_5 at all flow rates equal to or less than Q . This is the maximum Q for the existing conditions. Proceed to Step 6 for computations where Q is less than the maximum.

d. If EBP is greater than $p_5/\gamma + z_5$ proceed to Step 7.

Step 6: Knowing p_4'/γ and Q required compute the approximate number of holes required $= \frac{Q \times 14}{q}$ and $p_2/\gamma + z_2$. By trial and error adjust so that p_4'/γ , $(p_2/\gamma + z_2 - p_4'/\gamma - z_4)$, $(p_2/\gamma + z_2)$, and Q are compatible. This gives the desired Q and other data.

Step 7: $p_2/\gamma + z_2$ unknown, Q unknown, $p_5/\gamma + z_5$ unknown

a. Guess a reasonable value of Q and EBP

b. Compute q from $\frac{Q \times 14}{\text{number holes in use}} = q$

c. Determine $p_2/\gamma + z_2$ from number of holes vs $p_2/\gamma + z_2$

d. Compute $p_5/\gamma + z_5$ from $(p_2/\gamma + z_2 - p_5/\gamma - z_5)$ vs q using q from Step 7b and value of $p_2/\gamma + z_2$ from Step 7c.

e. Compute $p_2/\gamma + z_2 - p_4'/\gamma - z_4'$ using $p_2/\gamma + z_2$ from Step 7c and minimum value of $p_4'/\gamma + z_4'$ and compare with value from Figure 2 for q of Step 7b.

NOTE: If separation does not occur at P_4' , this step is not required since $p_4' + z_4' >$ minimum permissible.

f. Continue trial and error method until compatible values of $p_2/\gamma + z_2$, Q , ESP, $p_5'/\gamma + z_5'$, and $p_4'/\gamma + z_4'$ are obtained.

Step 8: Solutions for Q s less than maximum require techniques similar to Step 7. However, always check p_4'/γ to be certain it is not less than p_v or the arbitrary limit.

Orifice Design

We were also asked to select an orifice having certain characteristics:

- a. Bellmouth
- b. $p_2/\gamma + z_2$ limited, $p_4'/\gamma + z_4'$ limited, for a range of Q .
- c. Q maximum specified.

Although all of the desired characteristics may not be compatible, only a trial run will establish whether conflicts or redundant conditions are present in the specifications.

The steps to a solution follow:

Step 1: Select a diameter.

Step 2: Compute and plot theoretical curves $(p_2/\gamma + z_2 - p_4'/\gamma - z_4')$ vs q and $(p_2/\gamma + z_2 - p_5'/\gamma - z_5')$ vs q . These curves may be modified to agree more

closely with model data. This is a judgement factor based on comparing theoretical and model curves for similar orifices which were tested in the model.

Step 3: Proceed with the solution outlined on page 3 for existing orifice data.

Since a trial diameter was selected, this procedure must be repeated until the correct size has been selected.

T A B L E O F C O N T E N T S

	<u>Page</u>
Table of Contents	2
List of Figures	3
List of Tables	5
List of Reference Model Drawings	5
Summary	6
Acknowledgment	6
Introduction	7
Discussion	8
Requirements	12
Conclusions	18
Recommendations	20
Key to Symbols Used on Figures 1 through 29	56
Key to Conditions on Taped Data Sheets - (Figures 32 through 40)	68

L I S T O F F I G U R E S

<u>Figure No.</u>	<u>Description</u>	<u>Page</u>
1	Losses to Orifice - All Data	27
2	Loss Due to Orifice - Orifice 1	28
3	Loss Due to Orifice - Orifice 2	29
4	Loss Due to Orifice - Orifice 5	30
5	Loss Due to Orifice - Orifice 6	31
6	Loss Approach Tank to Effluent Elbow - Orifice 1	32
7	Loss Approach Tank to Effluent Elbow - Orifice 2	33
8	Loss Approach Tank to Effluent Elbow - Orifice 5	34
9	Loss Approach Tank to Effluent Elbow - Orifice 6	35
10	Pressure Drop to <u>Vena Contracta</u> - Orifice 1	36
11	Pressure Drop to <u>Vena Contracta</u> - Orifice 2	37
12	Pressure Drop to <u>Vena Contracta</u> - Orifice 5	38
13	Pressure at <u>Vena Contracta</u> - Orifice 6	39
14	P_4 versus P_5 - Orifice 1 - 7,000 gpm	40
15	P_4 versus P_5 - Orifice 2 - 6,900-7,400 gpm	41
16	P_4 versus P_5 - Orifice 5 - 7,350-7,700 gpm	42
17	P_4 versus P_5 - Orifice 6 - 6,700-8,000 gpm	43
18	P_4 versus P_5 - Orifice 1 - 9,000 gpm	44
19	P_4 versus P_5 - Orifice 2 - 8,650-9,400 gpm	45
20	P_4 versus P_5 - Orifice 5 - 9,250-10,100 gpm	46
21	P_4 versus P_5 - Orifice 6 - 9,250-10,000 gpm	47
22	P_4 versus P_5 - Orifice 1 - 11,200 gpm	48
23	P_4 versus P_5 - Orifice 2 - 10,500-11,400 gpm	49
24	P_4 versus P_5 - Orifice 5 - 10,850-11,100 gpm	50

(CONTINUED ON NEXT PAGE)

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LIST OF FIGURES - CONTINUED

<u>Figure No.</u>	<u>Description</u>	<u>Page</u>
25	P_4 versus P_5 - Orifice 6 - 11,000-11,550 gpm	51
26	P_4 versus P_5 - Orifice 1 - 12,500 gpm	52
27	P_4 versus P_5 - Orifice 2 - 12,400-15,100 gpm	53
28	P_4 versus P_5 - Orifice 5 - 12,900-15,300 gpm	54
29	P_4 versus P_5 - Orifice 6 - 15,000-15,300 gpm	55
30	Minimum Pressure versus P_4	57
31	<u>Effluent Back Pressure versus Q</u>	58
32	Run 5-15 - $Q = 3,550$ gpm - Orifice 1	59
33	Run 6-13 - $Q = 10,500$ gpm - Orifice 2	60
34	Run 9-16 - $Q = 11,200$ gpm - Orifice 2	61
35	Run 10-5 - $Q = 11,400$ gpm - Orifice 2	62
36	Run 10-16 - $Q = 9,450$ gpm - Orifice 2	63
37	Run 10-17 - $Q = 9,450$ gpm - Orifice 2	64
38	Run 11-11 - $Q = 9,250$ gpm - Orifice 6	65
39	Run 13-9 - $Q = 11,400$ gpm - Orifice 5	66
40	Run 15-8 - $Q = 11,200$ gpm - Orifice 5	67
41	Channel Details - Drawing No. 609-C-4	69

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LIST OF TABLES

<u>Table No.</u>	<u>Description</u>	<u>Page</u>
1	Maximum Flow Rates for Orifices Tested	14
2	Data for Photographs	26

LIST OF REFERENCE MODEL DRAWINGS

TRANSMITTED BY LETTER OF JUNE 23, 1961

<u>Drawing No.</u>	<u>Description</u>
609-C-2	Downcomer Orifice and Flange Detail
609-C-3	Downcomer Window Section Details
609-C-5	Downcomer Channel Location
609-B-6	Window Revisions

M O D E L T E S T S
O F
K - D O W N C O M E R O R I F I C E P L A T E S

INTRODUCTION

The model tests reported herein were conducted in accordance with Design, Development, and Research Contract DDR-111 between General Electric Company and Washington State University.

With the anticipated increase in flow rate through the K-Downcomer, the capacity of the existing orifice plate to pass the larger flow rate without cavitation or high water levels in the approach tank was questioned. Since this was a complex flow problem with multiple orifices and channelized flow passages, model tests were selected as the best means of evaluating the capacities of the proposed orifice plates. To supplement the model tests, an analytical study was made. The results of this study are given in report HW-WSU-1 (Rev. 1), "Analytical Considerations for K-Downcomer and Bellows."

A model of one channel of the K-Downcomer from the approach tank through the effluent bend was constructed to a scale of 1:3. This model was connected to the pumps, heat exchangers, meters, and other equipment previously used for the F- and DR-Downcomer tests.

Instrumentation was attached to the model to permit measurement of water temperature and pressures at locations identical to the P_3 , P_4 , and P_5 taps in the prototype. (See Figure 41.) Pressures were measured at locations similar, but not identical, to P_1 and P_2 in the prototype. Consolidated Electrodynamics pressure pickups, No. 4-313-25A, connected through Brush amplifiers, Model RD5612 00, to Brush six-channel recorders were used for the pressure records. An Edison Resistance Temperature Element, 249 N 90-1, connected through the same type of amplifier to the recorder provided a simultaneous temperature record.

In the early tests, it was found that air could not be prevented from entering the test channel due to a vortex in the approach tank. Additional baffles and a bell-mouth entrance from the approach tank were installed. These kept air from entering the test channel until the water level in the approach tank was lowered to an elevation slightly above the roof of the test channel.

Tests were made on the following orifice plates:

- No. 1 - Prototype diameter 2.563-inches.
- No. 2 - Prototype diameter 2.875-inches.
- No. 5 - Prototype diameter 2.563-inches with a bell-mouth entrance formed by a prototype radius of 15/32-inch.
- No. 6 - Same as No. 1 above, but with a 45° flare on the downstream edge of the hole. This was used to reduce the axial length of the cylindrical edge.

DISCUSSION

Model data were taken over a much wider range of variation in the control variables than exists in the prototype. This was done to obtain sufficient data to permit drawing curves and to study all the factors which could influence behavior of the downcomer.

Certain data have been excluded from the analyses and/or plotted points. Those factors which are causes for rejection of data are tabulated below. Justifications for rejection of these data are discussed in subsequent paragraphs.

1. When the water level in the approach tank drops to an elevation at or below the roof of the test channel; the test channel does not flow full for some distance downstream of entry. This is cause for rejecting any analysis wherein P_2 data are used.

2. Air entrained in the flow at the entrance has effects which influence all data. It changes the friction loss, bulks the flow and relieves the negative pressures at the separation points.
3. Jetting through a vapor pocket in a separation area in the vicinity of P_4 influences those analyses using P_4 and/or P_5 data.

Since the above effects vary from scarcely noticeable to extreme scatter of the data, some of the data influenced by these factors have been plotted and coded to indicate that they are questionable. All shaded symbols indicate questionable data. Their plotting serves two useful purposes: (1) They show how wide the scatter may be due to the above factors, and (2) When the factors influence is slight, they strengthen the valid data.

The above sketches provide visual illustration for the theoretical discussion of the behavior of the orifices. It is customary for sharp-edged orifices to be constructed as illustrated by I. The length of the cylindrical edge (parallel to the flow) is limited to a small percentage of the orifice diameter¹. When the plate is 'thick' the hole is tapered on the downstream side to meet this requirement. If the length of the cylindrical edge is too great,

¹ American Society of Mechanical Engineers - Fluid Meters, Their Theory and Application, 1959, p. 72, para. 213.

as shown by II, the opening becomes a short tube. Behavior of the flow through a short tube may be as shown in II-a or as shown in II-b. Furthermore, it is not possible to predict whether the flow will behave as shown in II-a or II-b; and, moreover, conditions where the flow vacillates between II-a and II-b occur. Factors influencing the flow behavior include sharpness of the edge, smoothness of the tube, turbulence upstream, entrained air or vapor, vapor pressure, viscosity, surface tension, downstream pressure, downstream turbulence, and past history of the flow; that is, was the prior flow rate lower or greater, and/or was the prior flow condition II-a or II-b.

If downstream conditions are similar, the energy losses for these orifices can be compared. Losses from the vena contracta to full expansion downstream depend upon the degree of the expansion. Therefore, I and II-b with the same value of C_c should have the same loss characteristics. II-a and III should have the same loss characteristics except for the loss within the tube in II-a. The latter is appreciable; but the sum of the losses from just upstream of the plate to full expansion downstream will be greater for II-b than II-a.

If flow from an orifice jets into a vapor pocket in a separation area, the expansion is delayed and full expansion occurs further downstream. Obviously, the loss characteristics are changed and higher losses are to be expected if the flow falls freely into a pool rather than gradually expanding to fill the conduit.

Accuracy of the data depends upon many factors, including flow regulation and measurement, temperature regulation and measurement, and pressure magnitudes.

At best, pressures can be read from the recording charts to the nearest $1/2$ division. Since the amplification varies, the accuracy also varies. For example, the data can be read to ± 1.5 feet prototype when the amplification is such that 1 cm = 30 ft. prototype. However, when pressures fluctuate greatly, it is difficult

to determine an average closer than 1 1/2 divisions; that is, ± 4.5 feet prototype. Although, attempts were made to reduce amplifier drift by frequent checks at the operating temperature, some drift has been observed. Causes for this drift are twofold: (1) Changes in the amplifiers, and (2) Loss of fluid from the Teflon tubing which is used to isolate the cells from the high temperature flow. The error may be of constant magnitude or vary with amplification; and, since the cause for any particular drift cannot be ascertained, no corrections have been made for it. Perhaps the best overall evaluation of accuracy is the scatter of the data. Judged on this basis, nearly all of the valid data (open symbols) are within ± 3 feet prototype of the averages.

The plotted data do not indicate the type of instability which was observed with the 'thick' plates. It was found that a particular flow rate and effluent back pressure did not guarantee the same flow conditions each time. The behavior screens the actual instability because no variable except flow rate remains constant. For example, at a particular flow rate, a given setting of the effluent control valve may give a variable effluent back pressure which in turn may result in overflow at the top, air entrainment, and/or jetting. Since all of these create questionable data, and since P_5 , P_4 , P_3 , and P_2 probably change, there is no way to separate questionable data resulting from unstable conditions from data produced by arbitrary changes of the effluent control valves. The above type of instability was not observed with Orifices 5 and 6.

The photographs presented here are typical of all those taken. Table 2 gives the conditions applicable to each photograph. These photographs illustrate various degrees of jetting, cavitation*,

* The term 'cavitation' is used throughout this report to describe vaporization in the flow due to a local reduction in pressure to the vapor pressure of the liquid. The vaporization can be intermittent or continuous and can vary from a slight haze to the large vapor pocket associated with jetting. As velocities decrease and pressures rise downstream, the vapor bubbles collapse. The collapse of the cavity may create erosion damage or serious vibrations.

and air-entrainment. Elevated temperatures reduced air-entrainment by vortices. Photograph 5063 illustrates a condition where the upper portion of the test channel did not flow full.

Figures 32 through 40 are sections cut from the taped records. These are typical of the many records taken. However, the tapes selected are either those for the rated discharge of the orifices, Table 1, or they illustrate some significant operational characteristics.

REQUIREMENTS

Prototype requirements can be summarized as follows:

1. Total flow of 200,000 gpm.
2. Effluent back pressure not greater than 490 with 200,000 gpm.
3. Temperature of 99°C. with the above flow rate.
4. Pressure at P_4 not less than the vapor pressure of zero at 99°C.
5. Tenth row of channels free of flow which requires a water surface elevation of not more than 523.9 at the entrance from the approach tank to the downcomer.
6. Excess energy at P_5 as low as possible to be consistent with the above requirements.

The above are the critical requirements but the downcomer must operate at lower temperatures and flow rates.

Model data were evaluated and compared with the above requirements by the following procedures:

1. Data were scaled to prototype values and corrected for excess model friction.

2. A maximum value of P_2 was assumed to be elevation 523.9 plus the velocity head in the approach tank. The minimum value of P_4' was assumed to be zero feet. In some cases it was necessary to estimate P_4' from P_4 data.
3. The value of $P_2 - P_4$ was computed and the maximum flow for the test channel read for this value on the $P_2 - P_4$ versus Q curve for the orifice. (For Orifice 2 use Figure 7.)
4. The total flow rate was obtained by multiplying a ratio $\left(\frac{\text{holes in use}}{\text{holes in test channel} = 14} \right)$ times the test channel flow.
5. The effluent back pressure corresponding to this rate of flow was obtained from Figure 31.
6. The maximum effluent back pressures from (5) above was compared with the model data by entering the P_4 versus P_5 plot with a value of P_4 or P_4' used in (2) above. (For Orifice 2 use Figure 23.)
7. If the effluent back pressure obtained from (6) was lower than the allowable in (5), then it was necessary to reduce the flow rate until equality was obtained. As a result P_4' increased. However, if the effluent back pressure from (6) exceeded that from (5), then the flow was correct, but jetting occurs between P_4 and P_5 and a flow discontinuity exists.

Table 1 gives results of the above analyses for each orifice plate.

TABLE 1 - MAXIMUM FLOW RATES FOR ORIFICES TESTED

Orifice No.	Q Test Channel gpm	$V^2/2g$ Test Channel feet	$P_2 - P_4$ Drop in H.G.L. feet	P_4 Actual feet	* Total Q gpm	Effluent Back Pressure		Holes in Use Est.	Rows in Use Est.	$P_2 - P_5$ Loss feet
						Fig. 31 El. H.G.L.	P_4 vs. P_5 El. H.G.L.			
1	9,000	5.2	45.9	+15.0	181,000	484.6	491.3	282	9	Indeterminate
2	11,300	8.8	45.5	+18.0	200,000	489.3	490.8	237	7+	39.5
5	11,700	8.8	48.3	+15.0	200,000	489.3	490.9	239	7+	41.5
6	8,750	4.7	46.4	+14.0	176,000	483.2	496.0	282	9	Indeterminate

NOTES:

P_4 = zero

Maximum Water Surface Elevation in Approach Tank = 523.9

No. of Holes in Nine Rows = 282

- Orifice No. 1 - Cavitation and Jetting.
- Orifice No. 2 - Slight Cavitation.
- Orifice No. 5 - Slight Cavitation.
- Orifice No. 6 - Cavitation and Jetting.

* Number of Holes in Use x Test Q.
14

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SAMPLE CALCULATION FOR TABLE 1.

Data

Total Flow: 200,000 gpm

Operating Temperature: 99°C.

Vapor Pressure at 99°C. = zero feet of water. (Elevation 500)

Elevation of Division web between Row 9 and Row 10 of channels is 523.8.

Effluent Back Pressure at P_5 = 489.3 Elevation of Hydraulic Gradient, Figure 31.

Consider Orifice No. 1

1. $P_4' =$ zero feet of water from above.
2. Assume the flow for the test channel to be 9,000 gpm.
3. Using data for Orifice No. 6, Figure 30. P_4 should be about 15 feet greater than P_4' . $\therefore P_4 = 15.0$ feet.
4. $\frac{v^2}{2g}$ for 9,000 gpm = 5.2 feet = $\frac{1}{2g} \left[\frac{Q}{A} \right]^2 = \left[\frac{9,000}{448} \right]^2 \cdot \frac{1}{1.1} \cdot \frac{1}{2g}$
5. Energy Level at entry assuming water level is at 523.9.
523.9 + 5.2 = 529.1

6. $P_2 - P_4$ drop in hydraulic gradient.

Elevation P_4 tap	468.2	529.1	Energy level at ent
Pressure @ P_4	<u>15.0</u>	<u>483.2</u>	
	483.2	45.9 = $P_2 - P_4$	

7. Enter Figure 10 with $P_2 - P_4 = 45.9$ and read $Q = 9,000$ gpm from model curve.
8. Enter Figure 13 with $P_4 = 15.0$ feet and read the Effluent Back Pressure, $P_5 = 491.3$.

9. Obtain total flow: $9,000 \frac{282}{14} = 181,000$ gpm.
10. Read effluent back pressure for this total flow, Figure 31, BBP = 484.6.
11. BBP from Step 10 is less than BBP from Step 8; therefore, cavitation and jetting will occur.

Consider Orifice No. 5

1. P_4 limit = zero feet.
2. Total Flow desired = 200,000 gpm.
3. Effluent Back Pressure for 200,000 gpm = 489.3, Figure 31.
4. Assume nine rows full Test Channel $Q = \frac{14}{282} 200,000 = 9,900$ gpm.
5. From Figure 12, $Q = 9,900$: $P_2 - P_4 = 36$ feet.
6. Compute P_4 for nine rows full:

523.8 Water Level in Approach Tank

6.4' $\frac{V^2}{2g}$ for 9,900 gpm.

530.2 Energy Gradient at Entry

468.2 Elevation of P_4 Tap

62.0' P_2 referred to P_4 Tap

36.0' $P_2 - P_4$

26.0' P_4

7. Revise Q upward since P_4 is too large. Figure 12 gives

$Q = 11,000$ gpm. $P_2 - P_4 = 43.3'$.

8. Compute P_4 for the values in (7) above:

523.2 Water Surface Elevation. 8 rows assumed full.
7.7 $\frac{v^2}{2g}$ for 11,000 gpm.

530.5 Energy Gradient at Entry.

43.1 $P_2 - P_4$

487.6 Hydraulic Gradient at P_4 .

468.2 Elevation P_4 Tap.

19.4' P_4

9. Figure 24 shows EBP 495.5 for $P_4 = 19.7'$.

10. P_4 to agree with EBP of 489.3 feet. $P_4 = 13.3$ feet, Figure 24.

This gives P_4' of $(-)$ 1.7 feet; therefore, P_4 must be 15.0 feet.

11. Recompute $P_2 - P_4$:

11. P_4 Tap = 468.2
 P_4 = 15.0
 483.2

7 rows full

11,550 gpm

W.S.El. = 522.7

$\frac{v^2}{2g}$ = 8.8

531.5

483.2

$P_2 - P_4 = 48.3$ feet

12. Figure 12 gives $Q = 11,700$ gpm for $P_2 - P_4 = 48.3$ feet..

13. Summary:

P_4' = zero feet
 P_4 = 15.0 feet. Figure 30.
EBP = 490.6. Figure 24 approximate Q.
Q = 11,700 gpm.
 $P_2 - P_4$ = 48.3 feet. Figure 12.

468.2

15.0

483.2

48.3

531.5

8.8

522.7 Water Surface Elevation

∴ Q is between 11,700 and 11,650 gpm.

$P_2 - P_4$ is between 48.3 and 48.0 feet.

CONCLUSIONS

Theoretically, both the model and prototype orifices have too long a cylindrical edge to guarantee flow characteristic of a sharp-edged orifice. Instabilities observed during the testing are believed to be due to the long cylindrical edges on Orifices 1 and 2. With 14 holes in the test plate and a potential for each to behave as a sharp-edged orifice or a short tube, their composite behavior can neither be predicted nor duplicated, except by chance.

From the model behavior, it might be anticipated that a dangerous condition could develop in the prototype with increased flow rate and/or temperature. If the orifices in the plate function as a series of short tubes at an existing flow rate and temperature, an increase in flow rate or temperature could produce separation

in the tube and force the openings in the plate to behave as sharp-edged orifices. This would require more head to force the same flow through the plate. Consequently, the water level in the approach tank and the back pressures in the risers would increase sharply.

It must be concluded that the model tests of orifices in 'thick' orifice plates will give results having such wide scatter as to limit predictions of prototype performance to 300% variation when the scatter factors also influencing the data. It appears that little can be achieved by comparing model and prototype data unless the scatter factors are known to be non-existent in the prototype data.

Visual observations of the flow indicated that pressures adjacent to the orifice plate were considerably lower than at P_4 . This was expected, since the lowest pressure should occur at the vena contracta which is located one-half to one orifice diameter downstream of the upstream edge of the plate. A new tap, P_4' , was installed and the results confirm the visual and theoretical conclusions, Figure 30.

Discontinuities in the flow are responsible for some scatter of the data, however, these data are not included in the correlations. Factors causing scatter are listed below:

1. Entrained air
2. Channel not full in the upstream portion.
3. Jetting downstream of the orifice plate sufficient to effect the loss between the plate and P_5 .
4. Cavitation downstream of the plate sufficient to effect the pressure at P_4 . With a vapor pocket P_4 equals P_4' .

The influence of temperature is dramatic when the minimum pressure downstream of the orifice plate is at or near the vapor pressure of the fluid. Tape records, Figures 36 and 37, illustrate this.

The data obtained by the model tests are in good agreement with the theoretical curves. See Figures 1 through 13. The theoretical curves drawn here have been extracted from HW-WSU-1 (Rev. 1).

Analysis of the data, Table 1, indicates that either Orifice 2 or 5 is satisfactory. One must consider the following factors in arriving at a final decision:

1. Are the assumptions fully justified?
2. Has the minimum pressure downstream of the orifice been accurately estimated?
3. It is correct to use an average minimum pressure downstream of the orifice or should a percent of time less than this minimum be used as the criteria? Figure 39 gives an indication of the variation which may be expected at the minimum pressure point.

RECOMMENDATIONS

The recommendations which follow are tempered with the reservation that our knowledge of the operating conditions is incomplete.

Observed high water levels in the approach tank for the prototype may be due either to the orifice restricting the flow or to the approach conditions restricting the flow. The model tests indicate that orifices of the 2.875-inch diameter will not be restrictive at flows less than 200,000 gpm. It is recommended, therefore, that the approach tank and entry conditions be model tested to determine the amount and nature of their restrictions.

From the model tests either Orifice 2 or 5 is suitable for the prototype. If Orifice 2 is selected, it is recommended that the downstream portion of the holes be beveled to meet the requirements for sharp-edged orifices.

It is recommended that, if size changes are required due to revised specifications, theoretical pressures be computed as was done in HW-WSU-1 (Rev. 1). The limitations can then be applied to these theoretical curves to determine maximum permissible flows. Some adjustment of the theoretical curves may be suggested by the model tests, but extrapolation of model data without theoretical basis is not recommended.

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3M-VSU-4

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HW-WSU-4

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TABLE 2 - DATA FOR PHOTOGRAPHS

	Photograph Numbers													
	4924	4988	4989	4990	5020	5024	5061	5063	5069	5071	5073	5074	5075	5076
Flow rate in test channel	6,900	12,500	12,500	12,500	9,600	9,600	11,200	7,800	11,200	11,400	11,400	11,400	9,650	9,650
Effluent Back Pressure	476.6	495.8	495.8	495.8	444.8	482.6	487.4	489.8	494.6	489.8	487.4	485.0	499.4	479.6
Temperature Op.	208	206	206	206	210	204	95	185	205	205	205	205	205	205
Orifice Plate Number	1	2	2	2	6	6	5	5	5	5	5	5	5	5
Notations:														
Air Entrained	No	No	No	No	No	No	Yes	Yes	No	No	No	No	Yes	Yes
Cavitation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Trace	Yes	Yes	Yes	No	Yes
Jetting	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	No	Yes
P ₄	1.2	-6.0	-6.0	-6.0	-6.0	-6.6	10.8	15.6	16.8	4.5	-6.0	-7.2	27.0	-4.5
P ₂	4.2	21.0	21.0	21.0	18.0	16.8	10.2	3.0	15.6	14.4	12.6	12.0	10.2	4.5

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ALBUQUERQUE LABORATORY WASHINGTON STATE UNIVERSITY	
LOSSES TO ORIFICE	
ALL DATA	
OR. NO.	MLB
DATE	5-22-61
IN. FT.	1/2
CRIMP	1/2
APPS	1/2

FIGURE 1

LOSS APPROACH TANK TO ORIFICE
 $(P_2 - P_3)$
FEET OF WATER

Q (1,000) gpm

FIGURE 3

ORIFICE THAT WAS USED

ALBUQUERQUE HYDRAULIC LABORATORY			
WASHINGTON STATE UNIVERSITY			
LOSS DUE TO ORIFICE			
ORIFICE 5			
DR. BY	MLB	DATE	5-6-81
TR. BY		CHECKED	609-A
SCALE		APPROVED	26

HW-WSU-4

DEFINITION

ALBUQUERQUE HYDRAULIC LABORATORY			
WASHINGTON STATE UNIVERSITY			
LOSS DUE TO ORIFICE			
ORIFICE 6			
DR. BY	MLB	DATE	6-6-61
PL. BY		CHKD.	
SCALE		APPR.	
			DWG. NO.
			609-A-23

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HW-NSU-4

HW-WSU-4

9 ENGLIS

LOSS APPROACH TANK TO EFFLUENT ELBOW

FIGURE 7

$P_2 - P_5$

1000000

Q (1,000) gpm

FIGURE 8

LOSS APPROACH TANK TO EFFLUENT ELBOW

$P_2 - P_1$

511-587-17

FIGURE 6

10/11/51

PRESSURE DROP TO VENA CONTRACTA

$$P_2 - P_4$$

ALABAMA HYDRAULIC LABORATORY	
WASHINGTON STATE UNIVERSITY	
PRESSURE DROP TO VENA CONTRACTA	
ORIFICE 2	
DATE: 6-2-61	BY: M.L.B.
CHD: 609-A	TR. BY: 1B
SCALE: 1B	

HW-WSU-4

FIGURE 11

11/11/1977

FIGURE 12

39
PRESSURE DROP TO VENA CONTRACTA

FIGURE 13

ALBION HYDRAULIC LABORATORY			
WASHINGTON STATE UNIVERSITY			
PRESSURE AT VENA CONTRACTA			
ORIFICE 6			
DR. BY	M. L. B.	DATE	5-29-60
PL. BY		COND.	609-A
SCALE		APPROX.	4

HW-WSU-4

FIGURE 14

FIGURE 15

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P_2
ELEVATION OF HYDRAULIC GRADIENT

ALUMINUM HYDRAULIC LABORATORY	
WASHINGTON STATE UNIVERSITY	
P_1 vs P_2	DRIFTS 2
0.500 - 1.500	0.500 - 1.500
MLB	DATE: 5-31-81
IN. NO.	600-A
SCALE	10

43

FIGURE 17

HW-WSU-4

HW-WSU-4

FIGURE 19

FIGURE 20

FIGURE 21

48

P_4 IN FEET OF WATER

FIGURE 22

ALBION HYDRAULIC LABORATORY			
WASHINGTON STATE UNIVERSITY			
B vs P_4			
ORIFICE 1			
11,200 gpm			
DR. BY: M. B.	DATE: 6-6	600-A	17
TD. BY:	CHD:	600-A	
SCALE:	AMPL:		

HW-WSU-4

P_2
ELEVATION OF HYDRAULIC GRADIENT

F_1 , IN FEET OF WATER

FIGURE 23

FIGURE 25

P_4 , IN FEET OF WATER

P_5

CORTEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS.
PRINTED IN U.S.A.

11 WAYS BUY 10 DIVISIONS.

P₅
ELEVATION OF HYDRAULIC GRADIENT

P₄, IN FEET OF WATER

HW-WSU-4

FIGURE 28

HW-WSU-4

FIGURE 29

DATA CODING

Temperature	Valid Data		Questionable Data	
	P_4	P_4'	P_4	P_4' †
205°F.	△	▽	▲	▼
185°F.	□	◇	■	◆
95°F.	○	◯	●	◐

∴ Small dots inside a symbol indicate multiple points.

C Common curve for comparison purposes.

P Model data scaled to prototype and corrected for excess friction.

T Theoretical curve from HW-WSU-1 (Rev. 1):

Q Flow rate in gpm prototype for test channel.

† Data taken at P_4 location during jetting are indicated by these symbols since $P_4 = P_4'$ during jetting.

Pressures are in feet of water prototype except P_5 values which are elevations of hydraulic gradient; they are identical to Effluent Back Pressures.

_____ Theoretical Curves

_____ Model Data Curves

- - - - - Model Data Curves Corrected for
Excess Model Friction

- - - - - P_4' Curves

_____ P_4' Curves Corrected for Excess
Model Friction

RECEIVED

FIGURE 30

RUN 15

HW-W50-4

ALSBACH HYDRAULIC LABORATORY		
WASHINGTON STATE UNIVERSITY		
RUN 3-15	Q = 0.550 gpm	
Orifice No. 1		
Orifice	0.550	
Area	0.001	
Flow	34

180°F
2.5°F

[REDACTED]

ALBROOK HYDRAULIC LABORATORY		
WASHINGTON STATE UNIVERSITY		
Rm. E-13 G-17, 500 th Ave.		
Office A6-2		
DR. BY: E	DATE: 5-6-61	FILE: A
TR. BY:	TIME:	609-A
SCALE:	APPROX:	12

Fig. 33

ALUMINUM HYDROLYSIS LABORATORY		
WASHINGTON STATE UNIVERSITY		
Run 9-16 Q = 11,200 gpm		
Dr. Fred No. 2		
Dr. No. 2	Run 5-5-67	609-5
RETRY	CRIP	9
YOUNG	DATE

180°F

increase

12.5°F

61

Fin 24

ALUMINUM THERMISTOR		
WASHINGTON STATE UNIVERSITY		
RUN 10-5	Q = 16,400 gm	
Ch. Pice No. 2		
DATE	TIME	TEMP.
10-5-51	10:00	209-A
10-5-51	10:00	35

10 sec. 205°F
 62 Increase 25°F
 Fig. 35

2

3

(-)
(+)

5

6

Unstable due to temperature variation

(-)
(+)

1

2

2

(-)
(+)

(-)
(+)

2

1

5

ALBION STEERING LABORATORY	
WASHINGTON STATE UNIVERSITY	
Run 10-16 Q=9450 sp	
Orifice No. 2	
DR. BY: S	DATE: 5-5-61
TR. BY:	60913
SCALE:	-12

(-)
(+)

2

6

0

205°

5 sec

Picture
4995

increase
2.5°F

DATE 12/5/65

1

1

2

(-)

2

2'

(+)

3

3

2'

(+)

(-)

4

4

1'

(+)

5

5

1'

(+)

14

WASHINGTON STATE UNIVERSITY		
Run 11-12 Q = 32.55		
QUALITY No. 5		
DATE	TIME	TEMP.
12/5/65	10:00	40A-A
COND.	WIND	33

90°F

2.5"

INCREASING

10' sec.

2

3

ALBION HYDRAULIC LABORATORY		
WASHINGTON STATE UNIVERSITY		
Run 13-4 Q = 11,200 gpm		
Orifice No 5		
OR. NO. 2	DATE 10	TIME 10
IN. BY	CHAS.	664-8
SCALE	APPROX.	8

10 sec 1 sec

[REDACTED]

1

2

(-)
(+)
2'

2

3

(-)
(+)
2'

3

4

(-)
(+)
1'

[REDACTED]

5

(-)
(+)
4'

UNIVERSITY OF CALIFORNIA	
DIVERSITY STATE UNIVERSITY	
Run 5-8	4-11-50
Office No. 5	
1	2
3	4
5	6
7	8
9	10

6

205°F
Increase
25°F

6

INFORMATION ON TAPED DATA SHEETS

1. A time scale is shown on each tape.
2. The temperature base and scale per division are shown on each tape.
3. Trace 1 is for P_1 , trace 2 for P_2 , trace 3 for P_3 , trace 4 for P_4 , trace 5 for P_5 , and trace 6 for the temperature, except for Figure 39, where trace 3 is for P_3' and trace 4 for P_4' .
4. Pressure zeros, (+) and (-) directions of deflection, and the actual model pressure per division are shown. Prototype pressures will be three times the model values.

Ref. Dwg. 609-C-5

09-C-5

⑤

— DRILL $\frac{1}{8}$ " TAP FOR $\frac{1}{4}$ " SWAGelok
FLUSH WITH INSIDE WALL.

DETAIL I

SCALE: 3" = 1'-0"

	PC	DESCRIPTION	MAT	NO REQ
△	1	10 GAUGE	STEEL	25 Sf.
△	2	$\frac{3}{8}$ " PLATE	"	4
△	3	3" x 12"	SIERRACIM	8
	4	REDUCER FROM ROUND TO RECT.	STEEL	1
△	5	$\frac{3}{16}$ x $8\frac{1}{4}$ " x $6\frac{3}{8}$ "	BRASS	1
△	6	$\frac{3}{8}$ " Tube to $\frac{1}{4}$ " Pipe Swage Lok	BRASS	3
	7	3' x 3' x 1' 10ga.	STEEL	40 Sf.
	8	4" THINWALL PIPE	"	50 ft.
△	9	1" SCH 40 PIPE	"	10 ft.
	10	Gasket $\frac{1}{8}$ "	Neoprene	3
	11	$\frac{3}{8}$ -16 NC x $1\frac{1}{2}$ " Bolt	steel	40
	12	$\frac{3}{8}$ -16 NC Nuts	steel	40
	13	4" Gate Valve	steel	1
	14	Flange 4" Thinwall	steel	4
	15	Gasket $\frac{1}{8}$ "	Neoprene	4
	16	6" Gate Valve	steel	1
	17	6" Thinwall Pipe	steel	7 L.F.
	18	6" Pipe Flange	steel	2
	19	6" Pipe Gasket	Neoprene	2
	20	$\frac{3}{4}$ -10 NC x $1\frac{1}{2}$ " Bolt	Steel	16
	21	$\frac{3}{4}$ -10 NC Nuts	Steel	16
	22	$\frac{5}{8}$ -11 NC x $1\frac{1}{2}$ " Bolt	Steel	24
	23	$\frac{5}{8}$ -11 NC Nuts	Steel	24

	PC	DESCRIPTION	MAT	NO REQ	SOURCE
△	1	10 GAUGE	STEEL	25 Sf.	O.H.
△	2	$\frac{3}{8}$ " PLATE	"	4	See Dwg. 609-C-2
△	3	3" x 12"	SIERRACIN	8	See Dwg. 609-C-3
	4	REDUCER FROM ROUND TO RECT.	STEEL	1	Fabricate
△	5	$\frac{3}{16}$ x $8\frac{1}{4}$ " x $6\frac{3}{8}$ "	BRASS	1	See Dwg. 609-C-2
△	6	$\frac{3}{8}$ " Tube to $\frac{1}{4}$ " Pipe <small>Swage Lok</small>	BRASS	3	See Dwg. 540-B-2 Type 2
	7	3' x 3' x 1' 10ga.	STEEL	40 Sf.	O.H.
	8	4" THINWALL PIPE	"	50 ft.	O.H.
△	9	1" SCH 40 PIPE	"	10 ft.	O.H.
	10	Gasket $\frac{1}{8}$ "	Neoprene	3	See Dwg. 609-C-2
	11	$\frac{3}{8}$ -16 NC x $1\frac{1}{2}$ " Bolt	Steel	40	" " "
	12	$\frac{3}{8}$ -16 NC Nuts	steel	40	" " "
	13	4" Gate Valve	steel	1	O.H.
	14	Flange 4" Thinwall	steel	4	See Sta.-B-1
	15	Gasket $\frac{1}{8}$ "	Neoprene	4	O.H.
	16	6" Gate Valve	steel	1	O.H.
	17	6" Thinwall Pipe	steel	7 L.F.	O.H.
	18	6" Pipe Flange	Steel	2	See Sta-B-1
	19	6" Pipe Gasket	Neoprene	2	O.H.
	20	$\frac{3}{4}$ "-10 NC x $1\frac{1}{2}$ " Bolt	Steel	16	O.H.
	21	$\frac{3}{4}$ "-10 NC Nuts	Steel	16	O.H.
	22	$\frac{5}{8}$ "-11 NC x $1\frac{1}{2}$ " Bolt	steel	24	O.H.
	23	$\frac{5}{8}$ "-11 NC Nuts	Steel	24	O.H.

TOGETHER

Ref. Dwg.
609-C-5

E

ELEV
SCALE

ELEVATION
 SCALE: 1/2" = 1'

4.2
 1.8

PEAK AT CORNER

SECTION A-A
SCALE - FULL

DETAIL
SCALE

NOTE 1: SEE

DET.
SCALE

PC	DESCRIPTION	MA
24	12" THINWALL PIPE	ST

4	PF
3	SE
2	A DIM CHA
1	Det to Adc

Alteration

WASHI
INST
DIVISION

THE R. L

CH

DR. BY LH

CHKD. BY E

NOTE 1: SEE DWG 609-C-3 FOR DETAILS

DETAIL 2
SCALE 2" = 1'-0"

DETAIL 3

SCALE 3" = 1'-0"

AP FOR $\frac{1}{4}$ " SWAGELOK
WITH INSIDE WALL.

	PC	DESCRIPTION	MAT	NO REQ	SOURCE
②	24	12" THINWALL PIPE	STEEL	7 ft	

④	PRESSURE PICKUP ADDED	6-9-61
③	SEE DWG 609-C-5 REV. ②	1-16-61
②	ADD 12" THINWALL PIPE, DIMENSION ON OVERFLOW HEIGHT CHANGED TO 4'	1-30-61
①	Details, Pc. No's & Sects. Added to Elev. View. Detail & Pc. No's, Added to Def. 3.	1-16-61
Alteration	Description	Date

WASHINGTON STATE UNIVERSITY
INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL RESEARCH

THE R. L. ALBROOK HYDRAULIC LABORATORY

DOWNCOMER CHANNEL DETAIL

DR. BY LH

TR. BY _____

DATE 1-11-60

CHKD. BY E

SCALE AS SHOWN

DWG 609-C-4

2 R DETAILS

DATE

FILMED

8/26/94

END