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A Joint Venture for Heavy Water Organic Cooled Reactors

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AUTHOR L. D. Felten* 141
R. B. Cassidy 1208
J. W. Dodd 140
DEPT & GROUP NO. 736-62

TITLE
HWOCR MULTICHANNEL CROSS FLOW STUDIES

PROGRAM

HWOCR

SUBACCOUNT TITLE

Hydraulic and Mechanical Tests

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STATEMENT OF PROBLEM

Determine quantitatively cross flow, velocity profile and mixing in a multichannel cross flow test section of HWOCR finned fuel pins.

ABSTRACT

Velocity measurements have confirmed that the velocity profile is essentially flat over the tricuspid and side flow channels of the multichannel test section used for the present experiment.

The ratio of cross flow to axial flow for the tricuspid channel was $0.65 \times 0.16 \text{ ft}^{-1}$ which is equivalent to $0.44 \pm 0.11 \text{ lb/sec ft}$ for 120°F water at a velocity of 26 ft/sec . This value is not significantly different from the similar measurements made on the dual channel test of reference 1.

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I. OBJECTIVE

The objective of this test is to measure the interchannel cross flow and velocity profile within a 10 pin HWOCR partial fuel bundle assembly. The multichannel assembly will allow cross flow to be measured between the center channels which are unperturbed by edge effects.

II. DESCRIPTION

Tests will be performed with the multichannel test section. Flow velocity and pressure drop information will be recorded for flows between 60 and 120 gpm, which correspond to velocities between 15 ft/sec and 30 ft/sec. The nominal velocity for cross flow and mixing studies is 22 ft/sec. Data acquisition and reduction will be performed as described in reference 1. In general this is a continuation of efforts reported in reference 1.

A. Test Methods

The velocity profile measurements will be performed by the correlation technique which is described in reference 2.

The cross flow measurement test method uses the proportionality between electrode resistance and tracer salt concentration to determine the cross flow. A DC recording at each cell in the central tri-cusp channels for tracer injection in one channel will yield the tracer concentration change in each channel and therefore the cross flow. Of primary interest will be the magnitude of cross flow.

B. Test Section

A specially constructed ten pin multichannel test section will be used during this test. This test section has been assembled to close tolerances with rigid quality control. Both pressure taps and conductivity cells are used for multiple parameter measurements. Seven conductivity cells are located at six inch intervals in each of ten flow channels; channels 1, 2, 5, 6, 9, 10, 11, 12, 13, and 14 as shown in Figure 1. The first electrode is located $5\frac{1}{2}$ inches above the top of the lower grid plate. A specially designed 14 channel spider injection ring has been designed with individual valves and pressure indicators. This arrangement allows injection into any or all channels and ensures by pressure equalization even tracer injection. A sketch of the test section is presented in figures 1 and 2.

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The dimensions of the elements, and the test section are given in Table 1. The calculated individual flow areas for partial channels and the tri-cusp channels are also shown in Table 1. The calculated total net flow area for this section is 1.27 in². Each tube in the array has twelve spiral fins at a pitch of 90° per ft.

TABLE I

Element Dimensions (Center)

OD of Cladding	=	0.512"
ID of Cladding	=	0.455"
OD, Fin to Fin	=	0.642"
Fin Width	=	0.039"
Fin Height	=	0.065"

Individual Flow Areas Calculated

	<u>No. of Ch.</u>	<u>Total Areas</u>
Tri-Cusp Channel = 0.0603 in ²	10 ea	0.603 in ²
Wall Channels = 0.0879 in ²	4 ea	0.3516 in ²
Partial Channels = 0.0302 in ²	4 ea	0.1208 in ²
Additional area at edges		0.197 in ²

$$\text{Total } A_F = 1.272 \text{ in}^2 \text{ or } 0.00884 \text{ ft}^2$$

C. Test Loop

The test will be performed in the large (500 GPM) test loop in Building 049 (Santa Susana). This loop is diagrammed in figure 3. The loop will use water as a circulating fluid and the temperature of the water will be held constant at 120°F.

III. ANALYSIS

As derived in reference 1 the cross flow can be related to concentration by the relation:

$$Q_1 \frac{dK_1}{dz} = \frac{Q_c}{\Delta Z} (K_{10} + K_2 + K_9 - 3K_1)$$

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where

Q_1 = axial flow in channel 1

$Q_c/\Delta Z$ = cross flow between channels per unit length

K_1 = salt concentration in channel 1

K_{10}, K_2, K_9 = salt concentration in channels which connect with channel 1

An equation of the above type can be written for each channel of the test section. This results in a total of 18 coupled linear differential equations when the four partial channels are included. The solution of these equations in terms of unknowns is an insurmountable problem. However, assumptions of similarity can be made for special cases, and these solutions can be approximated for the channels of interest.

As an example, for salt injection into channel 1 (see figure 1), one can assume that salt concentrations in the adjacent channels 2, 9 and 10 behave identically and that the concentrations in channels 3 and 14 behave identically. With the further boundary assumption that channels 3 and 14 interchange only with channel 10, we can then solve for the concentration in the three unique channels 1, 10 and 3. The results for the normalized concentration are:

$$K_1 = 1/10 - \frac{2}{5} e^{-5Q_c z / \Delta z Q_1} + \frac{1}{2} e^{-2Q_c z / \Delta z Q_1}$$

$$K_{10} = 1/10 - \frac{4}{15} e^{-5Q_c z / \Delta z Q_{10}} + 1/6 e^{-2Q_c z / \Delta z Q_{10}}$$

$$K_3 = 1/10 + \frac{1}{15} e^{-5Q_c z / \Delta z Q_3} - 1/6 e^{-2Q_c z / \Delta z Q_3}$$

These results will be compared with the concentrations measured in channels 1 and 10 to estimate the cross flow term $Q_c/\Delta Z$. This estimate can then be used as a first trial to numerically solve the 18 coupled equations exactly with a computer. The computer value of cross flow can then be varied to match the concentration change to that actually measured.

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Dynamic similarity between the water and organic system are achieved when the Reynolds numbers are equal. Santowax OM containing 10% HB has a kinematic viscosity of 0.43×10^{-6} ft²/sec (ref. 5). To match this part of the Reynolds number would require a water temperature of 165°F which was not attainable with the present test section. Reynolds numbers for the 120°F water used in the test are equivalent to organic Reynolds number with velocity 2/3 that of the water system. Fortunately, unlike natural mixing effects, forced cross flow with fins is only negligibly dependent on Reynolds similarity as outlined below. Cross flow is expected to be directly proportional to axial velocity over the range of the test. Neither the present tests nor the previous dual channel tests (ref. 1) showed a definite relationship of cross flow to axial flow ratio with Reynolds number. This would be expected from the formulation developed by Rogers (ref. 6) for forced cross flow in which the Reynolds number appears to the $n/3$ power. "n" is the dependence of friction factor on Reynolds number and has a value of 1/5 for turbulent flow. Thus, the Reynolds number appears to the 1/15 power in the correlation.

IV. EXPECTED RESULTS

The interchannel cross flow is not expected to be appreciably different from that reported in reference 1, which gives a value of 0.33 lb/sec for $Q_c/\Delta Z$ for an axial velocity of 26 ft/sec. Typical concentration profiles are shown in Figure 4.

The axial velocity distribution is expected to be very nearly flat except for the four partial channels at the corners which should have velocities about 12% lower than the average.

V. PROCEDURE

A. Checkout

1. Set up and check out test loop and test loop instrumentation. All flowmeter, pressure indicators and manometers should be calibrated and indicating. Fill test loop with fresh (non-salted) water. Maintain flowing water at 120°F.

2. Set up and calibrate data acquisition equipment. Balance amplifiers and calibrate tape recorder center frequencies. Check out and calibrate digital recording system. Optimize scanning rate for maximum data per unit time and minimum scatter. Connect appropriate cells to signal conditioning circuitry.

B. Local Velocity Measurement

1. Record conductivity cell variations for each specified flow condition in each channel. Two adjacent tri-cusp channels or fourteen cells will be recorded for a given flow rate at any one time. Several tri-cusp channels will be used for optimum analysis. Tracer injection channels are the order in which they are run is given in the run list, Table II.

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C. Mixing Measurement

1. Set signal conditioning oscillator at 1000 cps and calibration channel at 2000 ohms.
2. Before each test condition, record cell resistance variations on 21 cells in three specified tri-cusp channels with no salt injection. These runs were not used in the final analysis and are not recorded in Table III.
3. Record cell resistance variations for a specified injection channel for each test condition. The cells recorded, tracer injection channels and flow rates are given in the run list, Table III.
4. The tracer injection cycle for each test condition is off for 3 data scans, on for 3 scans, and off for 3 scans.

D. Data Acquisition

1. The following quantities will be recorded for each run.
 - a) Water temperature
 - b) Flow
 - c) Pressure drop
 - d) Conductivity cell signals

The pressure drops are measured by manometers, the flow by orifice flowmeters and the temperatures by a thermometer.

2. The correlation method employs a tape recorder, signal conditioner and differential amplifiers as described in reference 2.

3. The DC resistance method for evaluating cross flow employs a Hewlett Packard (Model DY-2010B) digital data acquisition system. An oscillator, constant current source, digital voltmeter and a digital printer make up the basic unit. The system produces an AC voltage that is proportional to resistance. A diagram of the system used is shown in figure 5.

E. Data Reduction

1. Local Velocity Measurement

Each set of data recorded on magnetic tape is cut into loops and analyzed. The data is electronically correlated and transit time measurements between any pair of electrodes determined. These transit times will be analyzed and compared to determine velocity profile. A description of the electronic correlator is presented in reference 2.

2. Mixing Measurement

This method uses the proportionality between electrode resistance and tracer concentration to determine mixing ratio. The cell resistances are first corrected because of data system non-linearities. These non-linearities are due to known input impedances and internal shunt capacitance in the acquisition system. Resistance measurements for three channels are taken before and during tracer injection. Concentration of salt tracer is inversely proportional to resistance. The concentration change ΔC is

$$\Delta C = k(1/R_I - 1/R_O)$$

The proportionality constant is removed by dividing the concentration change for single channel injection by the concentration change for injection in all channels. The manipulation also normalizes individual cell characteristics. At this point the data is a number of normalized concentration changes as a function of axial channel distance and have the appearance of figure 4. The data is then fitted (ref. 4) with an exponential of the form

$$C/C_O = A \pm B \exp(-CZ) \pm D \exp(-EZ)$$

From the derivation, the cross flow ratio is then

$$Q_X/Q_Z \Delta Z = f_1(C) \mp f_2(E)$$

and an estimate can be determined according to the method described in Section III.

VI. RESULTS

The results of the velocity measurements are given in Table II. The velocities calculated from the flowmeter reading and flow area are approximately 10% higher than the velocities measured by the correlation method. This difference is discussed further in the next section. The individual transit times and correlation coefficients are tabulated in Appendix I along with the resulting average velocity both before and after being corrected for conductivity cell effects. The standard deviation of the corrected velocity is also given.

The cross flow results are shown in Table III. Run numbers missing from the sequence are those for which there was no salt injection and the data was not used in the final analysis. The normalization runs for which salt was injected into all channels either at the needles or from upstream do not give cross flow measurements. The remaining blanks in the cross flow column of Table III are for channels other than the center channels, 1 and 2, where edge effects prevented a good measurement.

The average ratio of cross flow to axial flow as determined by channels 1 and 2 is $0.75 \pm 0.25 \text{ ft}^{-1}$. The single channel injection data is considered to be more accurate and gives an average cross flow ratio of $0.65 \pm 0.16 \text{ ft}^{-1}$. This is equivalent to a cross flow of $0.44 \pm 0.11 \text{ lb/sec ft}$ of 120°F water. Plots of cross flow data normalized to the theoretical model are shown in Appendix 2.

The pressure drop through the test section is shown in Figure 6 as a function of velocity.

Details of the runs are recorded in Atomics International notebooks B316101 and B299401.

VII. DISCUSSION OF RESULTS

A. Velocity Measurements

The velocity measurements shown in Table II confirm the prediction that the tricuspid flow channels and the side channels have essentially the same velocity. The measured channel velocities were determined by averaging the last four transient time measurements up the flow channel. Six transit time measurements are possible for each instrumented flow channel. The first measurement, however, is usually non-existent or not useable because of the low correlation coefficient between the first two electrodes after the grid plate. With the conductivity electrodes spaced at six inch intervals every other electrode is located in a fin and the remaining ones between the fins. These two different types of electrodes may have slightly different time constants and thus have an effect on the transit time data. Much of the data does indeed show a trend of alternate high and low transit time measurements. Because of this, only the last four measurements were used so as to average an equal number of high and low measurements.

The measured transit times are corrected for flow distribution in the channel. This correction has been determined experimentally as a function of Reynolds number and is reported in reference 3. The fuel pins of reference 3 had the fins machined off around the area

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of the electrode and the electrode was then flush with the cladding. The validity of the correction constants for electrodes in the fins and between the fins should be determined during the next single channel or dual channel test.

The standard deviation of the transit times measured in a channel varied from five to ten percent. The accuracy of the loop flowmeter is about three percent. The measured velocities for the 15 ft/sec and 22 ft/sec runs are about 10% below the velocities calculated from the loop flow. This comparison, then, falls within the standard deviation of the measurements. However, the consistently high velocities as calculated from the loop flow indicate error sources other than data scatter. A possible change in transit time correction factor has already been mentioned. An error in flow area calculation is another possibility. The flow area was calculated from the as built dimensions of the test section before assembly. The actual as assembled area was not volumetrically determined for this test.

The flowmeter manometer was fluctuating badly during the 30 ft/sec run and thus the flow could not be accurately determined. Comparison of the pressure drop through the test section (Figure 6) with the lower velocity runs indicates that the reading was low relative to the other runs. This was confirmed by the transit time measurements which did not give velocities 10% lower than those from the flowmeter as was typical of the other two velocity tests.

B. Cross Flow Measurement

All of the cross flow measurements used were those from the two center channels 1 and 2 of Figure 1. These two channels were essentially unaffected by edge effects at the outside of the test section and thus are the most reliable.

It was not possible to successfully fit the data with its associated scatter to more than one exponential term. Consequently, the theoretical concentrations at the electrode positions were fit to a single exponential and these were compared to a single exponential fit of the data points. This procedure could only be applied to channels into which salt was injected. The salt concentration in channels adjacent to the injection channels first increases and then decreases from the bottom to the top of the channel and cannot, therefore, be fit to a single exponential. Data from channels two removed from the injection channel was not sufficient to make a cross flow estimate.

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Flow pressure at the injection point was observed to vary by several psi from (injection) needle to needle. This caused an uncertainty in the relative amounts of salt injected into each channel during multichannel injections. The single channel injection data is therefore considered the best and the cross flow result is derived from this data.

The average cross flow ratio, $0.65 \pm 0.16 \text{ ft}^{-1}$ is equivalent to a cross flow of $0.44 \pm 0.11 \text{ lb/sec ft}$ at a velocity of 26 ft/sec and a temperature of 120°F . This compares to the cross flow of $0.326 \text{ lb/sec ft} \pm 12.6\%$ reported in reference 1 for the dual channel test with 102°F water. Water density varies by less than $\frac{1}{2}\%$ between these two temperatures and is, therefore, not significant. The first thing to be emphasized in the above comparison is that the two numbers overlap within the standard deviations. Analysis of the dual channel data in reference 1 showed two groups of data. The data for the injection channel in general gave higher cross flow results than that from the receiving channel. This corresponds to the result determined from the present work where all the useable data came from the injection channel. Reference 1 postulates the pressure of fluid swirling during the test and showed that the effect on the data was more for the injection channel than for the receiving one. Consequently, reference 1 used the lower data from the receiving channel to compute the cross flow result. Swirling was not identified from the data in the more complex multichannel system being reported here. Consistently high or low points in the data are probably due to scatter in the normalization data.

Several sets of data from channels adjacent to the injection channels shows a lack of salt in the first cross flow coming into the channel. This indicates that the salt was not well mixed in the injection channel during the first portion of the test section. Future tests should remedy this situation as outlined in item 4 below.

Several changes in the test method which would improve the data are listed below.

1. Make at least three normalization runs at each condition. Since the data runs are normalized to the normalization runs, an error in a normalization point is propagated throughout the data.
2. Inject salt for the normalization runs far enough upstream of the test section to allow it to become thoroughly mixed before it enters the test section. The present experiment was changed to do this for the normalization runs.

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3. Locate the injection needles in the flow channel into which salt is to be injected. This will positively prevent salt from entering the wrong channel. The injection needles in the present system are located just at the inlet of the flow channel.
4. Seal the cross flow channels for 6 to 12 inches beyond where the salt has been injected. This will allow the salt solution to become thoroughly mixed in the stream before the cross flow begins.
5. Locate quick closing valves in the injection lines just upstream of the injection needle.

VIII. CONCLUSIONS

The ratio of cross flow to axial flow for the finned tricuspid channel tested was $0.65 \pm 0.16 \text{ ft}^{-1}$ which is equivalent to $0.44 \pm 0.11 \text{ lb/sec ft}$ for 120°F water at 26 ft/sec. This is not significantly different from the dual channel measurements which were made (ref. 1). Therefore, basic parameter measurements can be more easily made in the less complex dual channel systems and the final designs then tested as multichannel bundle tests.

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TABLE III

HWO CR MULTI-CHANNEL MIXING TEST

Run No.	H ₂ O Temp. °F	Channel Inj.	Channel Recorded	Flow in GPM	ΔP-PSI 30" Length Test Sec	Velocity Ft/Sec	Cross Fl. Axial Fl.		
31	119	2	1,2,5	60.0	6.206	15.1	0.602		
32	119	2	1,2,10	60.0	6.206	15.1	Poor Data		
33	119	10	1,2,10	60.0	6.206	15.1			
34	119	13,14	1,10,14	60.0	6.206	15.1			
35	119	2,3,8	1,2,5	60.0	6.206	15.1	0.697		
36	119	11,12,13,14	1,10,14	60.0	6.206	15.1			
37	123	All	1,2,5	90	13.001	22.7			
38	123	UpStream	1,2,5	91	13.27	23.0			
39	122	UpStream	10,14,6	91	13.27	23.0			
40	122	UpStream	9,11,12	91	13.27	23.0			
41	118	All	1,2,5	90.5	13.18	22.8			
42	118	All	9,11,12	90.5	13.18	22.8			
43	119	1,2	1,2,5	90.5	13.18	22.8	0.888* 1.353		
44	120	1,2	1,10,14	90.5	13.18	22.8	0.484		
45	120	1,2	1,2,10	90.5	13.18	22.8	No Zero Data		
46	120	1	1,2,5	90.5	13.18	22.8	0.709		
47	120	1	1,2,9	90.5	13.18	22.8	0.713		
48	120	1	1,2,6	90.5	13.18	22.8	0.519		
49	120	2	1,2,5	90.5	13.18	22.8	0.944		
50	120	2	1,2,10	90.5	13.18	22.8	0.752		
51	120	10	1,2,10	90.5	13.18	22.8			
52	120	13,14	1,10,14	90.5	13.18	22.8			
53	120	11,12,13,14	1,10,14	90.5	13.18	22.8			
54	120	2,3,8	1,2,5	90.5	13.18	22.8	1.105		
55	120	UpStream	1,2,5	60	6.36	15.1			
56	120	UpStream	10,14,6	60	6.36	15.1			
57	120	UpStream	9,11,12	60	6.36	15.1			
58	120	UpStream	1,2,5	60	6.36	15.1			
59	120	UpStream	10,14,6	60	6.36	15.1			
60	120	1,2	1,2,5	117	22.65	29.2	1.093		

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FIGURE 1. CROSS SECTION
HWOCR MULTI-CHANNEL TEST SECTION

FIGURE 2.
HWOCR MULTI-CHANNEL TEST SECTION

FIGURE 3
HYDRAULIC TEST LOOP

Figure 4.
Typical Salt Concentration Profiles
for Injection into Channel 1. (Calculated)

FIGURE 5.
DIGITAL DATA ACQUISITION SYSTEM BLOCK DIAGRAM

VELOCITY (FT/SEC)

FIG. 6
PRESSURE DROP THROUGH 30" LENGTH OF TEST SECTION
□ PRESSURE MEASUREMENTS MADE DURING MIXING TESTS

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APPENDIX 1

TRANSIT TIMES AND CORRELATION COEFFICIENTS

FOR CHANNEL VELOCITY MEASUREMENTS

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HWOCR FLOW VELOCITY MEASUREMENTS

21 feet per second

Run No.	Flow Ch.	Tape Ch.	Transit Time	Correl. Coeff.	Uncorr. Velocity ft/sec	Correct Avg. Velocity ft/sec			
1	1	1-3							
1	1	3-5	0.604	0.37					
1	1	5-7	0.674	0.65					
1	1	7-9	0.706	0.57					
1	1	9-11	0.710	0.33					
1	1	11-13	0.737	0.55	22.1	20.1	±1.0		
1	2	2-4							
1	2	4-6	0.700	0.69					
1	2	6-8	(	)	*				
1	2	8-10							
1	2	10-12	0.625	0.80					
1	2	12-14	0.77	0.85	22.9	20.8	±2.4		
2	1	1-3							
2	1	3-5	0.598	0.35					
2	1	5-7	0.677	0.64					
2	1	7-9	0.712	0.54					
2	1	9-11	0.683	0.46					
2	1	11-13	0.691	0.57	22.6	20.6	±0.9		
2	10	2-4	0.650	0.24					
2	10	4-6	0.680	0.48					
2	10	6-8	(	)					
2	10	8-10							
2	10	10-12	0.695	0.64					
2	10	12-14	0.662	0.62	22.7	20.6	±1.0		

*Transit time was determined between Ch. 6 and 10

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HWOGR FLOW VELOCITY MEASUREMENTS

21 feet per second

Run No.	Flow Ch.	Tape Ch.	Transit Time	Correl. Coeff.	Uncorr. Velocity ft/sec	Correct Avg. Velocity ft/sec			
3	2	1-3							
3	2	3-5	0.666	0.44					
3	2	5-7	0.655	0.37					
3	2	7-9	0.742	0.52					
3	2	9-11	0.645	0.46					
3	2	11-13	0.736	0.50	22.5	20.5	±1.7		
3	5	2-4	0.540	0.13					
3	5	4-6	0.668	0.47					
3	5	6-8	(	)	*				
3	5	8-10	1.30	0.60					
3	5	10-12	0.641	0.77					
3	5	12-14	0.687	0.81	23.7	21.6	±1.1		
6	9	1-3	0.730	0.38					
6	9	3-5	0.696	0.59					
6	9	5-7	0.688	0.70					
6	9	7-9	0.645	0.60					
6	9	9-11	0.679	0.77					
6	9	11-13	0.691	0.70	23.1	21.0	±1.0		
6	13	2-4	0.747	0.43					
6	13	4-6	0.685	0.82					
6	13	6-8	(	)					
6	13	8-10	1.365	0.70					
6	13	10-12	0.648	0.80					
6	13	12-14	0.680	0.83	23.3	21.2	±1.0		

*Transit time was determined between Ch. 6 and 10

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HWOGR FLOW VELOCITY MEASUREMENTS

14 feet per second

Run No.	Flow Ch.	Tape Ch.	Transit Time	Correl. Coeff.	Uncorr. Velocity ft/sec	Correct Avg. Velocity ft/sec			
7	1	1-3							
7	1	3-5	0.938	0.57					
7	1	5-7	0.965	0.55					
7	1	7-9	1.02	0.55					
7	1	9-11	0.985	0.53					
7	1	11-13	1.065	0.65	15.5	13.6	± 0.8		
7	2	2-4	0.88	0.05					
7	2	4-6	1.006	0.41					
7	2	6-8	0.905	0.68					
7	2	8-10	1.025	0.65					
7	2	10-12	0.940	0.68					
7	2	12-14	1.088	0.75	15.8	13.9	± 1.3		
8	1	1-3							
8	1	3-5	0.915	0.52					
8	1	5-7	0.972	0.60					
8	1	7-9	1.05	0.50					
8	1	9-11	0.985	0.56					
8	1	11-13	0.995	0.53	15.6	13.7	± 0.7		
8	10	2-4	0.932	0.22					
8	10	4-6	1.00	0.37					
8	10	6-8	1.02	0.64					
8	10	8-10	1.08	0.72					
8	10	10-12	0.998	0.65					
8	10	12-14	0.997	0.57	15.3	13.4	± 0.7		

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HWOGR FLOW VELOCITY MEASUREMENTS

14 feet per second

Run No.	Flow Ch.	Tape Ch.	Transit Time	Correl. Coeff.	Uncorr. Velocity ft/sec	Correct Avg. Velocity ft/sec			
9	2	1-3							
9	2	3-5	1.00	0.43					
9	2	5-7	0.950	0.35					
9	2	7-9	1.07	0.45					
9	2	9-11	0.965	0.55					
9	2	11-13	1.068	0.46	15.4	13.6	±1.0		
9	5	2-4	0.950	0.12					
9	5	4-6	0.932	0.36					
9	5	6-8	0.975	0.68					
9	5	8-10	0.973	0.67					
9	5	10-12	0.943	0.71					
9	5	12-14	1.02	0.76	16.0	14.1	±0.7		
10	9	1-3	0.965	0.41					
10	9	3-5	1.015	0.50					
10	9	5-7	0.988	0.62					
10	9	7-9	0.950	0.52					
10	9	9-11	1.005	0.61					
10	9	11-13	0.992	0.54	15.9	14.0	±0.6		
10	13	2-4	1.068	0.42					
10	13	4-6	0.982	0.72					
10	13	6-8	0.980	0.77					
10	13	8-10	1.012	0.73					
10	13	10-12	0.925	0.74					
10	13	12-14	0.970	0.74	16.1	14.2	±0.7		

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HWOCR FLOW VELOCITY MEASUREMENTS

21 feet per second

Run No.	Flow Ch.	Tape Ch.	Transit Time	Correl. Coeff.	Uncorr. Velocity ft/sec	Correct Avg. Velocity ft/sec			
11	1	1-3							
11	1	3-5	0.625	0.34					
11	1	5-7	0.658	0.43					
11	1	7-9	0.682	0.53					
11	1	9-11	0.675	0.54					
11	1	11-13	0.715	0.66	22.9	20.8	± 1.0		
11	2	2-4	0.630	0.12					
11	2	4-6	0.685	0.52					
11	2	6-8	0.592	0.70					
11	2	8-10	0.705	0.66					
11	2	10-12	0.625	0.68					
11	2	12-14	0.750	0.70	23.4	21.3	± 2.4		
12	1	1-3							
12	1	3-5	0.630	0.33					
12	1	5-7	0.665	0.55					
12	1	7-9	0.705	0.47					
12	1	9-11	0.682	0.54					
12	1	11-13	0.687	0.57	22.8	20.8	± 0.9		
12	10	2-4	0.620	0.23					
12	10	4-6	0.660	0.35					
12	10	6-8	0.675	0.70					
12	10	8-10	0.732	0.77					
12	10	10-12	0.695	0.63					
12	10	12-14	0.665	0.60	22.6	20.6	± 1.1		

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HWOGR FLOW VELOCITY MEASUREMENTS

30 feet per second

Run No.	Flow Ch.	Tape Ch.	Transit Time	Correl. Coeff.	Uncorr. Velocity ft/sec	Correct Avg. Velocity ft/sec			
14	9	1-3	0.535	0.32					
14	9	3-5	0.500	0.63					
14	9	5-7	0.485	0.79					
14	9	7-9	0.455	0.58					
14	9	9-11	0.510	0.76					
14	9	11-13	0.475	0.70	32.5	30.8	±1.8		
14	13	2-4	0.510	0.55					
14	13	4-6	0.485	0.90					
14	13	6-8	0.490	0.87					
14	13	8-10	0.517	0.85					
14	13	10-12	0.460	0.85					
14	13	12-14	0.490	0.87	31.9	30.3	±1.8		
15	1	1-3							
15	1	3-5	0.433	0.40					
15	1	5-7	0.470	0.56					
15	1	7-9	0.490	0.56					
15	1	9-11	0.490	0.57					
15	1	11-13	0.543	0.67	31.4	29.8	±2.1		
15	2	2-4							
15	2	4-6	0.487	0.50					
15	2	6-8	0.450	0.75					
15	2	8-10	0.512	0.67					
15	2	10-12	0.460	0.73					
15	2	12-14	0.543	0.80	31.8	30.2	±2.9		

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HWOCR FLOW VELOCITY MEASUREMENTS

30 feet per second

Run No.	Flow Ch.	Tape Ch.	Transit Time	Correl. Coeff.	Uncorr. Velocity ft/sec	Correct Avg. Velocity ft/sec			
16	1	1-3							
16	1	3-5	0.440	0.24					
16	1	5-7	0.480	0.60					
16	1	7-9	0.510	0.54					
16	1	9-11	0.500	0.50					
16	1	11-13	0.515	0.60	31.2	29.6	±1.4		
16	10	2-4			*				
16	10	4-6	0.897	0.63					
16	10	6-8	0.497	0.70					
16	10	8-10	0.532	0.74					
16	10	10-12	0.510	0.67					
16	10	12-14	0.515	0.66	30.4	28.9	±1.3		
17	2	103							
17	2	3-5	0.490	0.48					
17	2	5-7	0.470	0.54					
17	2	7-9	0.535	0.63					
17	2	9-11	0.473	0.68					
17	2	11-13	0.550	0.49	30.8	29.3	±1.2		
17	5	2-4	0.460	0.13					
17	5	4-6	0.455	0.48					
17	5	6-8	0.485	0.65					
17	5	8-10	0.495	0.65					
17	5	10-12	0.480	0.74					
17	5	12-14	0.495	0.74	32.0	30.4	±1.1		

*Transit time was determined between Ch. 2 and 6.

APPENDIX 2

SALT CONCENTRATION DATA FROM CROSS FLOW TEST

NORMALIZED TO THEORETICAL MODEL

(Theoretical is shown by solid line)