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An Empirical Method to Calculate Clinch River Breeder Reactor (CRBR) Inlet Plenum Transient Temperatures

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SUMMARY

Sodium flow enters the CRBR inlet plenum via three loops or inlets. An empirical equation was developed to calculate transient temperatures in the CRBR inlet plenum from known loop flows and temperatures. The constants in the empirical equation were derived from 1/4 scale Inlet Plenum Model tests using water as the test fluid. The sodium temperature distribution was simulated by an electrolyte. Step electrolyte transients at 100% model flow were used to calculate the equation constants. Step electrolyte runs at 50% and 10% flow confirmed that the constants were independent of flow. Also, a transient was tested which varied simultaneously flow rate and electrolyte. Agreement of the test results with the empirical equation results was good which verifies the empirical equation.

INTRODUCTION

The trend in the Liquid Metal Fast Breeder Reactor heat transfer system is towards the loop or pipe type primary system arrangement for the commercial plant. Clinch River Breeder Reactor has three loops in the primary heat transfer system. These loops enter the CRBR inlet plenum through three symmetrically located 24 inch diameter inlet nozzles shown in Fig. 1. Knowledge of how the inlet plenum mitigates the loop transients is important to reduce the thermal stresses in the plenum components and to predict the sodium temperatures into the 61 inlet modules located on the top of

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the plenum. The inlet modules support and distribute sodium to the fuel assemblies, radial blanket assemblies, control assemblies and removable radial shielding assemblies.

Presently, analytical techniques are not available to accurately calculate the inlet plenum mixing characteristics. Tests are required to measure the mixing characteristics. A test program to test the many CRBR inlet plenum transients from which an empirical equation could be fitted to duplicate each transient would be an extensive one. Also, changes in the design and/or mode of operation of the CRBR plant could change the inlet plenum transients sufficiently to negate some or all of the test results. Thus, the practical approach is to conduct a test program that uses a fundamental test transient and to use a more complex empirical equation to calculate all CRBR inlet plenum transients. The type of test transient selected was a step transient and the empirical equation to transpose step data to CRBR transient data is defined herein.

EMPIRICAL EQUATION

The empirical equation selected to calculate the transient mixing temperature of a probe located in the CRBRP inlet plenum is:

$$\frac{dT(t)}{dt} = W \left\{ C_1(T_1(t-\tau_1) - T(t)) + C_2(T_2(t-\tau_2) - T(t)) + C_3(T_3(t-\tau_3) - T(t)) \right\} \qquad (1)$$

The basis of equation 1 is the energy equation. It assumes that the probe rate of energy change is proportional to the sum of the loop and probe energy differences.

The transport time, τ_n, in equation (1) is determined from equation (2). This equation defines the flow path a temperature perturbation travels from the loop exit to a point in the inlet plenum.

$$\int_{t-\tau_n}^{t} w_n(t)\, dt = \text{constant} \tag{2}$$

The constants in equation (1) and (2) are determined from step electrolyte transients at constant flow. Integration of equation (1) and (2) for a step temperature change in loop 1 gives :

$$\frac{T-To}{\Delta T_1} = \frac{C_1}{\Sigma C}\left(1 - e^{-w\Sigma C(t-\tau_1)}\right) \tag{3}$$

$$W_1\tau_1 = \text{constant} \tag{4}$$

Similar equations apply for loops 2 and 3. These equations are now in a form where their unknowns can be readily solved from step transient data.

There are two restrictions on equations (1) and (2). The first is that the flow distribution of the three loops must be the same for steady state and transient operations. Finally, the temperature calculations are limited to the tested probe locations in the inlet plenum.

TEST

A 0.248 scale model of the inlet plenum was fabricated and tested by Hanford Engineering Development Laboratory (HEDL). Fig. 1 shows the inlet plenum. Three symmetrically located inlet nozzles supply fluid to the inlet plenum, mixes and enters the core through 61 inlet modules which supports the core assemblies.

The fluid in the CRBRP is sodium which poses handling problems in a model test. Water was used instead of sodium and concentration distributions of NaOH and water simulated the temperature distributions in sodium. A similar approach was used by M. Norin[1][1] to show the correlation between the transient temperature distribution in the FERMI REactor operating with sodium and the predicted temperature distributions [2] based on conductivity measurements.

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[1] Numbers in brackets designate references at end of paper.

Fig. 1 and Table 1 define the location of the 34 conductivity probes in the inlet plenum. These locations were selected to provide transient temperature boundary conditions for the components in the inlet plenum for stress analyses and to define the inlet fluid temperature into the core.

The tests conducted are tabulated in Table 2. The first three tests define the mixing equation constants. The next two tests assess the effect of Reynold's Number and verify that the time delay satisfies equation 4. Finally, the last two runs provide the transient test data to verify that the empirical equation can predict a transient based on step transients.

A step transient is performed by the injection of a solution of NaOH and water at a constant flow rate into one of the loops. An electrolyte conductivity probe located after the injection point in the loop measures the step concentration input to the inlet plenum and conductivity probes located in the inlet plenum measure the response of the step input. Typical responses of these probes are shown in Fig. 2.

TEST RESULTS

a) EMPIRICAL EQUATION CONSTANTS

Test data from runs A5.5, A5.6 and A5.7 defined the empirical equation unknowns. An average step transient was calculated from 10 injection cycles to decrease the conductivity probe noise error. Not all of the probe data was reported to reduce the amount of data to be published. Instead, test results were reported for each different type of designated probe in Table 1.

The time delay is the time it takes for the injected concentration to travel from the loop to a conductivity probe. This time was calculated by subtracting the initial response time of a probe in the inlet plenum from a probe in the loop for each injection cycle. Then the average time delay was calculated by averaging the 10 time delays. Tabulated in Table 3 are the time delays.

The constants of the empirical equation (C_1, C_2 and C_3) are calculated from the step transient constants in equation 3. The first one, $C_n/\Sigma C$, is the equilibrium mixing constant for a step change in conductivity in the n^{th} loop. It equals the ratio of equilibrium probe conductivity change divided by the step probe conductivity change. Fig. 2 illustrates these conductivity changes. The constants are calculated for a step transient in each of the three loops. When summed, these ratios should equal one. The variation from one was within the conductivity ratio measurement uncertainty. Since the empirical equation requires the sum to equal one, the individual ratios were divided by the sum to obtain a sum equal to one. The reason for the requirement is to satisfy the conservation of energy for equation 1. Tabulated in Table 4 are the adjusted $C_n/\Sigma C$'s for the selected probes.

The next constant in the step equation is the slope of the step decay in conductivity. The slope was calculated by an exponential linear regression fit of the conductivity data. Fig. 3 shows a typical regression fit of the test data. The slope of the linear curve was calculated which equals $W\Sigma C$. Dividing the slope by the flow, W, gives ΣC. Tabulated in Table 5 are the ΣC's. The empirical equation requires that a probe ΣC be independent of the injected loop. The test data showed that the requirement was met within the test data uncertainties.

Sufficient step test data is now available to calculated equation 1 constants. Multiply the values of $C_n/\Sigma C$ in Table 4 by the values of ΣC in Table 5 yields the desired constants. They are tabulated in Table 6.

b) VERIFICATION OF EMPIRICAL EQUATION

The selected empirical and time delay equations were verified by first checking that the constants in equations 3 and 4 were independent of the model flow at which the step transients were taken. Then the empirical equation was used to calculate the same transient that was tested. This transient was different from a step transient because both flow and concentration were varied simultaneously. If the checks are as postulated, then the empirical equation is valid.

The CRBR flow range is from 100% to 10% flow. The constants (C_1, C_2 and C_3 and equation 2 constant) were calculated from step transient data at 100% flow. A check was made to determine if they were independent of flow. Step transient data were taken at 50% and 10% flow. The test data showed that the mixing is highly turbulent over the tested flow range and is independent of Reynold's number.

The transient test flow was varied exponentially from 100% to 10% and the NaOH water solution was injected at a constant flow rate at the start of flow shutdown. The comparison of transient test data and calculated data from the empirical equation was good.

CONCLUSION

The validity of the empirical equation to calculate CRBR inlet plenum temperatures at probe locations has been demonstrated by two types of confirmation tests, (1) additional step data tests at 50% and 10% flow and (2) a severe transient test where the flow was varied exponentially from 100% to 10% for a constant electrolyte injection flow rate.

The equation constants apply only to equal flow in all three loops. The equation can be used to predict two loop flow and different loop flow distributions. However, the constants would have to be determined from step transient data.

All the constants in the report are for the 1/4 scale inlet plenum model. To convert the model constants to prototype constants, the method and equations are given in the Appendix.

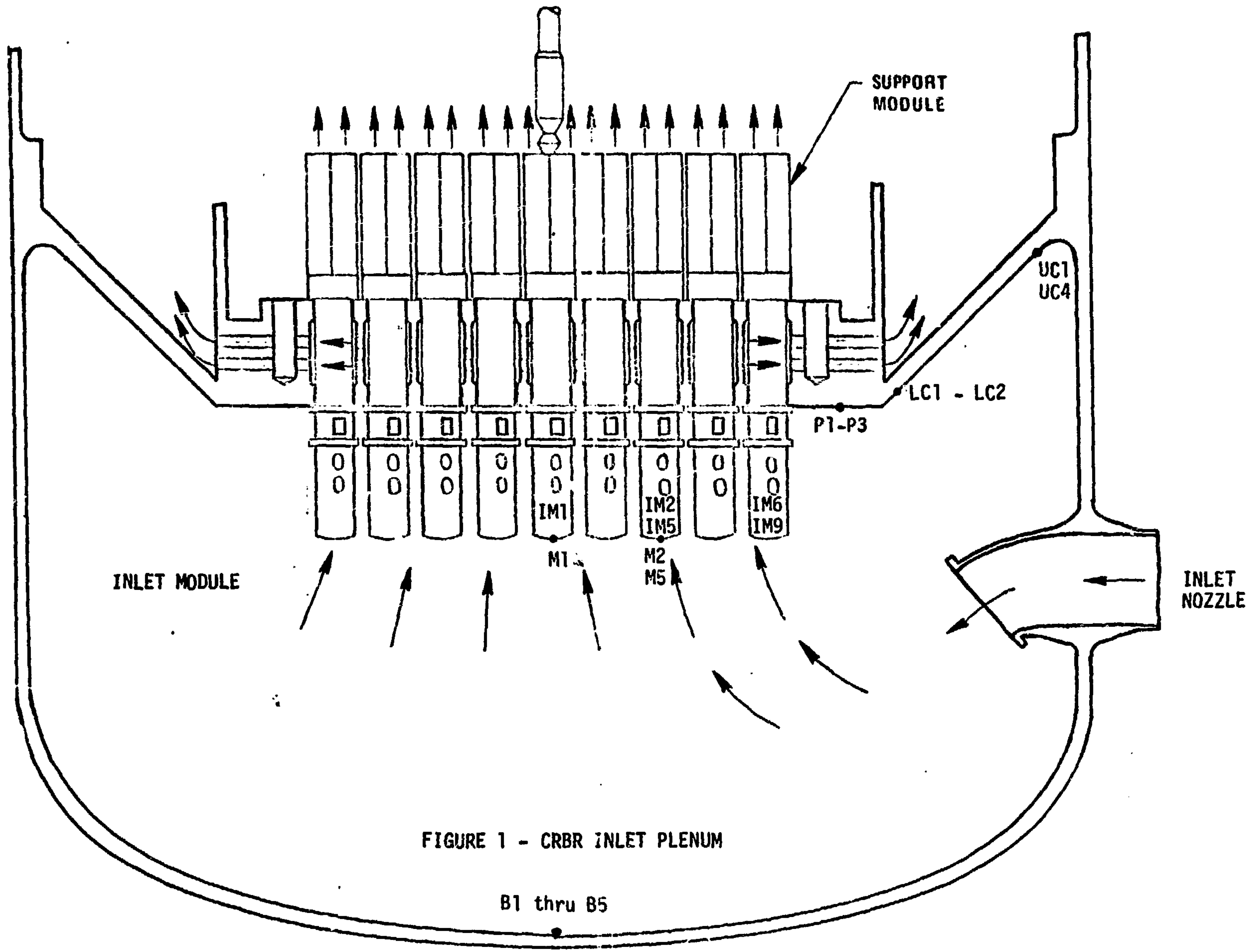

FIGURE 1 - CRBR INLET PLENUM

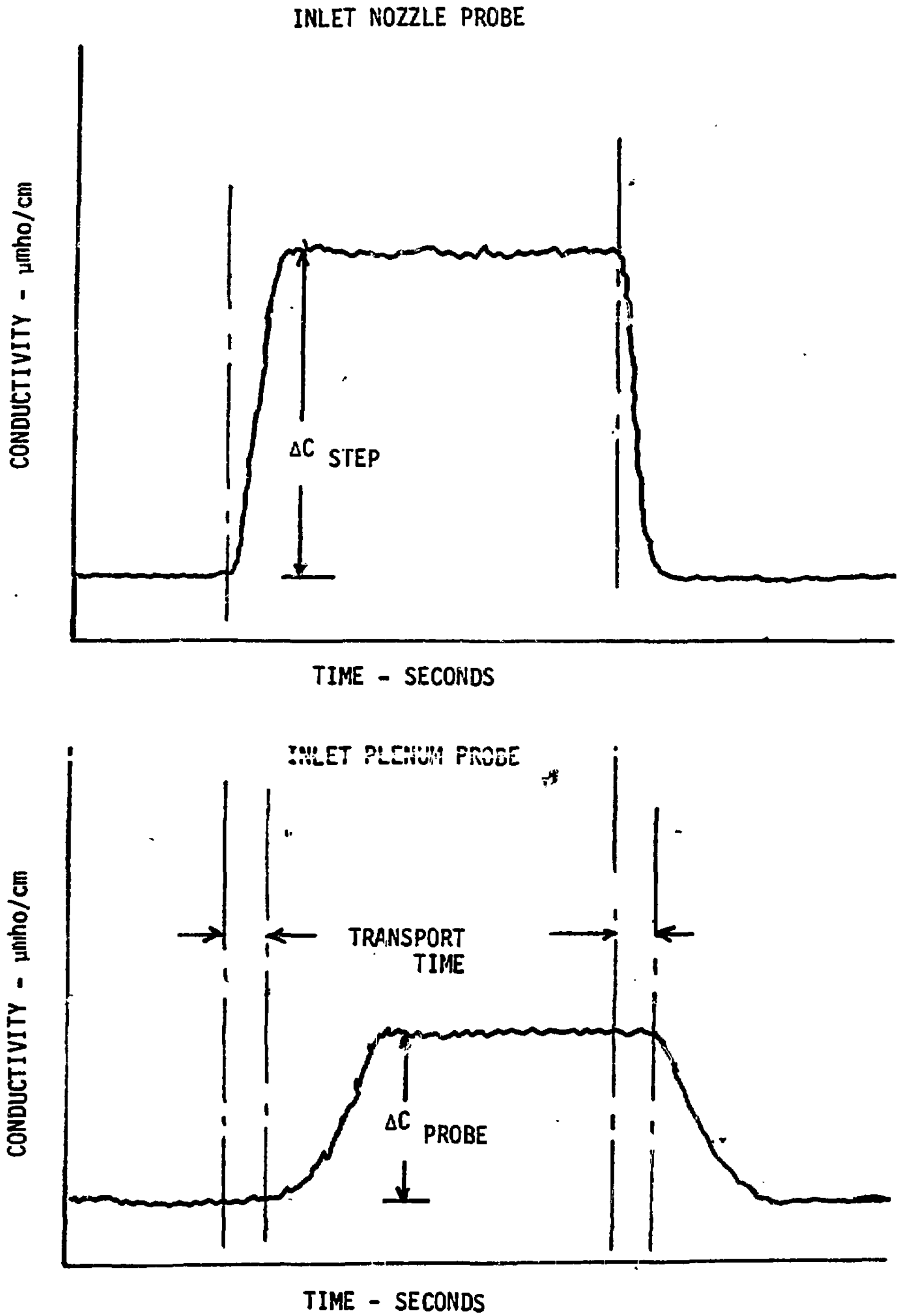

FIGURE 2 - Typical Probe Response to a Step Change in Inlet Nozzle Conductivity

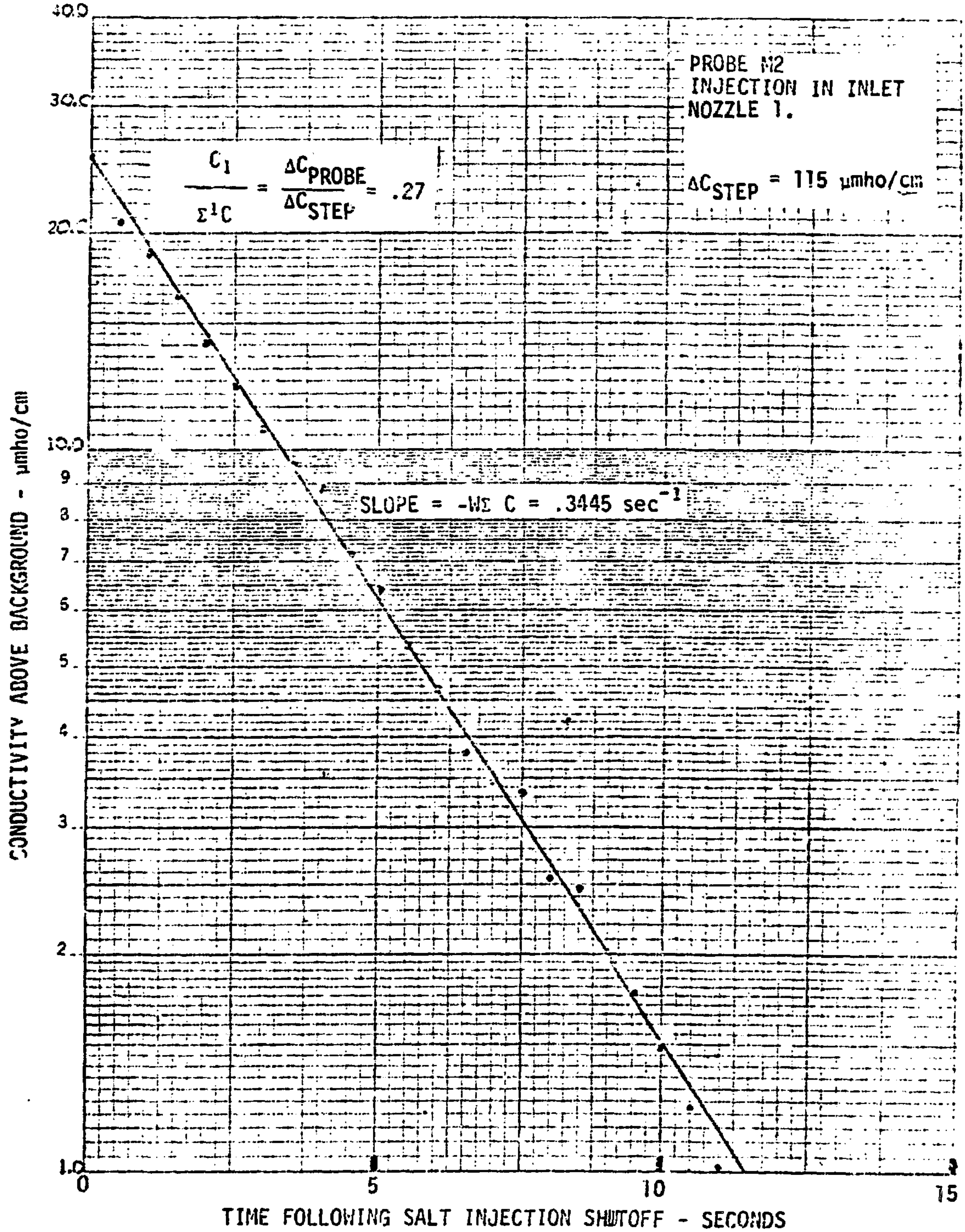

FIGURE 3

CURVE FIT OF EXPERIMENTAL DATA

TABLE 1 - Conductivity Probe Location

Probe Name	Location
M1	bottom of center module nozzle
M2 to M5	bottom of fourth row module nozzle. See Fig. 1.
IM1	inside center module. See Fig. 1.
IM2 to IM5	inside third row modules. See Fig. 1.
IM6 to IM9	inside outer row modules. See Fig. 1.
P1	bottom of core support structure - 90°
P2	bottom of core support structure - 210°
P3	bottom of core support structure - 330°
LC1	bottom of core support structure skirt - 90°
LC2	bottom of core support structure skirt - 150°
LC3	bottom of core support structure skirt - 210°
LC4	bottom of core support structure skirt - 270°
UC1	top of core support structure skirt - 90°
UC2	top of core support structure skirt - 30°
UC3	top of core support structure skirt - 330°
UC4	top of core support structure skirt - 270°
B1	center of inlet plenum bottom
B2	bottom of inlet plenum - 90°
B3	bottom of inlet plenum - 30°
B4	bottom of inlet plenum - 330°
B5	bottom of inlet plenum - 270°
X1	Loop 1 exit
X2	Loop 2 exit
X3	Loop 3 exit
Z1	In exit pipe above model

TABLE 2 - 1/4 Scale Inlet Plenum Feature Model Test Runs

Run No.	Test Description
A5.5	Loop 1 Step Transient @ 100% flow and 3 loop operation - 10 injection cycles
A5.6	Loop 2 Step Transient @ 100% flow and 3 loop operation - 10 injection cycles
A5.6	Loop 3 Step Transient @ 100% flow and 3 loop operation - 10 injection cycles
A5.9	Loop 1 Step Transient @ 50% flow and 3 loop operation - single injection cycle
A5.16	Loop 1 Step Transient @ 10% flow and 3 loop operation - single injection cycle
A5.8	Pump shutoff from 100% to 10% flow. Constant injection from time of pump shutoff

TABLE 3 - Time Delay - Sec.

Probe	τ_1	τ_2	τ_3
M1	0.7	0.7	0.7
IM1	1.2	1.2	1.2
P1	2.1	2.3	2.3
LC1	2.0	2.2	2.2
UC1	2.1	2.3	2.3
B1	0.7	0.7	0.7

TABLE 4 - Equilibrium Mixing Constant

Probe	$C_1/\Sigma C$	$C_2/\Sigma C$	$C_3/\Sigma C$
M1	0.444	0.261	0.296
IM1	0.444	0.333	0.222
P1	0.386	0.197	0.417
LC1	0.348	0.318	0.334
UC1	0.383	0.226	0.391
B1	0.215	0.185	0.600

TABLE 5 - Exponential Constant, LB_m^{-1}

Probe	ΣC
M1	1.04×10^{-3}
IM1	1.16×10^{-3}
P1	1.16×10^{-3}
LC1	1.12×10^{-3}
UC1	1.17×10^{-3}
B1	1.40×10^{-3}

TABLE 6 - Empirical Equation Constants, LB_m^{-1}

Probe	C_1	C_2	C_3
M1	4.55×10^{-4}	2.7×10^{-4}	3.06
IM1	5.16×10^{-4}	3.87×10^{-4}	2.58
P1	4.47×10^{-4}	2.28×10^{-4}	4.83
LC1	3.90×10^{-4}	3.57×10^{-4}	3.75
UC1	4.47×10^{-4}	2.64×10^{-4}	4.56
B1	3.00×10^{-4}	2.58×10^{-4}	8.37

ACKNOWLEDGEMENT

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REFERENCES

1. M. P. Norin, "An Electrolytic Method for Transient Mixing Measurements," Lab Note, Journ. Franklin Inst., Vol. 266, No. 3 (Sept. 1958).

2. F. R. Boyers and M. P. Norin, "The Effect of Mixing in the Outlet Plenum of the Fermi Reactor," Trans. Am. Nuclear Soc., Vol. 3, No. 1, 1960, p. 1861.

NOMENCLATURE

A	=	flow area, sq. ft.
C_n	=	loop n constant, lb_m^{-1}
ΣC	=	$C_1 + C_2 + C_3$, lb_m^{-1}
ΔC_{STEP}	=	loop probe conductivity step change, μmho/cm
ΔC_{PROBE}	=	inlet plenum probe conductivity change, μmho/cm
T_o	=	initial plenum temperature, °F
ΔT_1	=	loop 1 temperature step, °F
$T(t)$	=	fluid temperature inside inlet plenum, °F
$T_n(t-\tau_n)$	=	loop n exit temperature, °F
t	=	time, seconds
V	=	velocity, ft/sec
W_n	=	loop n flow rate, lb_m/sec
W	=	$W_1 = W_2 = W_2$, lb_m/sec
ρ	=	density, lb/ft^3
τ_n	=	loop n time delay, seconds
L	=	length, ft.

Subscripts

m	=	model
n	=	loop number (1, 2 or 3)
p	=	prototype

APPENDIX

Scaling Model Data to Prototype Data

The model time is scaled to the prototype time by the dimensionless Stroudahl number:

$$\frac{t_m V_m}{L_m} = \frac{t_p V_p}{L_p} \tag{5}$$

Since the model and prototype velocity are equal, the time scale factor equals the geometric scale factor.

$$\frac{t_m}{t_p} = \frac{L_m}{L_p} = 0.248 \tag{6}$$

Equation 1 model constants are converted to prototype constants by the dimensionless equation:

$$(W\ C_n t)_m = (WC_n t)_p \tag{7}$$

Substituting the flow equation 8 and equation 6 in equation 7 gives equation 9.

$$W=\rho AV \tag{8}$$

$$(C_n)_p = \frac{\rho_m}{\rho_p} \frac{L_m^3}{L_p^3} (C_n)_m = 0.0176\ (C_n)_m \tag{9}$$

Equations 6 and 9 are the only ones needed to change model constants to prototype constants.