CEN-167(A)-NP

REACTOR VESSEL OPEN CORE FLOW MODEL
TEST REPORT

June, 1981

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ABSTRACT

This report describes the hydraulic tests on a 1/5-scale flow model of a four loop, two steam generator NSSS System with 217 fuel assemblies. The tests were conducted with a modelled open core which allowed cross-flow among adjacent core tubes. Flow and pressure distributions at the core inlet and exit were measured. A description of the model design, the test methods followed and the test results are presented in this report.

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1.0 INTRODUCTION

Flow model tests applicable to C-E's 3410 MW(t) class PWR's were performed to determine the hydraulic performance of this particular reactor design. This report presents a description of the model design, the test methods followed and the test results.

The model simulated the 217 fuel assembly, four loop, two steam generator NSSS System of the 3410 MW(t) reactor. In this model, the open core of the reactor was simulated with core tubes containing flow holes which allowed cross-flow among adjacent tubes. The open core model was necessary to be consistent with the open core thermal margin analysis methods to be used in licensing this reactor.

The objective of this test program was to determine or verify design values for key steady state hydraulic parameters for 3410 MW(t) class reactors. Of particular interest was the determination of the flow and pressure distribution at both the inlet and exit planes of the core.

The core inlet flow distribution and exit pressure distribution shown in CEN-139(A)-P, (Reference 1-1), were based upon measured data on a 1/5 scale flow model. In addition, the inlet flow distribution uncertainties given in CEN-139(A)-P were based upon the measured variances of the test data.

1.1 References for Section 1.0

1-1 "Responses to First Round Questions on the Statistical Combination of Uncertainties Program: CETOP-D Code Structure and Modeling Methods", CEN-139(A)-P, March,1981.

2.0 TEST APPARATUS

2.1 Large Scale Hydraulic Test Facility

The flow model, Figure 2-1, was installed in the large scale hydraulic test facility located in the Development Department of C-E. The test loop consists of a stainless steel, cold water, low pressure re-circulating test loop and an instrumentation console with a capacity for reading 1500 pressure instrumentation taps.

The test loop was designed to flow 15,000 gallons/minute with an irrecoverable test section pressure loss of 35 pounds/square inch. The maximum system operating pressure and temperature were 140 psig and 175°F, respectively. A heat exchanger bypass to the main loop was used for temperature control. The loop water was constantly filtered using a 30 micron bypass filter. Figure 2-2 shows the piping and installation drawing of the test loop.

The model was installed inside of the flow distribution manifold as shown in Figure 2-2. The manifold was connected to the main discharge header. Flow metering was accomplished via eight inch Gentile flow meters upstream of each inlet. The pipe runs from the manifold to a point downstream of the flow meter, including the control valve and flow straightener, were previously calibrated by the Alden Research Laboratories of Worcester Polytechnic Institute. The outlets of the flow model were returned to the suction header via two pipe runs which contained flow balancing valves. Pipe elbow taps on elbows downstream of the model monitored outlet flow.

2.2 Model Description

The flow model, shown in Figures 2-1 and 2-3, was designed to simulate the hydraulic characteristics of four loop, 217 fuel assembly C-E PWRs of the 3410 Mw(t) reactor class. The flow model, with the exception of the core region, is scaled geometrically at 1/5 of the reactor size. The model simulates the reactor internal flow paths and components starting from the vessel inlet nozzles and ending at the vessel outlet nozzles.

The model core consisted of 217 square core tubes arranged in a scaled pattern of the reactor, Figure 2-4. Each core tube contained six flow resistor plates of which one at the inlet and one at the outlet were instrumented to function as inlet and outlet flowmeters. The six flow resistor plates were distributed over the length of the model bundle to provide axial hydraulic resistance. The sides of the core tubes contained holes for crossflow to occur among adjacent tubes, see Figures 2-5 and 2-6. The flow holes were sized to simulate the fuel bundle lateral hydraulic resistance. The outer tubes in the pattern had solid walls so all model flow was contained in the core.

2.3 Instrumentation

Instrumentation for this program fulfilled two basic functions. The first was for the measurement of flow at various flow metering locations in the model. This instrumentation consisted of inlet flow meters, outlet flow meters and core tube resistor plates. In addition, loop temperature measurements are included in this category. The second was for the measurement of absolute pressures upstream of the inlet and outlet resistor plates.

2.3.1 Vessel Inlet and Outlet Flow Instrumentation

The inlet flow was set and balanced by prescribing appropriate differential pressures for the mercury manometers permanently connected to the Gentile flow meters of the test facility.

Outlet flow was balanced using elbow taps placed in the elbows downstream of the model. The elbows were cross-calibrated against the inlet Gentile flow meters. The pressure signals were obtained as mercury manometer column heights.

Flow metering for the part-loop tests consisted of a Stauscheibe Flow Meter and a Gentile Flowmeter installed in the 4 inch reverse inlet flow lines which were calibrated in TF-2; and a Gentile flow meter in an 8 inch line installed at the reverse outlet nozzle, which was calibrated at the Alden Labs.

The test facility water temperature was regulated and monitored continuously by a Honeywell Recorder.

2.3.2 Model Instrumentation

The core inlet and outlet flow distributions over the 217 model core locations were determined by measurement of pressure differentials across the core tube inlet and outlet resistor plates. Each core tube was individually calibrated for core tube inlet and outlet flow measurement. The inlet metering plate calibrations took into account the respective core tube upstream geometry.

The core inlet and outlet pressure distributions over the 217 model core locations were determined by measurement of absolute pressures upstream of the core inlet and outlet resistor plates. The inlet pressure is used directly to indicate the bundle inlet pressure. The absolute pressure measured upstream of the outlet orifice is used with a calibration coefficient and outlet flow rate to determine a calculated core exit pressure field for a station just above the upper end fitting.

2.4 Data Acquisition

Hydraulic pressure data from the model was acquired by means of variable reluctance type Pace P3D and P7D transducers and recorded by a Non-Linear Systems data logger. The data acquisition system consists of instrument manifold panels, pressure transducers, calibration system, and a data logger.

The block diagram of Figure 2-7 shows the flow of information from the hydraulic pressure source to the recorded output on magnetic tape and teletype copy. Essentially, hydraulic pressures from the model were transmitted through pressure tap leads to the Pace instruments via electrically operated manifold values. The data logger sequentially actuated the manifold valves connecting selected individual pressure tap locations to the pressure measurement stations equipped with Pace instruments. Static and total pressures in the model were measured relative to reference pressures provided by mercury columns. Differential pressures across selected model locations were measured directly by the Pace instruments. The Pace instruments were calibrated using the mercury columns or with water columns. Each pressure reading was the average of 45 sample readings and was recorded onto magnetic tape and on teletype paper by means of the data logger. The paper copy became the laboratory file copy of the data. The raw data on magnetic tape was processed further on the company's CDC 7600 computer.

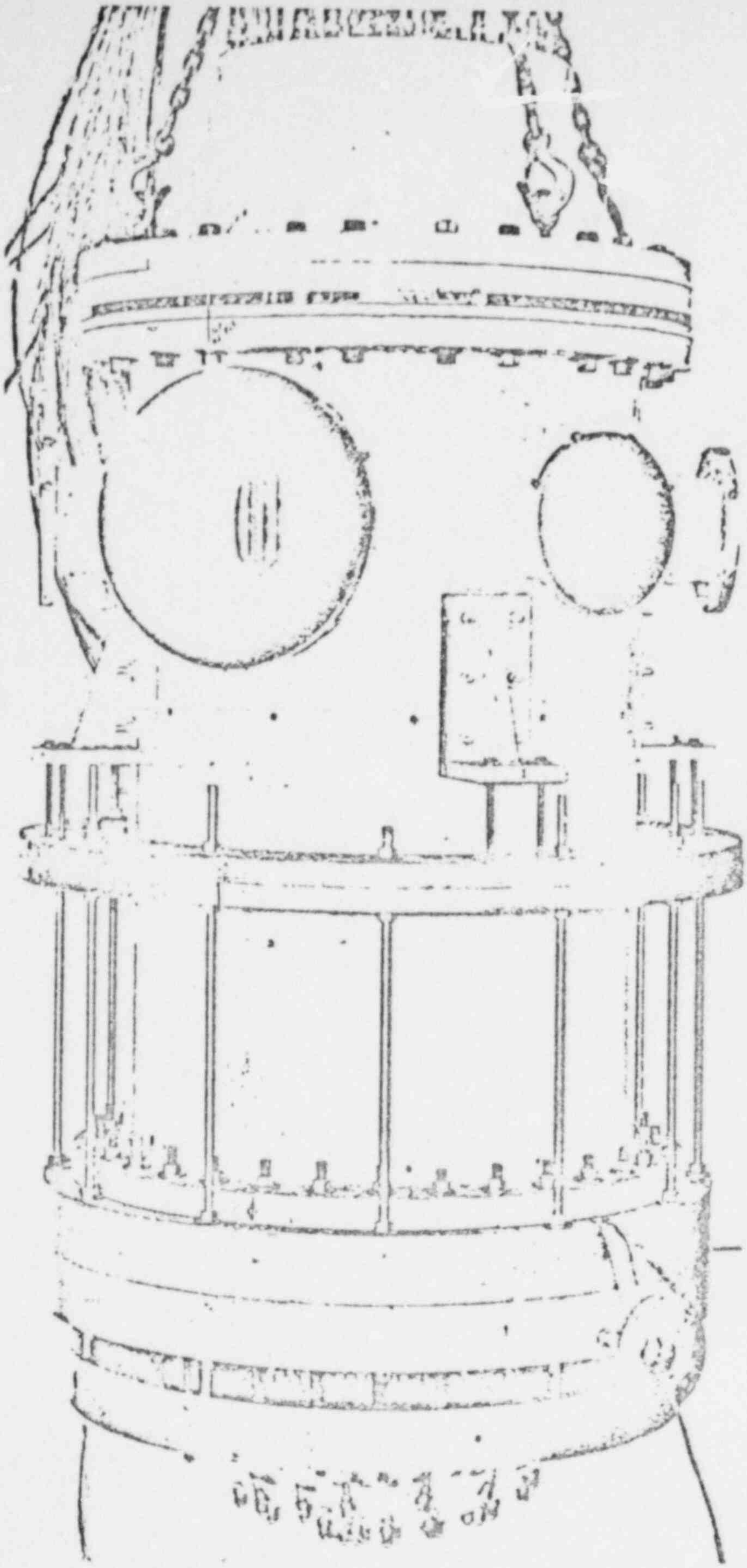


Figure 2-1 Photograph of 3410 Mw(t) Open Core Flow Model

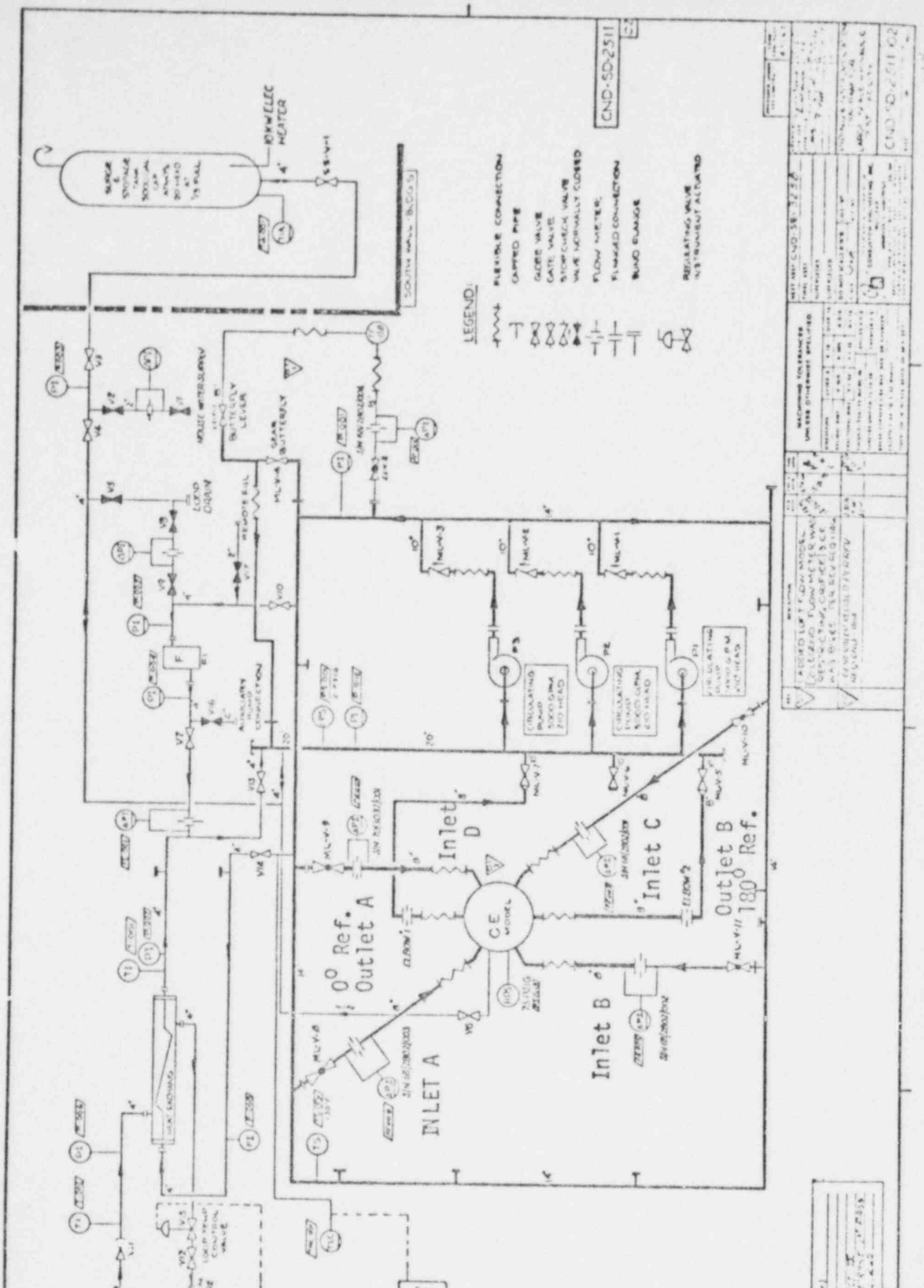
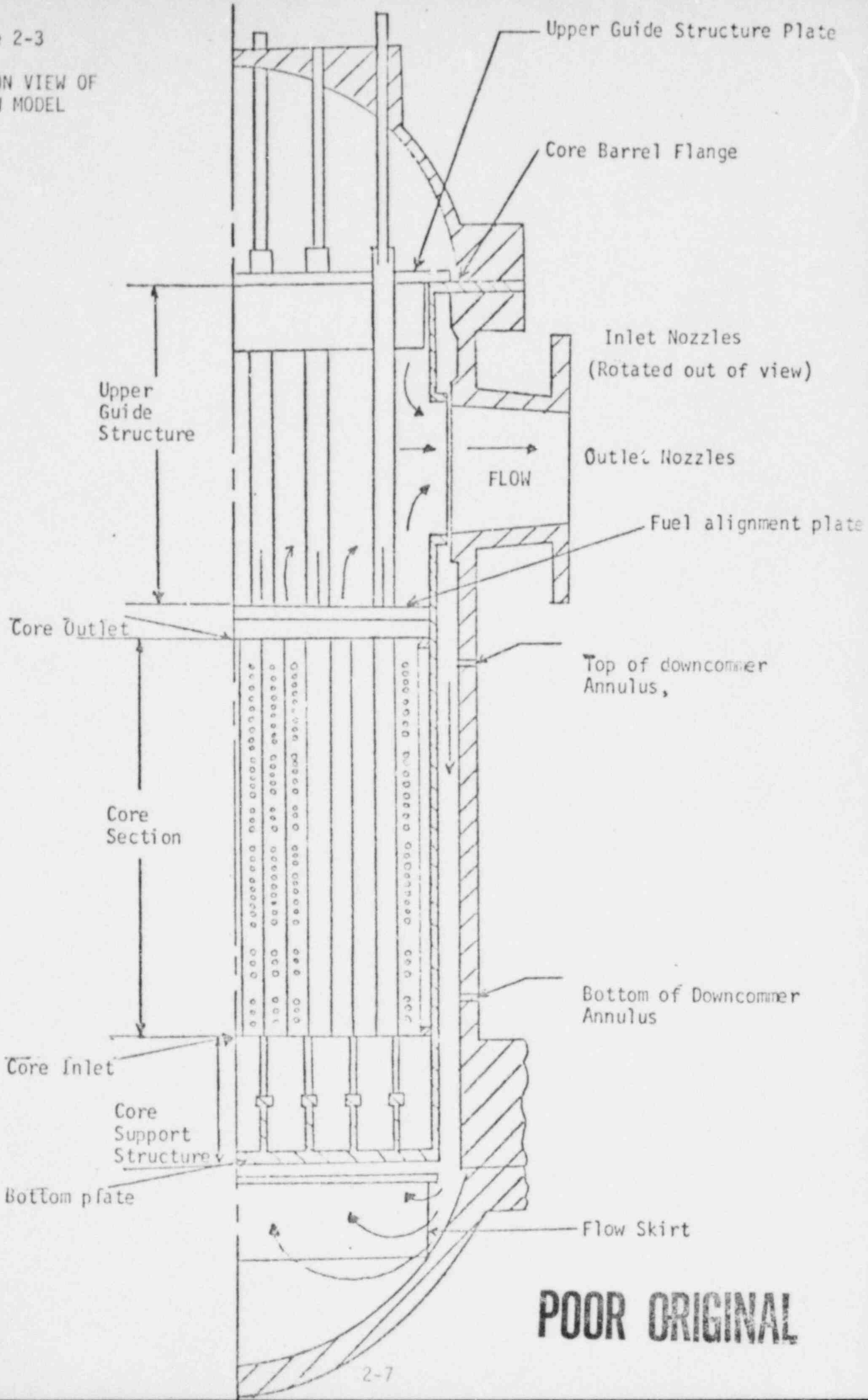

CE MODEL
INLET A
Inlet B
Inlet C
Inlet D
0° Ref. Outlet A
Outlet B 180° Ref.
CIRCULATING PUMP 5000 GPM 210' HEAD
SURGE & STORAGE TANK
IMMERSION HEATER
SOUTH WALL (BLDG 5)
HOUSE WATER SUPPLY
BUTTERFLY LEVER
GEAR BUTTERFLY
REMOTE FILL
AUXILIARY PUMP CONNECTION
HEAT EXCHANGER
COOLING TOWER WATER SUPPLY
COOLING TOWER WATER RETURN
TEMP CONTROL VALVE
TEMP RECORDER CONTROLLER
LEGEND:
FLEXIBLE CONNECTION
CAPPED PIPE
GLOBE VALVE
GATE VALVE
STOP CHECK VALVE
VALVE NORMALLY CLOSED
FLOW METER
FLANGED CONNECTION
BLIND FLANGE
REGULATING VALVE INSTRUMENT ACTUATED
CND-SD-2511

Figure 2-2

Figure 2-3

ELEVATION VIEW OF
FLOW MODEL



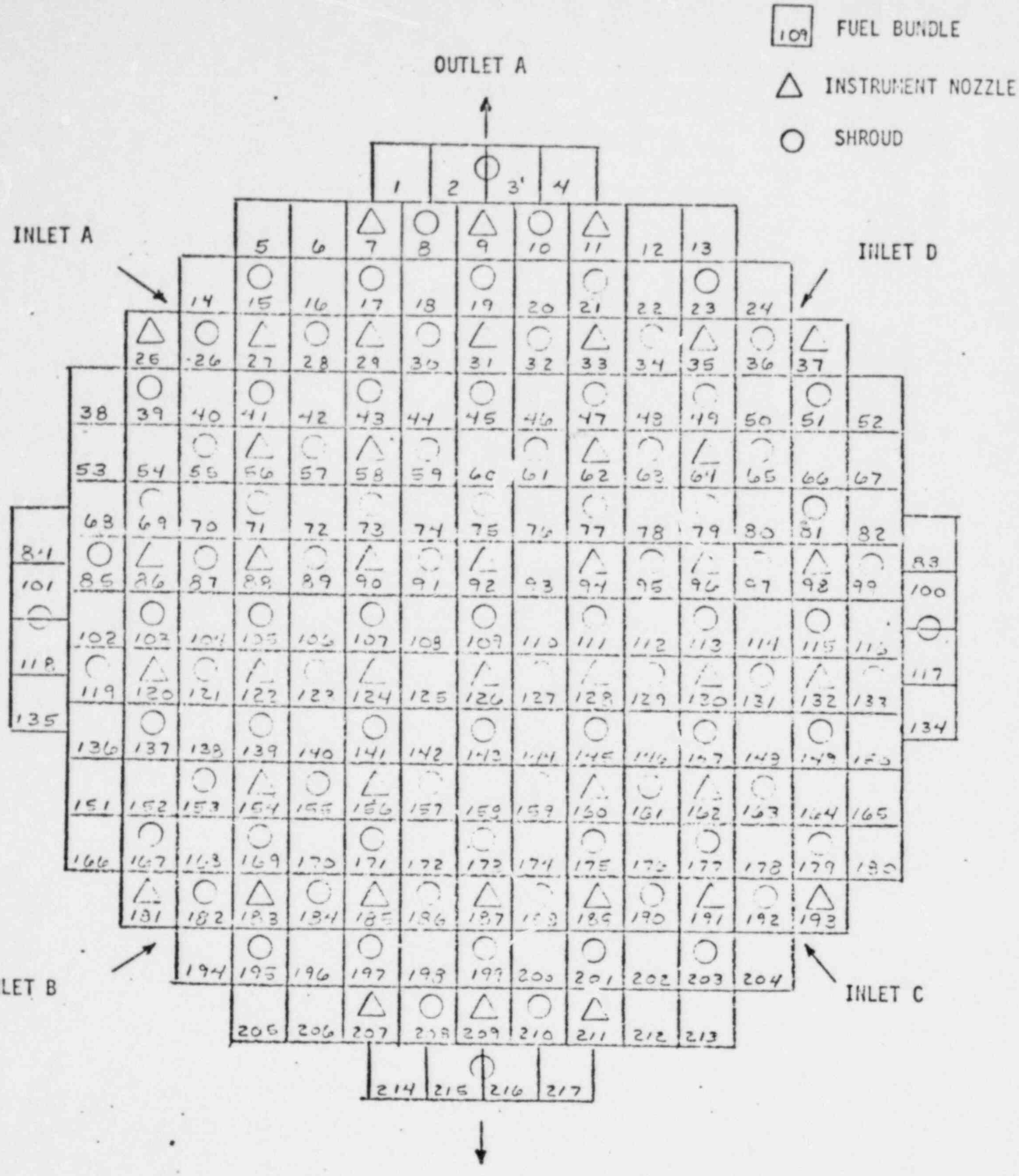
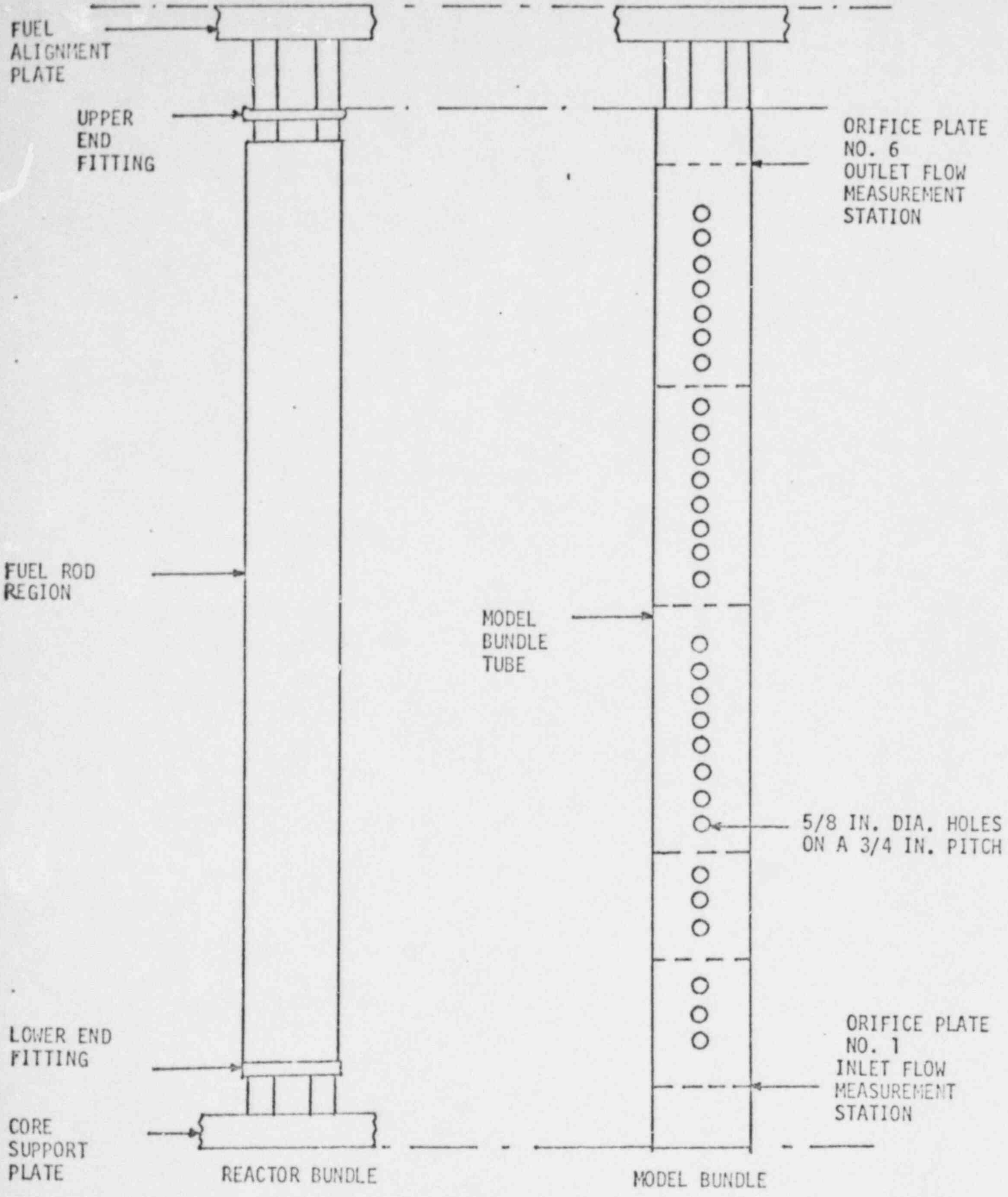


Figure 2-4 - Arrangement of Flow Model Core



POOR ORIGINAL

FIGURE 2-5
COMPARISON OF REACTOR AND MODEL FUEL BUNDLE GEOMETRIES

FIGURE 2-6
PHOTOGRAPH OF A MODEL CORE TUBE

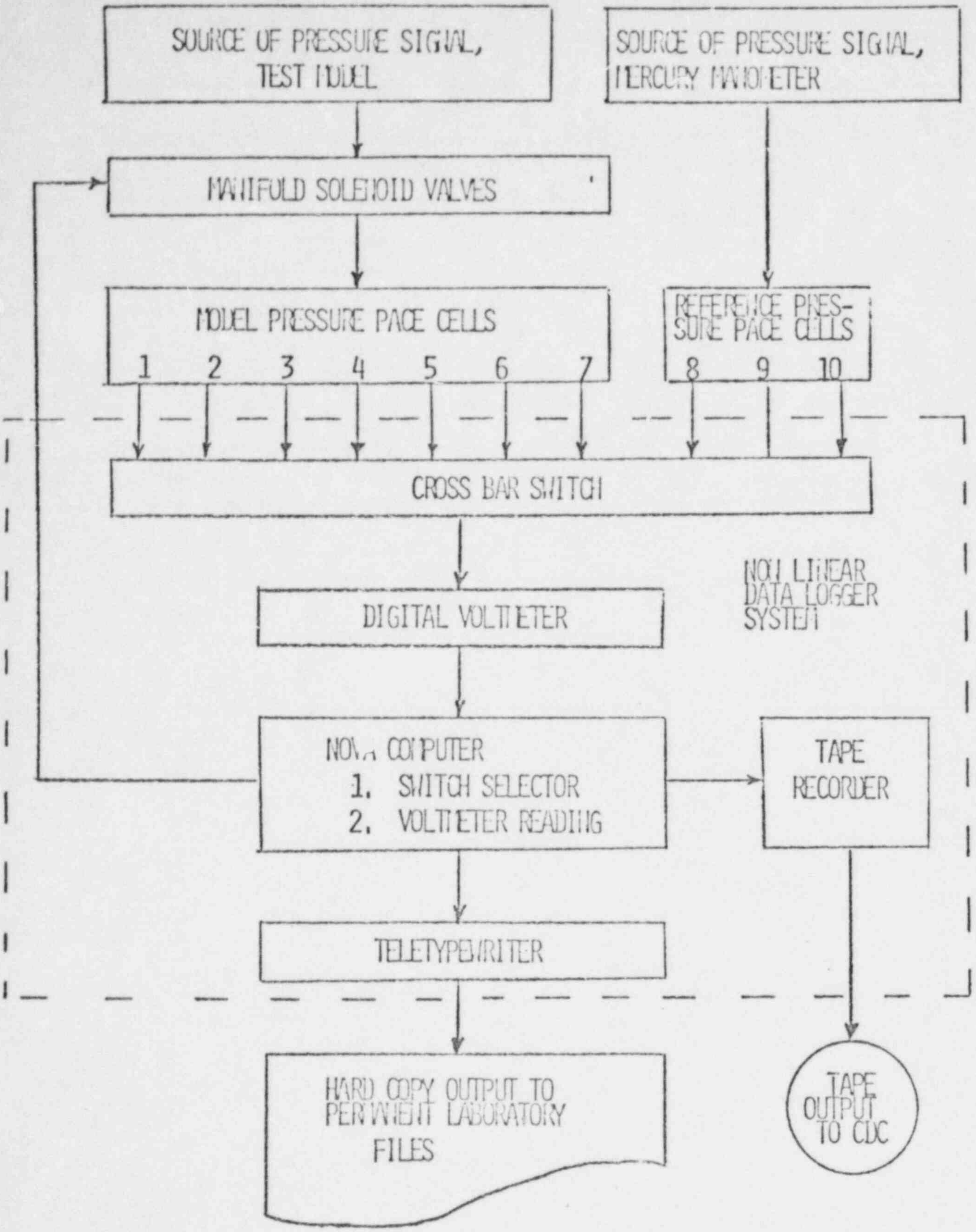


FIGURE 2-7

SCHEMATIC OF DATA LOGGING COMPONENTS

3.0 TEST PROGRAM

3.1 Test Procedure

A list of test runs, the type of tests, and the test objectives are presented in Table 3-1. Four basic four loop tests were performed with balanced and unbalanced flow conditions. Each of the four loop tests consisted of at least 3 test runs.

The test procedure was to establish loop operation and model flows to obtain stable loop flow/test conditions as indicated by Table 3-2. Prior to taking test data, the Pace instruments were calibrated against water or mercury columns, the calibration data being recorded with the data logger. The data for each test was then recorded automatically with the Pace instruments and the data logger. Additionally, loop pressure, flow and temperature monitoring data were recorded manually on data sheets. After each test, post-test calibrations were performed on the Pace instruments.

3.2 Data Processing

Data obtained with the four loop balanced and unbalanced loop configurations were reduced via utility computer codes on the company's CDC 7600 computer. The computer codes are used to read the data logger created data file and convert the Pace voltages to engineering pressure units via the calibration data. The data is then reduced to provide:

1. Core inlet and outlet pressure distributions
2. Core inlet and outlet flow distributions
3. Mass balance: core inlet vs. model inlet
4. Core mass balances: core inlet vs. core outlet
5. Mass balance: model inlet vs. model outlet

The part-loop test data were reduced via modified versions of the four-loop computer codes. The modifications allowed for reverse flow at the inlets and outlets of the model.

TABLE 3-1

LIST OF TEST RUNS

RUN NO.	TEST NO. (see Table 3-2)	DATE	OBJECTIVE	COMMENTS
1	2	7/8/76	Balanced 4 loop flow-hydraulic data	
2	2	7/9/76	Balanced 4 loop flow - hydraulic data	Several inconsistant data values at times of data logger trips.
3	2	7/9/76	Balanced 4 loop flow - hydraulic data	
4	1	7/19/76	Balanced 4 loop flow - hydraulic data	
5	1	7/20/76	Balanced 4 loop flow - hydraulic data	
6	1	7/21/76	Balanced 4 loop flow hydraulic data	
7	3	7/22/76	5% low flow inlet A-hydraulic data	
8	3	7/26/76	5% low flow inlet A - hydraulic data	
9	3	7/27/76	5% low flow inlet A - hydraulic data	
10A	-	8/2/76	Visual study of flow patterns	Several flow conditions studied
10	-	8/3/76	7% low flow inlet A - hydraulic data	
11	3A	8/4/76	7% low flow inlet D - hydraulic data	
12	3A	8/16/76	7% low flow inlet D - hydraulic data	
13	3A	8/17/76	7% low flow inlet D - hydraulic data	
14	3A	8/18/76	7% low flow inlet D - hydraulic data	
15	4	12/8/76	Part loop tests - hydraulic data	Insufficient instrument range
16	4	12/10/76	Part loop tests - hydraulic data	Flow rate change at inlet A during test

Table 3-1 (cont.)

RUN NO.	TEST NO.	DATE	OBJECTIVE	COMMENTS
17	4	12/11/76	Part loop tests - hydraulic data	Insufficient Instrument range
18	4	12/13/76	Part loop tests - hydraulic data	Insufficient Instrument range
19	4	12/20/76	Part loop tests - hydraulic data	Solenoid valve panel had post test leaks
20	4	12/21/76	Part loop tests - hydraulic data	
21	4	12/28/76	Part loop tests - hydraulic data	Calibration zero shift
22	4	12/29/76	Part loop tests - hydraulic data	
23	4	12/30/76	Part loop tests - hydraulic data	

TABLE 3-2

MODEL FLOW CONFIGURATIONS

Test No.	No. of Loops	Flow Configuration	Inlet Flow, gpm				Outlet Flow gpm		Total Flow gpm
			A	B	C	D	A	B	
1	4	Equal in four loops	2750	2750	2750	2750	5500	5500	11000
2	4	Equal in four loops	1875	1875	1875	1875	3750	3750	7500
3	4	5% low in inlet A	2612	2796	2796	2796	5408	5592	11000
3a	4	7% low in inlet D	2817	2816	2817	2550	5366	5634	11000
4	2	Loops on same side. Equal flow in both loops	4493	-743	-743	4493	8986	-1486	7500

4.0 TEST RESULTS

Data from individual test runs were combined to obtain average results for core flow and distribution maps. The test data for the model core are presented in the following forms:

1. Core inlet flow distribution, expressed in the form of the ratio of local to average bundle inlet flow rates, $Wi/\overline{W}$) inlet.
2. Core inlet pressure distribution, expressed in the form of the ratio:

$$Ei_{inlet} = \frac{P_{in\ i} - \overline{P_{in}}}{\overline{P_{in}} - \overline{P_{out}}}$$

where:

P_{in} is the inlet static pressure for bundle i

$\overline{P_{in}}$ is the average inlet static pressure for the core

$\overline{P_{out}}$ is the average outlet static pressure for the core

3. Core exit flow distribution, expressed in the form of the ratio of local to average bundle outlet flow rates, $(Wi/\overline{W})$ outlet.
4. Core exit pressure distribution, expressed in the form of the ratio:

$$Ei_{outlet} = \frac{P_{out\ i} - \overline{P_{out}}}{\overline{P_{in}} - \overline{P_{out}}}$$

where:

$P_{out\ i}$ is the outlet static pressure for bundle i

4.1 Four Loop Tests

The major objective of this study was to determine the core flow and pressure distributions within the 3410 MW(t) Class PWR reactor for four loop operation. Core flow and pressure distribution data from individual four loop test runs were combined to obtain average results. A visual inspection of the data indicates that the test results from balanced and unbalanced flow tests are sufficiently similar to also be combined to provide four loop average results. In addition, quadrant maps were generated, where data from symmetrical locations were combined.

The core inlet and outlet flow distributions on the symmetrical quadrant basis are shown in Figures 4-1 and 4-2. The core inlet and outlet pressure distributions on the symmetrical quadrant basis are shown in Figures 4-3 and 4-4. The use of quadrant summary maps assumes that the model core can be divided into four similar quadrants which are then considered to be equal. Examination of the data brought out the basic similarity among symmetrical quadrant values for the tested four loop conditions. The standard deviation for each of the quadrant maps is presented on the maps.

The core flow distribution on a full core basis is presented in Figures 4-5 and 4-6 for the inlet and Figures 4-7 and 4-8 for the outlet. Figures 4-5 and 4-7 show the core flow distribution in percentage deviations from average flow. The core locations shown with asterisks were locations with no data. These results were re-plotted into segregated core maps as shown in Figures 4-6 and 4-8, where regions of high and low flow can easily be visualized.

It is also apparent from Figures 4-5 through 4-8 that the distribution at the core inlet shows more variation than the distribution at the core outlet. The core wide inlet distribution showed flow deviations from average between [ ]. The core outlet had deviations between [ ] of average flow. When averaged to a symmetrical quadrant, the core inlet deviations ranged between [ ] of average flow and the outlet deviations ranged between [ ] of average flow.

A comparison of the mass balance at the model and core inlets and outlets is shown in Table 4-1. The average variation was 1% of model inlet flow.

4.2 Part Loop Tests

Core flow and pressure distribution data were taken for a one-steam generator, 2 pumps configuration. This test configuration was considered to be the theoretical worst case for changes in four loop flow and pressure distribution. The data were reduced to core and pressure distribution maps on an individual test run basis. There was no attempt made to average and consolidate the results as with the four loop test data.

Figures 4-9 and 4-10 illustrate the core inlet and core outlet flow distributions for test run 20. Segregated core maps, Figure 4-11, are also presented to show with visual clarity the effect of this test configuration. There was more flow variability in both inlet and outlet flow distributions as compared to the four loop configuration. [ ]

4.3 Data Scatter and Uncertainties

The measured experimental scatter and calculated uncertainties shown in Table 4-2 are due to:

1. Instrumentation repeatability. Repeatability of the data, based on an analysis of the calibration data was determined to be ± 0.1% (1σ limits) of full scale. This was increased to ± 0.2% (1σ limits) if drift of the transducers were taken into account.
2. Repeatability of flow setting. Operation of the test facility over several start-ups will introduce small variations to the flow splits, even for repeated tests runs. This produces some unquantified random fluctuation on the variable being measured.
3. Assumed similarity among balanced and unbalanced flow test conditions. A visual observation of data indicates that test results are sufficiently similar to be combined. However, variation of flow splits will produce some unquantified fluctuation of variable being measured.
4. Reduction of data on basis of symmetrical quadrants. Although visual inspection of figures 4-5 through 4-8 indicates there is probably sufficient symmetry to warrant this quadrant analysis, the quadrant to quadrant scatter which is more systematic than random,is included in the experimental scatter.

4.4 References for Section 4.0

4-1 Kline, S. J. and McClintock, F. A., "Describing Uncertainties in Single Sample Experiments", Mechanical Engineering, pp 3-8, January, 1953.

TABLE 4-1

TABULATION OF MASS BALANCE AT CORE AND MODEL INLET, CORE AND MODEL OUTLET

Test Run #	E_1 Core Inlet vs Model Inlet % of Model Inlet	E_2 Core Outlet vs Core Inlet % of Model inlet	E_3 Model Inlet vs. Model Outlet % of Model inlet
3	0.3	1.8	1.1
4	1.2	0.07	1.05
5	0.2	1.8	1.3
6	1.6	0.2	1.3
7	0.7	1.5	1.1
8	0.6	1.4	1.5
9	1.0	1.3	1.4
10	1.3	1.0	1.4
11	0.8	1.2	1.6
12	0.8	1.2	1.7
13	1.3	1.1	1.4
14	0.3	0.3	2.6
15	1.4	1.0	1.2
16	1.0	1.4	1.2
Average all runs	0.9	1.1	1.4

E_1 = (Total Flow at Inlet Nozzles - Total Flow at core inlet) x 100%/Total Flow at outlet nozzles.

E_2 = (Total Flow at Core Inlet - Total Flow at Core Outlet) x 100%/Total Flow at Inlet Nozzles.

E_3 = (Total Flow at Outlet Nozzles - Total Flow at Inlet Nozzles) x 100%/Total Flow at Outlet Nozzles.

Note: Core inlet and Core outlet total flow = average flow thru core tubes with functioning flow measurement times 217 core tubes.

TABLE 4-2

EXPERIMENTAL SCATTER

Experimental Variable Name		Experimental Scatter	Uncertainty+
Core Inlet Flow Distribution	-Full core	1.6%	0.9%
	-Quadrant	3.0%	*
Core Outlet Flow Dsstribution	-Full core	0.55%	0.7%
	-Quadrant	1.2%	*
Core Inlet Pressure Dist.	-Full core	0.54%	0.7%
	-Quadrant	0.87%	*
Core Outlet Pressure Dist.	-Full core	0.35%	0.9%
	-Quadrant	0.62%	*
Mass Balance			
(Model Inlets-Core Inlet)/Model Inlet		.9%	*
(Core Inlet-Core Outlet)/Model Inlet		1.1%	*
(Model Outlet-Model Inlet)/Model Inlet		1.4%	*

+Calculated uncertainties based on single sample method of Kline and McClintock (Reference 4-1).

*Not calculated

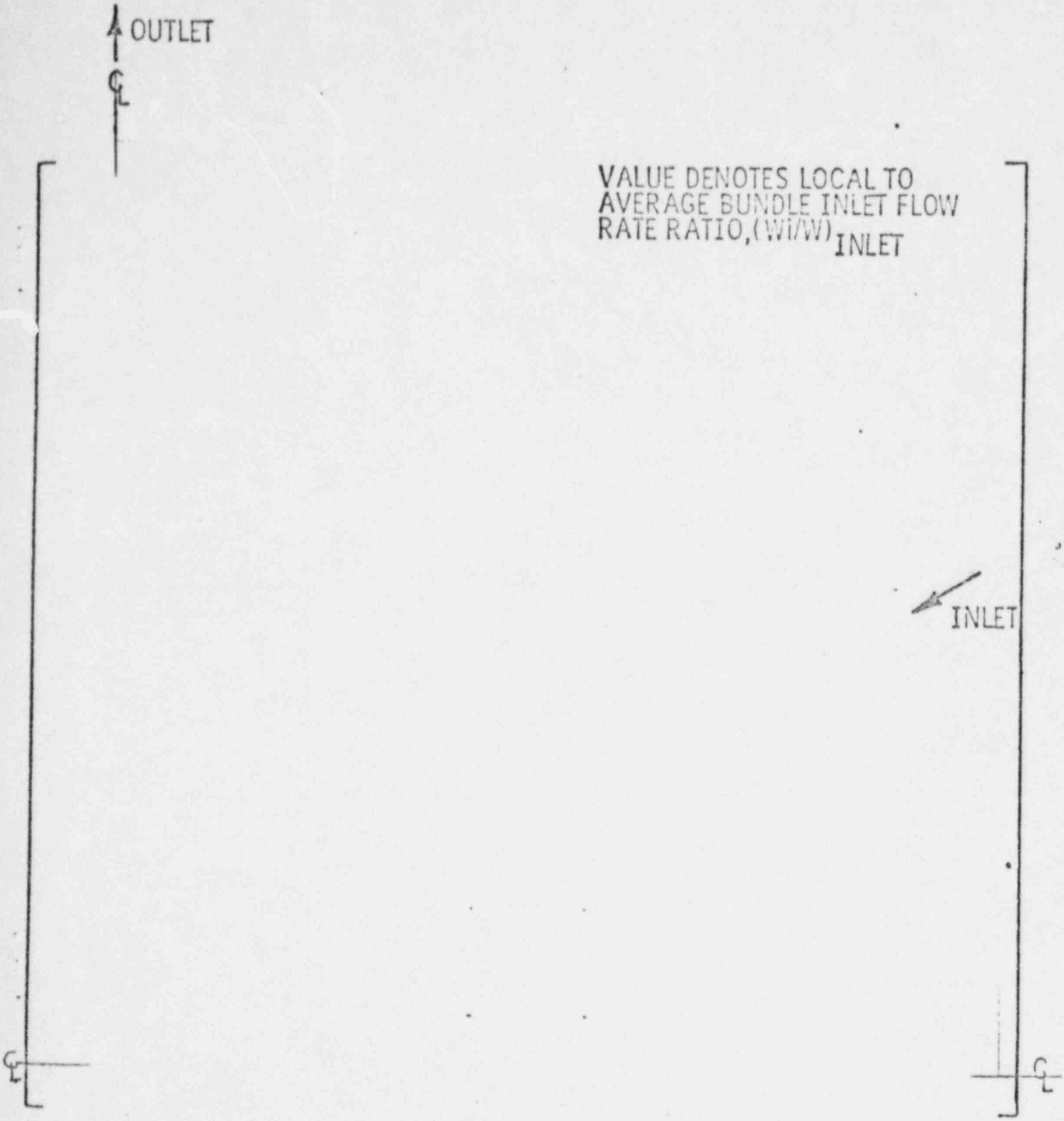


FIGURE 4-1

MODEL CORE INLET FLOW DISTRIBUTION - QUADRANT

VALUES DENOTE LOCAL TO AVERAGE BUNDLE OUTLET FLOW RATE RATIO, $(W_i/W)_{OUTLET}$

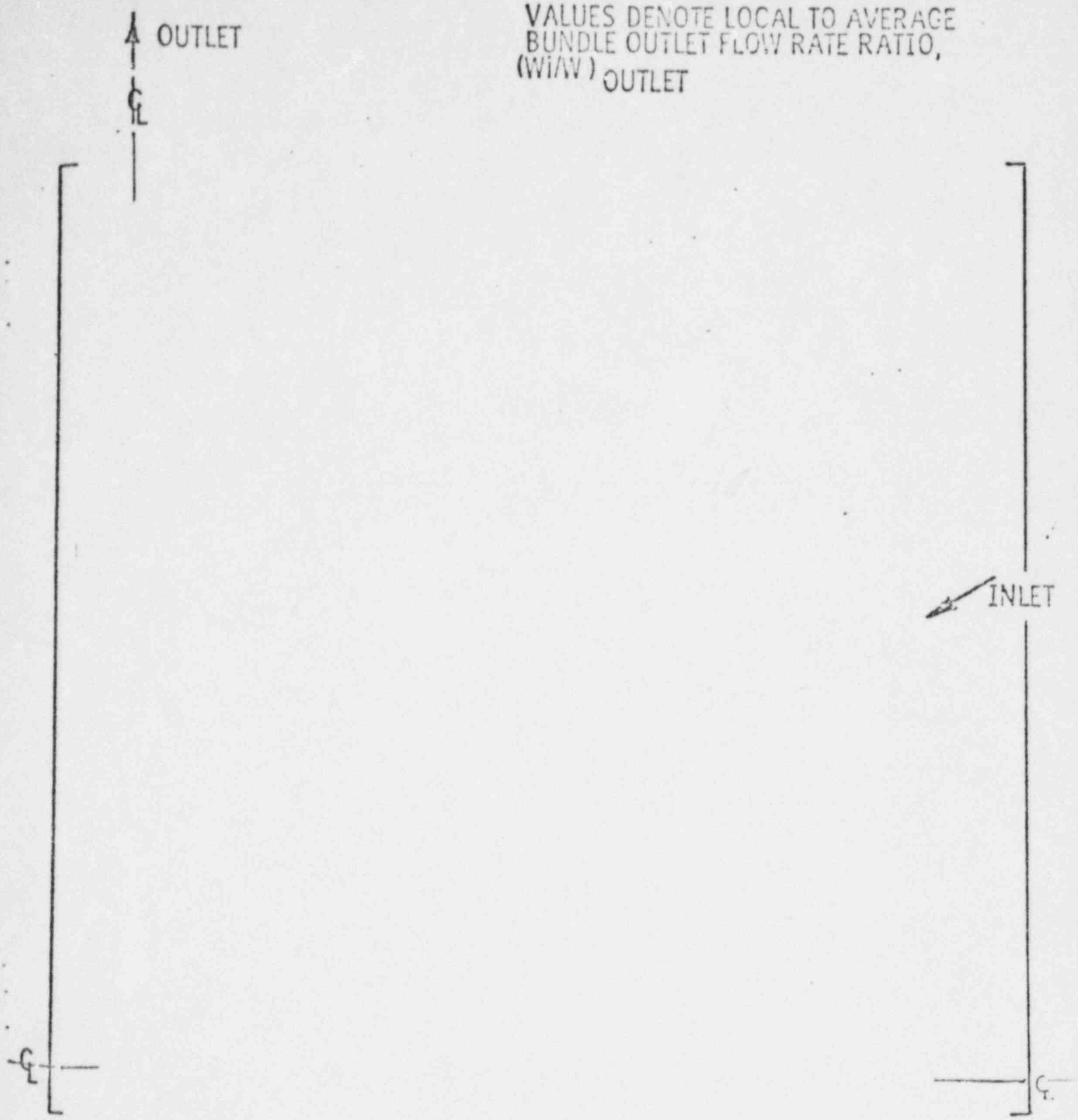


FIGURE 4-2

MODEL CORE OUTLET FLOW DISTRIBUTION - QUADRANT

OUTLET

℄

VALUE DENOTES THE DIMENSIONLESS INLET PRESSURE DISTRIBUTION

$$E(i)_{INLET} = \frac{P_{INi} - \bar{P}_{IN}}{\bar{P}_{IN} - \bar{P}_{OUT}}$$

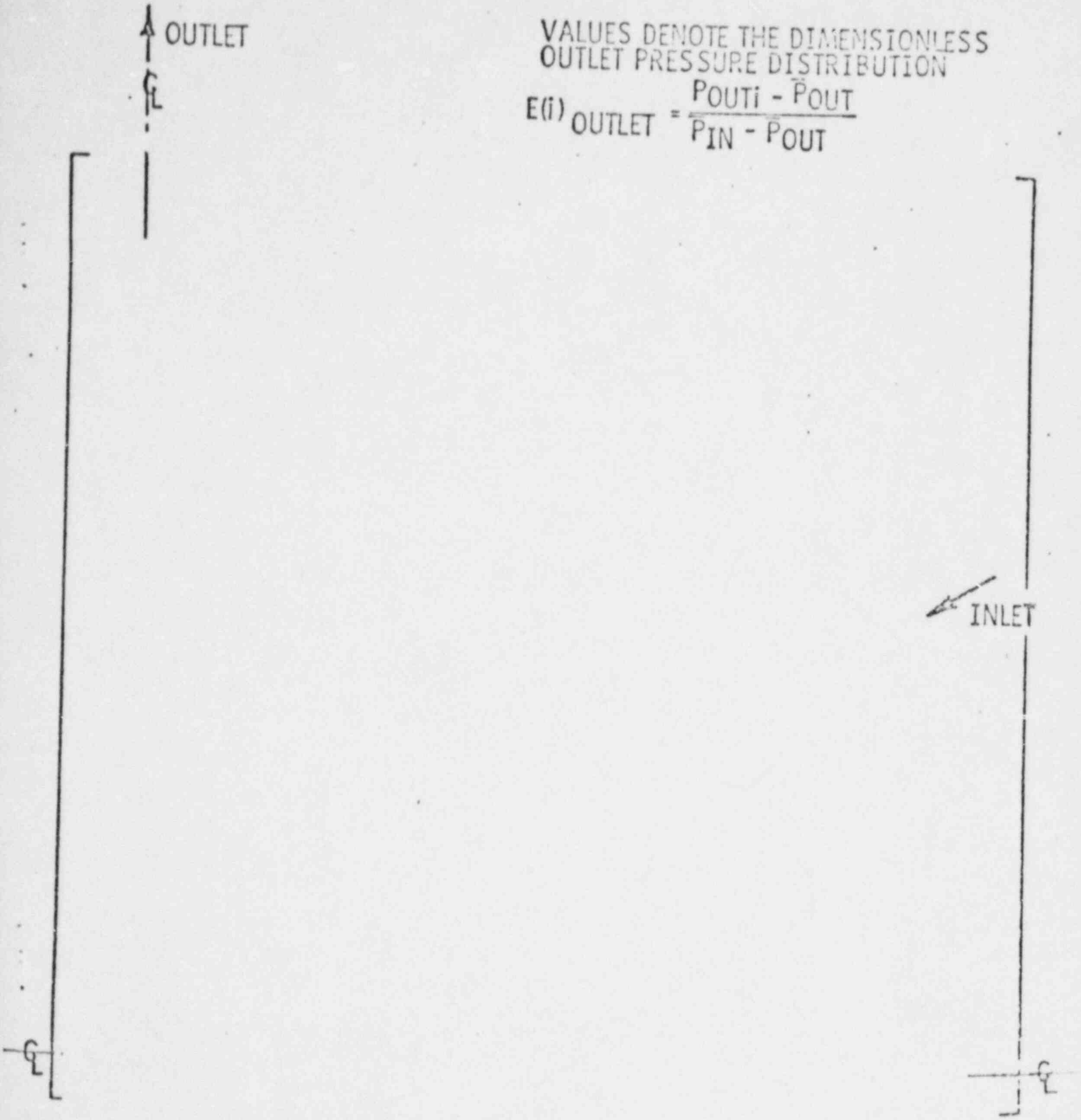
INLET

℄

℄

FIGURE 4-3

MODEL CORE INLET PRESSURE DISTRIBUTION - QUADRANT

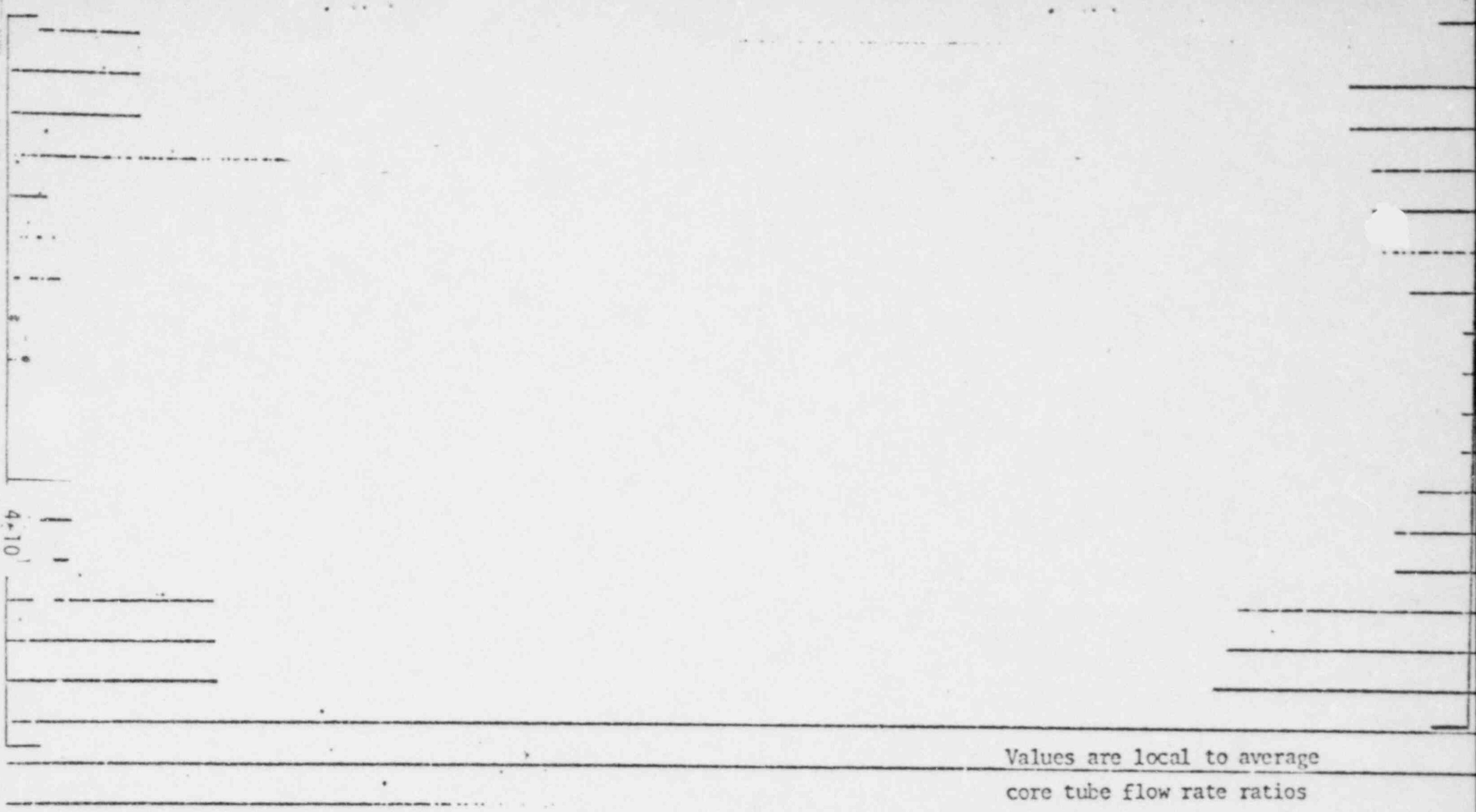


VALUES DENOTE THE DIMENSIONLESS OUTLET PRESSURE DISTRIBUTION

$$E(i)_{OUTLET} = \frac{P_{OUTi} - \bar{P}_{OUT}}{P_{IN} - \bar{P}_{OUT}}$$

FIGURE 4-4

MODEL CORE OUTLET PRESSURE
DISTRIBUTION QUADRANT



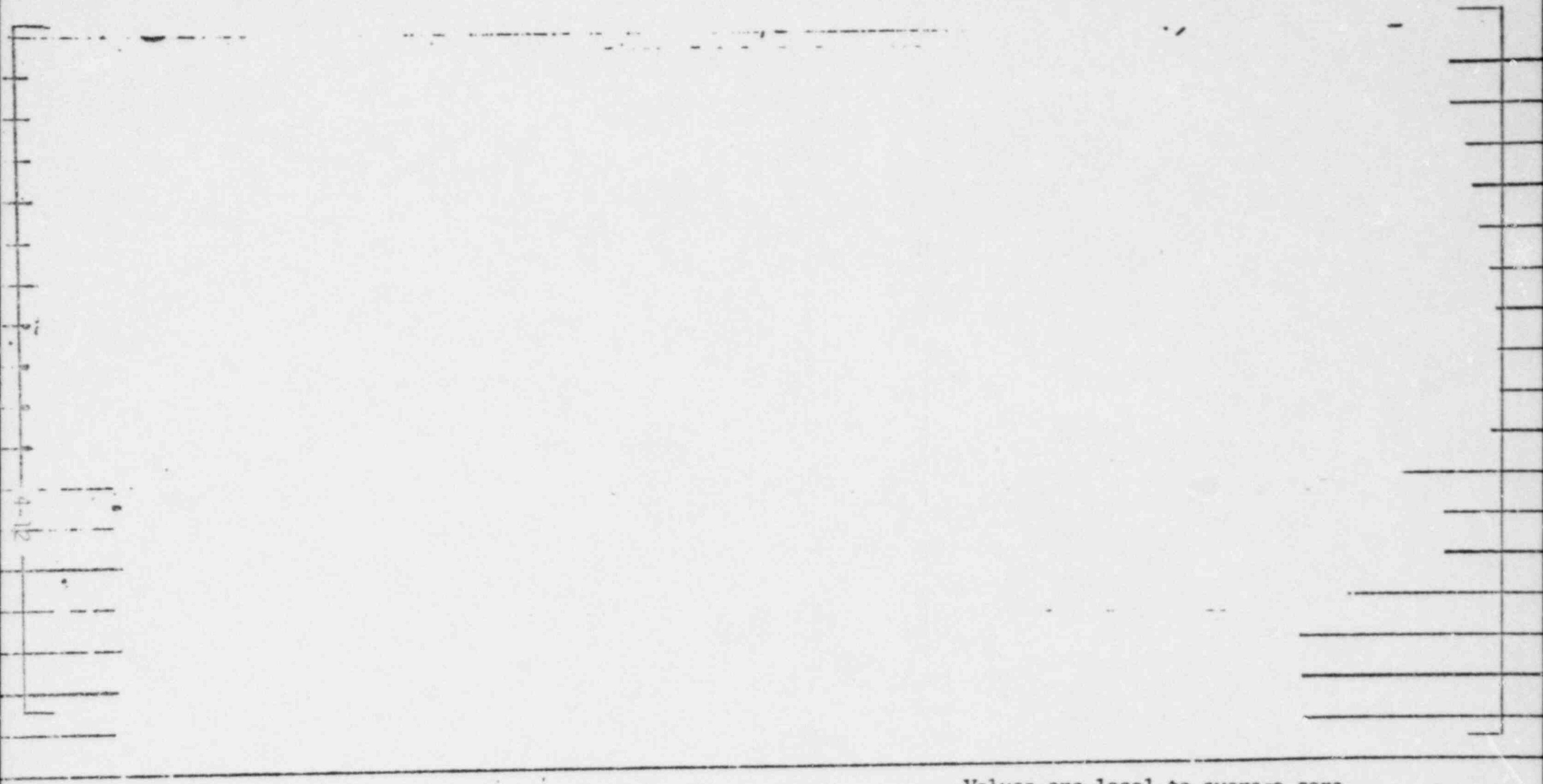
Values are local to average core tube flow rate ratios

******* No test data

FIGURE 4-5

MODEL CORE INLET FLOW DISTRIBUTION - FULL CORE

Figure 4-6 SEGREGATED MAPS OF FLOW DEVIATION FROM AVERAGE CORE INLET



Values are local to average core tube flow rate ratios

****** No test data

Figure 4-7 MODEL CORE OUTLET FLOW DISTRIBUTION - FULL CORE

FIGURE 4-8 SEGREGATED MAPS OF FLOW DEVIATION FROM AVERAGE CORE OUTLET

TWO LOOP-ONE STEAM GENERATOR TESTS, 6700 GPM NOMINAL FLOW,
REVERSE FLOW THRU INLETS 2 AND 3 AND OUTLET 2,
TEST IDENTIFICATION= 20- 7
CERTIFICATION NOT REQUIRED

CORE INLET FLOW DEVIATION FROM AVERAGE, PERCENT

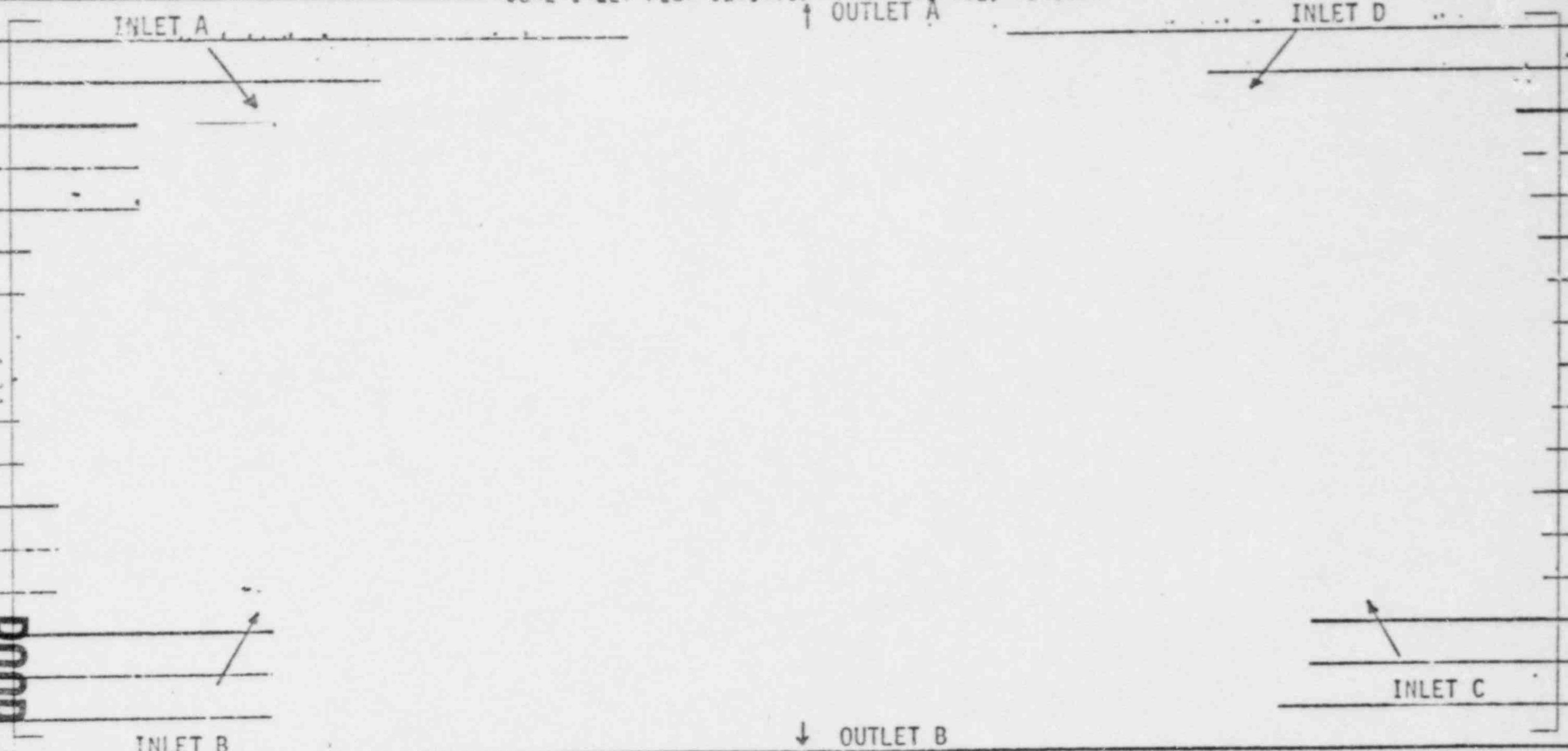


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FIGURE 4-9 CORE INLET FLOW DISTRIBUTION FOR PART-LOOP TEST RUN 20

TWO LOOP-ONE STEAM GENERATOR TESTS. 6700 GPM NOMINAL FLOW.
REVERSE FLOW THRU INLETS 2 AND 3 AND OUTLET 2.
TEST IDENTIFICATION- 2 - 7
CERTIFICATION NOT REQUIRED

CORE OUTLET FLOW DEVIATION FROM AVERAGE, PERCENT

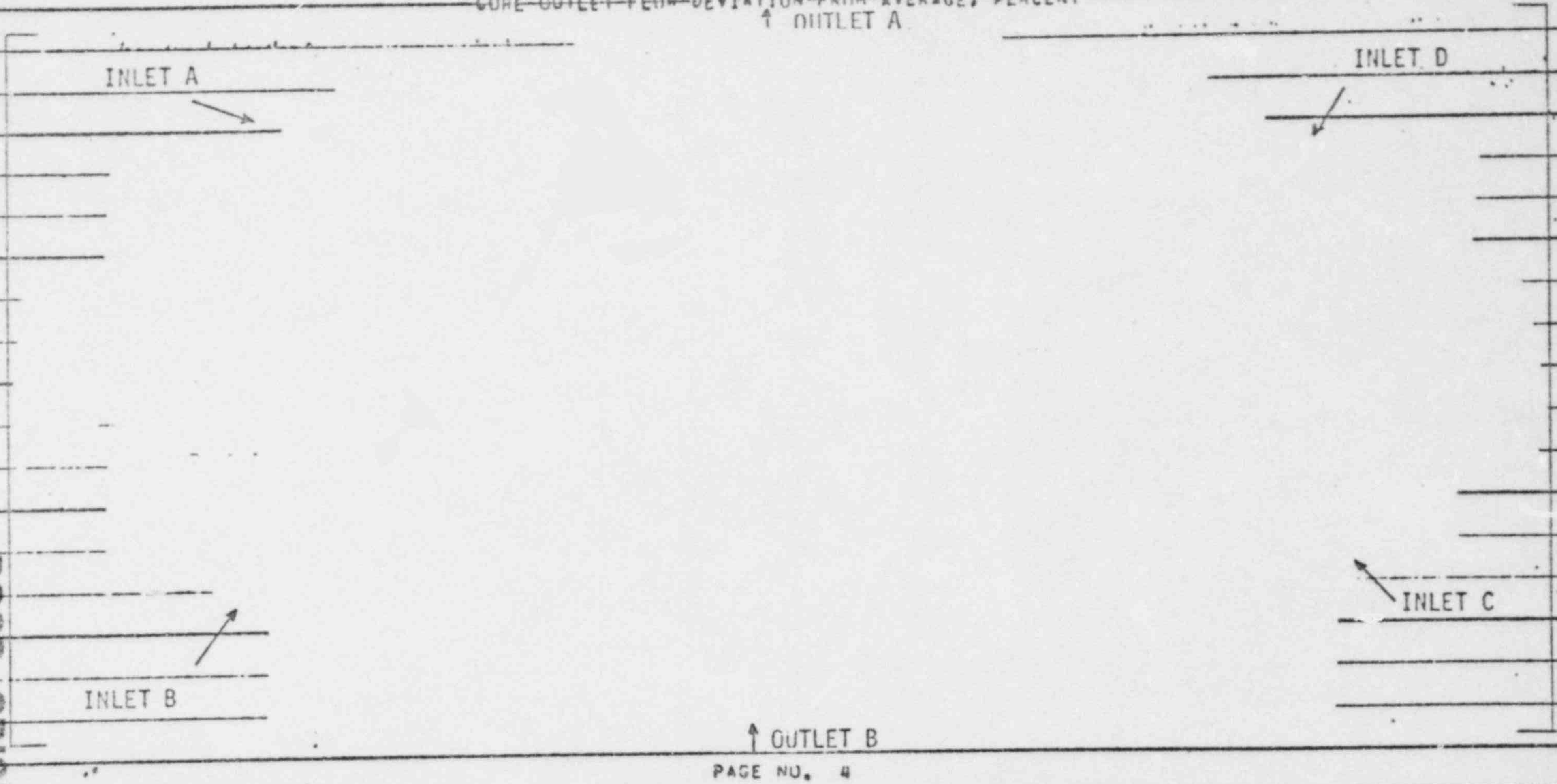

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FIGURE 4-10 CORE OUTLET FLOW DISTRIBUTION FOR PART LOOP TEST RUN 20

CORE INLET

CORE OUTLET

FIGURE 4-11 SEGREGATED CORE FLOW DISTRIBUTION MAPS FOR PART LOOP TESTS