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AN IMPROVED RELAP4 JET PUMP MODEL

BY
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INTERIM REPORT

ABSTRACT

An improved RELAP4 Jet Pump Model was developed based on subscale jet pump tests. This work was part of the INEL technical support to the NRC for Industry Cooperative Programs. Model evaluation results show the model to be an improvement of the previous model.

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SUMMARY

An improved RELAP4 jet pump model has been developed as part of the Jet Pump Test and Model Development Program[1] conducted at the INEL. Data from the program tests were used to develop the model.

Since the jet pump model currently available in RELAP4/MOD6 Update 4 is fundamentally sound, it is used as the basis of the improved model. The improved model is developed by correcting discrepancies between the current model and the test data with empirical parameters. This data is for a 1/6 scale jet pump operating under steady state, subcooled conditions.

Evaluation of the improved model shows significant improvement in calculating jet pump behavior. Not only are subscale calculations more realistic, but full scale results are also improved. Calculations for the TLTA show the new model to be well behaved with reasonable results.

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I. INTRODUCTION

As part of the Jet Pump Test and Model Development Program an improved RELAP4 jet pump model has been developed. Since jet pumps are used to circulate reactor coolant through the core of General Electric Co. Boiling Water Reactors (BWR), and are a major system component, their behavior during a loss of coolant accident (LOCA) must be calculated accurately if reliable safety analysis is to be performed. Jet pump response can significantly affect fuel rod temperatures, an important safety parameter. Consequently, this program was implemented with the objective of improving the RELAP4 jet pump modeling capabilities.

The current RELAP4 jet pump model is fundamentally sound and in general performs well. However, because known defects exist in the model a program was initiated at the Idaho National Engineering Laboratory (INEL) to generate subscale test data and improve the model. This program contained three phases; subscale testing, model development and model evaluation. This report emphasizes the results of the model development and evaluation portions of the program; however because the test data is the basis of this work, a brief description of the tests is provided in Section II. The development and evaluation of the improved model are covered in Sections III and IV, respectively. Jet pump terminology used in this report is defined in Appendix A.

II. TEST DESCRIPTION

This section describes the jet pump test hardware, instrumentation and testing. These tests were conducted in the LOFT Test Support Facility (LTSF) at the INEL and consisted of both subcooled steady state and two-phase transient tests. The jet pump was operated over a wide range of pressures and temperatures for normal and off-design conditions. Extensive subcooled steady state testing was accomplished to provide the primary data base for model development. Two transient two-phase tests were performed for the subsequent model evaluation. For a more detailed test description and presentation of the data see Reference 2.

1. TEST HARDWARE AND INSTRUMENTATION

The 1/6 scale jet pump which was supplied by the General Electric Co., Nuclear Energy Division was installed in the test assembly shown schematically in Figure 1. The test vessel was equipped with three ports allowing flow to be separately directed to or from the pump drive, suction, and discharge openings. The pump suction and discharge ports were provided with baffled plenums to assure uniform flow at jet pump boundaries.

The combination of on-off flow directing valves (FDV-X) and adjustable flow control valves (FCV-X) allowed the jet pump to be tested with any combination of positive and negative flows at the suction, drive and discharge ports, consistent with the main coolant pump (MCP) characteristics.

The pump suction was also provided with a small nitrogen reservoir or accumulator to absorb system pressure surges.

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Provisions were made to install orifices at the inlets and outlets to the jet pump vessel (and at FDV-1 and FDV-5) to control the flow rates and void fraction during the model evaluation (transient) tests. Piping spools also contained spaces for turbine meters, and other instrument penetrations as required.

The test assembly was installed in the facility as shown in Figure 2. For the model development tests, the drive flow from the main coolant pump (MCP) was routed through spool BF-11, through the jet pump test assembly, and returned to the pressure vessel through BF-1 and CV-9. For the model evaluation tests, FCV-6 was closed, and the flow came from the pressure vessel, through CV-9, BF-1, the test assembly, and out the blowdown valve. Because the density is not measured at the jet pump assembly inlet turbine meters, the fluid must be subcooled if data is to be meaningful. Subcooling is maintained by a large ($2.8m^3$) nitrogen accumulator attached to the top of the pressure vessel and flow restriction orifices upstream of the vessel as shown in Figure 1. Since the accumulator is much larger than the pressure vessel, it is capable of maintaining higher than saturation pressures over a time interval sufficient for collecting the required data.

Instrumentation used in the jet pump tests is shown schematically in Figure 1. The jet pump test instrumentation provides mass flow and differential pressure information throughout the jet pump over a complete range of on and off-design operating conditions, including transients. Instrument ranges and accuracies are listed in Table I.

Two gamma densitometer measurement locations (ρ) are shown on Figure 1, although only one densitometer was used per test. The densitometer was installed on the pump vessel discharge line for the first blowdown test, and on the drive line for the second, thereby recording the density of the two phase flow exiting the jet pump vessel.

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2. TESTING

As previously stated the steady state tests were performed over a wide range of environmental and flow conditions. The environment was varied from ambient to reactor operating conditions, thereby providing several degrees of subcooling. Desired conditions were as shown in Table II. The flow ranges over which the jet pump was exercised are given in Table III. Tests were conducted by maintaining a constant predetermined drive flow while varying the suction flow. This process was repeated for a number of positive and negative drive flow rates as shown in Table III and at each environment.

Two transient tests were performed. In the first test the flows through both the drive and suction were into the jet pump, exiting the discharge. The drive flow was reversed and choked at the nozzle in the second test. Both discharge and suction flows were into the jet pump. Initial conditions were established by operating the facility as in the steady state tests. Initial conditions are listed in Table IV. Less than 10.0 seconds before the start of the test, circulation through the LTSF was stopped and final preparations made. The blowdown valve was then opened and the system allowed to depressurize.

For a complete documentation of all test data refer to Reference 2.

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III. MODEL DESCRIPTION

The developmental methodology, analysis results and final model are presented in this section. RELAP4/MOD6, Update 4* is used for this analysis.

1. METHODOLOGY

The development work is performed within the following three general guidelines. First, the current model in RELAP4 is assumed correct and to be retained unless shown incorrect. Secondly, the general form of the momentum equation [3], shown below, is to remain unchanged with the exception of the two stream mixing term which is to be modified if changes are required.

$$I_{j1} \frac{dW_{j1}}{dt} = -I'_{j2} \frac{dW_{j2}}{dt} + \left(P_K + \frac{v_K W_K}{A_K} + P_{Kgj1}\right)$$

$$- \left(P_L + \frac{v_L W_L}{A_L} + P_{Lgj1}\right) - F_{f_K} - F_{f_L} \tag{1}$$

$$- F_{Kj1,j1,Lj1} + \Delta P_{j1}$$

where:

W	=	mass flow rate
v	=	average volume velocity
P	=	pressure
A	=	area
I	=	inertia

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* Configuration Control Number C001006 with associated steam table file H002011B.

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$F_{kj1,j1,Lj1}$ = form loss for flow through junction j1

ΔP_{j1} = two-stream mixing term

F_{f_K}, F_{f_L} = fanning friction loss

P_{Kgj1}, P_{Lgj1} = elevation head

Figure 3 shows the geometry over which the equation is applied. And finally, any new model is to be designed as a parallel option to the current RELAP4 model.

1.1 Analytical Method

A three step approach is used in improving the current model. First, a data comparison is made between the current model and the steady state data to determine which parts of the model require change. Secondly, a mixing term analogous to the RELAP4 term is calculated from the data to establish the trends. Finally corrections are made to the model using the data based trend and by applying empirical coefficients as required to achieve the correct overall jet pump behavior. The latter is simply a trial and error operation. Since this analysis depends on knowing the forward and reverse form loss coefficients for the drive and suction, these coefficients must be determined prior to performing the analysis.

1.1.1 Loss Coefficient Determination. Both forward and reverse form loss coefficients are determined for the jet pump drive nozzle and suction in this section. By applying the Bernoulli equation across the desired entry, solving for the loss coefficient and substituting data in the resulting equation, the coefficients can be determined. Only data in which no mixing occurs can be used for this technique, consequently data was taken which minimized mixing. Mixing was minimized by allowing flow through only one of the passages at a time and by operating drive and suction flows at equal velocities. The calculated values are then compared to handbook values[4,5] to increase confidence in the coefficients. These results are shown in Table V and used throughout the analysis. An example of this type of analysis is contained in Appendix B.

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1.1.2 Current Model Discrepancies. The current model is compared to the steady state data by comparing RELAP4 calculated M-N curves to data. The RELAP4 nodalization* diagram is shown in Figure 4. The nodalization consists of a single volume jet pump model (Volume 3) with boundary conditions being supplied by three time-dependent volumes. Pressures and temperatures in these volumes define the N-ratio and are taken from the data listed in Table VI. RELAP4 then calculates flow rates from which the M-ratio can be determined.

1.1.3 Mixing Term Trend. An analogous value to the RELAP4 mixing term is calculated from the data to determine the general trends of this term. By assuming steady state flow and solving the RELAP4 momentum equation (Eq. 1) for ΔP_{j1}, Equation 2 is obtained.

$$\Delta P_{j1} = \left(P_L + \frac{V_L W_L}{A_L} + P_{Lgj1}\right) - \left(P_k + \frac{V_k W_k}{A_1} + P_{kgj1}\right) + F_{k1} + F_{L1} + F_{kj1,j1,Lj1} \quad (2)$$

Measured data and the loss coefficients can be substituted and ΔP_{j1} calculated. This calculation is performed across both the suction entry and drive nozzle. The absolute magnitude of these values will be biased by wall effects, turbulence, and the application of one-dimensional assumptions to measured data; however, gross trends can be shown.

1.1.4 Model Corrections. Where discrepancies in calculated trend and overall jet pump behavior are found the current model is corrected. Corrections in trend are made first after which the overall jet pump calculation is evaluated for discrepancies as outlined in Section 1.1.2. The remaining discrepancies are corrected by applying empirical coefficients to the model until overall calculated behavior agrees with the data. This is a trial and error exercise.

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* Configuration Control Number H001884B.

2. MODEL RESULTS AND PRESENTATION

The results of the analysis outlined under methodology and the final model are presented in this section.

2.1 Current Model Deficiencies

Figure 5 shows a four-quadrant M-N curve comparing the current model and the data as outlined in Section 1.1.2. In Quadrant I for positive drive flow the current model calculates the slope correctly; however, the curve is to the left of the data. Entering Quadrant II the model shows a severe shift to the left of the data. It is concluded then that for positive drive flow the model must be adjusted for both positive and negative suction flow.

For negative drive in Quadrant II the model and data compare well leaving no need for improvement or further consideration. Although the model is reasonable in Quadrant IV small improvements can and will be made.

2.2 Evaluation of Model Trends

Figures 6 through 9 show the mixing term versus the M-ratio. Both the current RELAP4 and the data calculated values are shown. Recall that only trends are being determined from these figures.

The first two figures are for positive drive flow, with Figure 6 showing the mixing term across the jet pump suction and Figure 7 across the drive nozzle. For the suction case, the current model trends are reasonable except for negative M-ratios where curve slopes are of opposite sign. A change in the current model is required for this case. For the drive nozzle case the current model trends are generally in good agreement. There are model deficiencies in the M = -1.0

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region; however, flow patterns in this region are difficult to attain as can be seen by the exponential increase in N-ratio on Figure 5. Therefore, no changes will be considered unless required by overall behavior calculations.

For the negative drive case the current model trends, Figures 8 and 9, are generally well modeled with no apparent changes required.

Based on these comparisons the only calculated trend which is obviously incorrect is for positive drive flow and negative M-ratio across the suction flow path. Other regions appear reasonable. These results are consistent with those found in Section 2.1 where for positive drive flow and negative M-ratio the overall behavior was not calculated correctly.

2.3 Final Model

The improved model* is also presented in Figures 6 through 9. Note in Figure 6 the correction in trend for the suction mixing term with positive drive flow. The trend was corrected in part by applying the equation for M=0.0 over the entire range of positive and negative suction flow.

Although the model development work was based on RELAP4/MOD6 Update 4, it is compatible with RELAP4/MOD5 through MOD7. Actual coding may be specific to the RELAP4 version.

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* Configuration Control Number H001784B.

IV. MODEL EVALUATION

This section presents the results of the improved model evaluation. Comparisons between the improved model and both subscale and full scale data are presented. A calculation showing the performance of the model in a TLTA calculation is presented along with comparisons of the model to the two transient tests conducted in this program.

1. STEADY STATE SUBCOOLED DATA COMPARISONS

The nodalization diagram for both the subscale and full scale cases is as shown in Figure 4 and described under III.Model Description, Section 1.1.2. Temperatures thoughout the model are 555 K and pressures in Volume 4 are a constant 7.58 MPa. The remaining pressures required to drive the model and define the N-ratio are given in Table VII.

Figure 10 shows an M-N curve which presents the results of the subscale analysis with the improved model. The improvements are quite evident when compared to the current model calculations shown in Figure 5.

In Figure 11 only the on-design M-N characteristics (Quadrant I) are shown since this was the only obtainable data[6] for a full scale jet pump. The improvements over the current model are also quite evident for this case.

2. TLTA JET PUMP PERFORMANCE

The results of the Two Loop Test Apparatus (TLTA) calculations are presented in this section. The purpose of the calculation is to show proper functioning of the model under LOCA conditions. A complete TLTA

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data comparison is outside the scope of this work, however, trends can be determined from a limited comparison.

The TLTA nodalization diagram is shown in Figure 12. The TLTA is a single bundle electrically heated test system used to study blowdown and ECC phenomena in a BWR. There are two jet pumps, one to simulate the intact loop (Volume 9) and the other the broken loop (Volume 5). Reference 7 and 8 give detailed documentation of the test facility and model.

Figures 13 and 14 show the calculated and measured flows for both jet pumps. The data are for Test 6007 Run 26 (see Reference 9). For the intact loop drive flow decays smoothly as does the suction flow. Once suction uncovery occurs, suction flow decreases dramatically as does the data. In the broken loop the discharge flow is reversed and compares well with the data.

3. TWO-PHASE TRANSIENT TEST COMPARISONS

The improved model is compared to the two transient tests conducted as part of this program. The purpose of the comparisons is to show the model's capabilities at calculating overall two-phase jet pump behavior.

In the first test, flows are into the jet pump through the drive nozzle and suction entry, a similar flow pattern to that of the intact loop. The RELAP4 nodalization diagram is shown in Figure 15. Flow into and out of the vessel is through fill junctions 10, 11, and 14 using measured test data. Initial conditions are as described in Table IV.

A comparison of vessel pressures and flow rates in Figures 16, 17, and 18 show the calculations and data to agree well. Comparisons (Figures 19 and 20) between the differential pressures between suction

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and discharge (DP-6) and drive and discharge (DP-7) also show that, although good agreement is not achieved, the improved model calculates the correct sign for DP-6, a major improvement. After approximately 5.0 seconds data indicates that multi-dimensional effects are occurring in the downcomer region. Consequently, the jet pump suction entry flow and quality are not well known and could account for the discrepancy in magnitude between the data and improved model.

The drive nozzle flow is reversed and choked in the second test. Flow enters the jet pump through the suction and discharge. Figure 21 shows the nodalization diagram and Table IV the initial conditions. Figures 22, 23, and 24 show vessel pressures and flow rates. Comparisons to DP-6 and DP-7 are given in Figures 25 and 26. The trends are well calculated.

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V. CONCLUSIONS

The RELAP4 jet pump model developed as part of the Jet Pump Test and Model Development Program shows improvements over previously available models. Improvements for positive drive flow are particularly evident as shown in Figure 10 and more realistic calculations can be expected using this model. The model also gives better results for full scale BWR jet pump calculations as shown in Figure 11. Two-phase transient tests show the model to calculate trends correctly, although absolute magnitudes of differential pressures across the jet pump differ for Test 1 as shown in Figures 19 and 20. Because of multi-dimensional effects in the downcomer region jet pump suction entry flows and qualities are not well known resulting in this discrepancy.

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VI REFERENCES

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2. H. S. Crapo, Jet Pump Test Data Report. (to be published).

3. RELAP4/MOD5 User's Manual, Vol. 1, ANCR-NUREG-1335, (September 1976).

4. Crane Handbook, Crane Co., Technical Paper No. 410 (1976).

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6. G. W. Burnette and G. L. Sozzi, Two-Phase Pump Performance During Steady State Operation and During a Simulated LOCA Blowdown, NEDE-13239 (November 1971).

7. J. D. Milton, RELAP4 Test Prediction of BWR-BD/ECC Tests 6006 and 6007, PG-R-77-39 (December 1977).

8. R. J. Muzzy, Preliminary BWR Blowdown/Emergency Core Cooling Program Plan, GEAP-21255 (June 1976).

9. BWR Blowdown/Emergency Core Cooling Program - 64-Rod Bundle Blowdown Heat Transfer (8x8 BDHT), Final Report, GEAP-NUREG-23977, (Excerpts from to be issued document).

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TABLE I

MEASUREMENTS

Symbol	Description	Range and Accuracy[a]	(2σ)	Readout[d]	Units
PE-4	Test assembly inlet pressure	0-20.7 x	1%	DAS, DVM, panel gauge (hand record)	MPa
DPE-1	Suction throat ΔP	0 ± 700	1%	DAS, DVM	KPa
DPE-2	Suction throat ΔP	1 ± 25	1%	DAS, DVM	KPa
DPE-3	Throat-Diffuser ΔP	0 ± 75	1%	DAS, DVM	KPa
DPE-4	Diffuser-Outlet ΔP	0 ± 200	1%	DAS, DVM	KPa
DPE-5	Outlet-Discharge ΔP	0 ± 25	1%	DAS, DVM	KPa
DPE-6	Suction-Discharge ΔP	0 ± 700	1%	DAS, DVM	KPa
DPE-7	Drive Discharge ΔP	0 ± 1.4	1%	DAS, DVM	MPa
FE-DR	Drive Turbine	±1.25-29	6%[b]	DAS, DVM	1/s
FE-SU	Suction Turbine	±1.25-29	6%[b]	DAS, DVM	1/s
FE-PG	Discharge Turbine	±1.25-29	6%[b]	DAS, DVM	1/s
TE-DR	Drive Line Temp (TC)	0-600	±2	DAS, DVM	K
TE-SU	Suction Line Temp (TC)	0-600	±2	DAS, DVM	K
TE-DG	Discharge Line Temp (TC)	0-600	±2	DAS, DVM	K
PE-DR	Drive Line Press	0-20.7	1%	DAS, DVM	MPa
PE-SU	Suction Line Press	0-20.7	1%	DAS, DVM	MPa

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TABLE I (CONT'D)

MEASUREMENTS

Symbol	Description	Range and Accuracy[a]	(2σ)	Readout[d]	Units
PE-DG	Discharge Line Press	0-20.7	1%	DAS, DVM	MPa
DE-DR[c]	Drive Line ρ	0-1100	±30	DAS, DVM	kg/m^3
DE-DG[c]	Discharge Line ρ	0-1100	±30	DAS, DVM	kg/m^3

(a) Accuracy specified as percent of full scale (unless otherwise noted).

(b) Turbine accuracy ±.5% above 3 l/s; 1% from 1.35 to 3 l/s; not specified below 1.25 l/s.

(c) Only one densitometer required per test.

(d) Digital data sampled at 50/sec.

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TABLE II

DESIRED STEADY STATE OPERATING CONDITION

Pressure (MPa)	Temperature (K)
0.96	295
6.20	533
7.60	555

TABLE III

FLOW RANGE OF STEADY STATE TESTS

UNITS: l/s

	Maximum Suction Flow		Minimum Nonzero[a]	Suction Flow
Drive Flow	Positive	Negative	Positive	Negative
4.1	6.6	-7.9	1.26	-0.45
-4.1	4.3	-8.5	1.04	-0.45
2.8	8.6	-5.4	0.43	-0.81
-2.8	5.2	-8.5	1.05	-1.13
1.4	4.4	-3.1	0.67	-0.72
-1.4	12.1	-4.3	0.89	-1.07
0.0	13.0	-12.6	1.66	-1.76

a Minimum flows were limited by the response of the turbine meters, which was somewhat erratic at low flow rates.

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TABLE IV

TRANSIENT TESTS INITIAL CONDITIONS

Test Conditions	Test 1 Specified	Test 1 Actual	Test 2 Specified	Test 2 Actual
Pressure (MPa)				
Blowdown Vessel	7.9	8.0	7.9	8.1
N_2 Accumulator	7.9	7.6	7.9	7.4
Temperature (K)				
Jet Pump	555	556	555	557
Blowdown Vessel	555	555	555	555

TABLE V

FORM LOSS COEFFICIENT

	Drive			Suction		
	Calculation From Data	Handbook Value	Used	Calculation From Data	Handbook Value	Used
Forward	0.60	0.57-1.02	0.84	0.23-0.30	0.44	0.27
Reverse	1.06-1.18	0.38	0.78	1.11-1.16	1.0	1.0

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TABLE VI

STEADY STATE SUBSCALE TEST BOUNDARY CONDITIONS
TEMPERATURE = 555 K

	Pressure (MPa)			
Drive	Suction	Discharge	M	N-Ratio
Forward Drive (4.1 l/s)				
7.57	7.23	7.60	-1.95	118.05
7.57	7.30	7.60	-1.40	70.91
7.57	7.36	7.60	-0.95	44.55
7.64	7.42	7.60	-0.81	2.17
7.68	7.46	7.60	-0.36	0.97
7.70	7.48	7.60	-0.0	0.71
7.72	7.50	7.60	0.41	0.54
7.73	7.53	7.60	1.24	0.29
7.74	7.57	7.60	2.03	0.05
7.70	7.62	7.60	3.15	-0.31
Forward Drive (2.8 l/s)				
7.57	7.41	7.60	-1.94	108.4
7.57	7.45	7.60	-1.32	54.9
7.57	7.47	7.60	-0.94	32.5
7.61	7.51	7.60	-0.74	2.00
7.63	7.52	7.60	-0.36	0.94
7.64	7.53	7.60	0.0	0.69
7.64	7.54	7.60	0.34	0.54
7.65	7.55	7.60	1.22	0.27
7.65	7.57	7.60	2.00	0.05
7.15	7.60	7.60	3.08	-0.30
Reverse Drive (4.1 l/s)				
7.14	7.60	7.60	-1.04	0.02
7.15	7.58	7.60	0.79	0.01
7.19	7.57	7.60	-0.44	0.0
7.27	7.56	7.60	0.0	-0.04
7.31	7.55	7.60	0.42	-0.11
7.40	7.50	7.60	1.22	-0.42
7.45	7.44	7.60	1.98	-1.15
Reverse Drive (2.8 l/s)				
7.31	7.58	7.60	-1.75	0.02
7.38	7.58	7.60	-1.34	0.02
7.40	7.58	7.60	-0.96	0.02
7.40	7.58	7.60	-0.71	-0.02
7.38	7.58	7.60	-0.71	-0.02
7.38	7.57	7.60	-0.44	-0.03
7.45	7.57	7.60	0.0	-0.05
7.47	7.56	7.60	0.59	-0.13
7.51	7.55	7.60	1.14	-0.48
7.53	7.52	7.60	1.86	-1.41
7.54	7.46	7.60	2.88	-4.25

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TABLE VII

STEADY STATE BOUNDARY CONDITONS
FULL SCALE JET PUMP
TEMPERATURE = 555 K

Pressure (MPa)				
Drive	Suction	Discharge	M	N-Ratio
Forward Drive (4.1 l/s)				
7.54	7.19	7.60	-1.50	17.0
7.60	7.39	7.60	-1.0	4.5
7.67	7.45	7.60	-0.7	2.5
7.68	7.47	7.60	0.0	0.76
7.70	7.50	7.60	1.0	0.31
7.71	7.53	7.60	2.4	0.06

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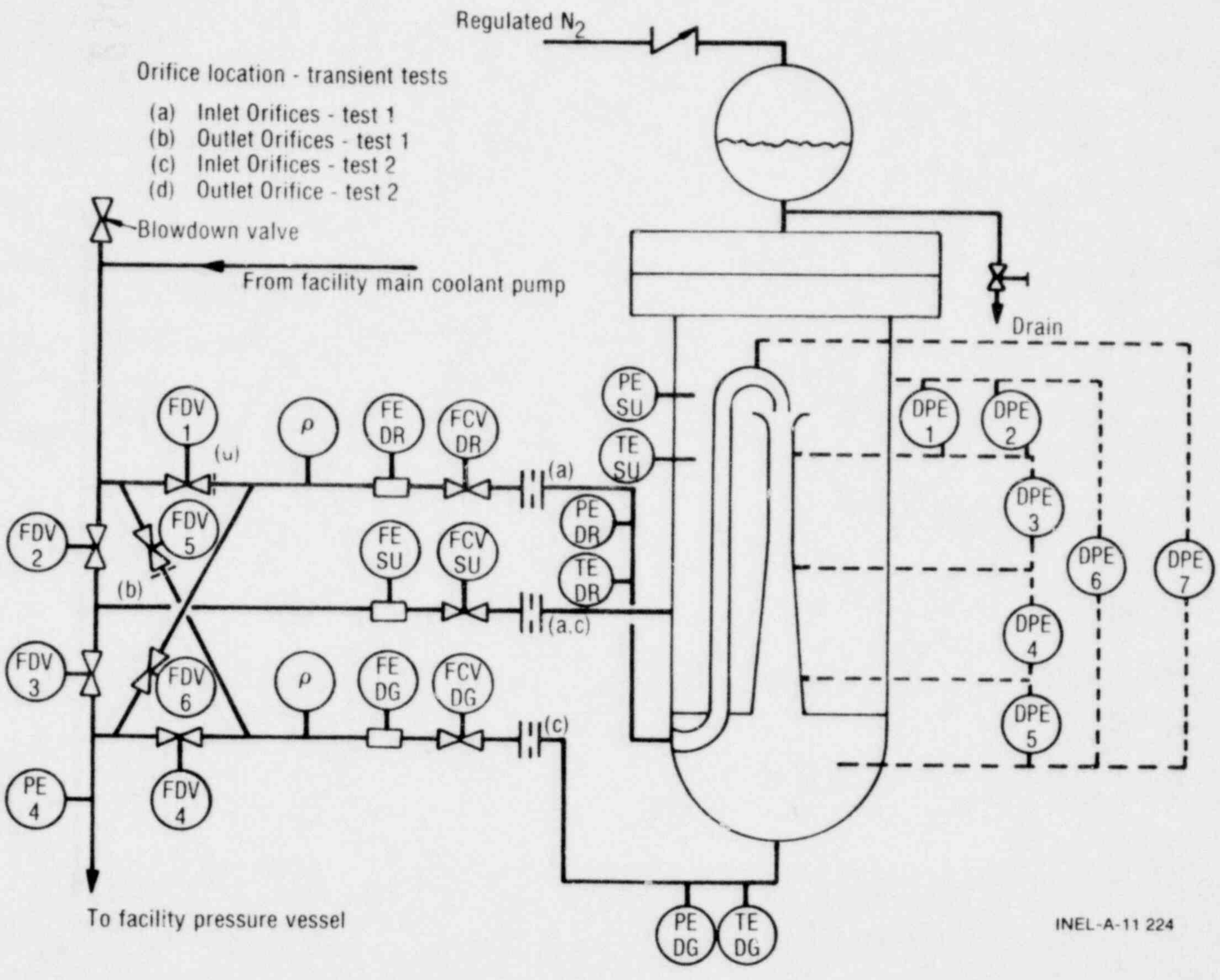

Fig. 1 Jet pump test assembly schematic.

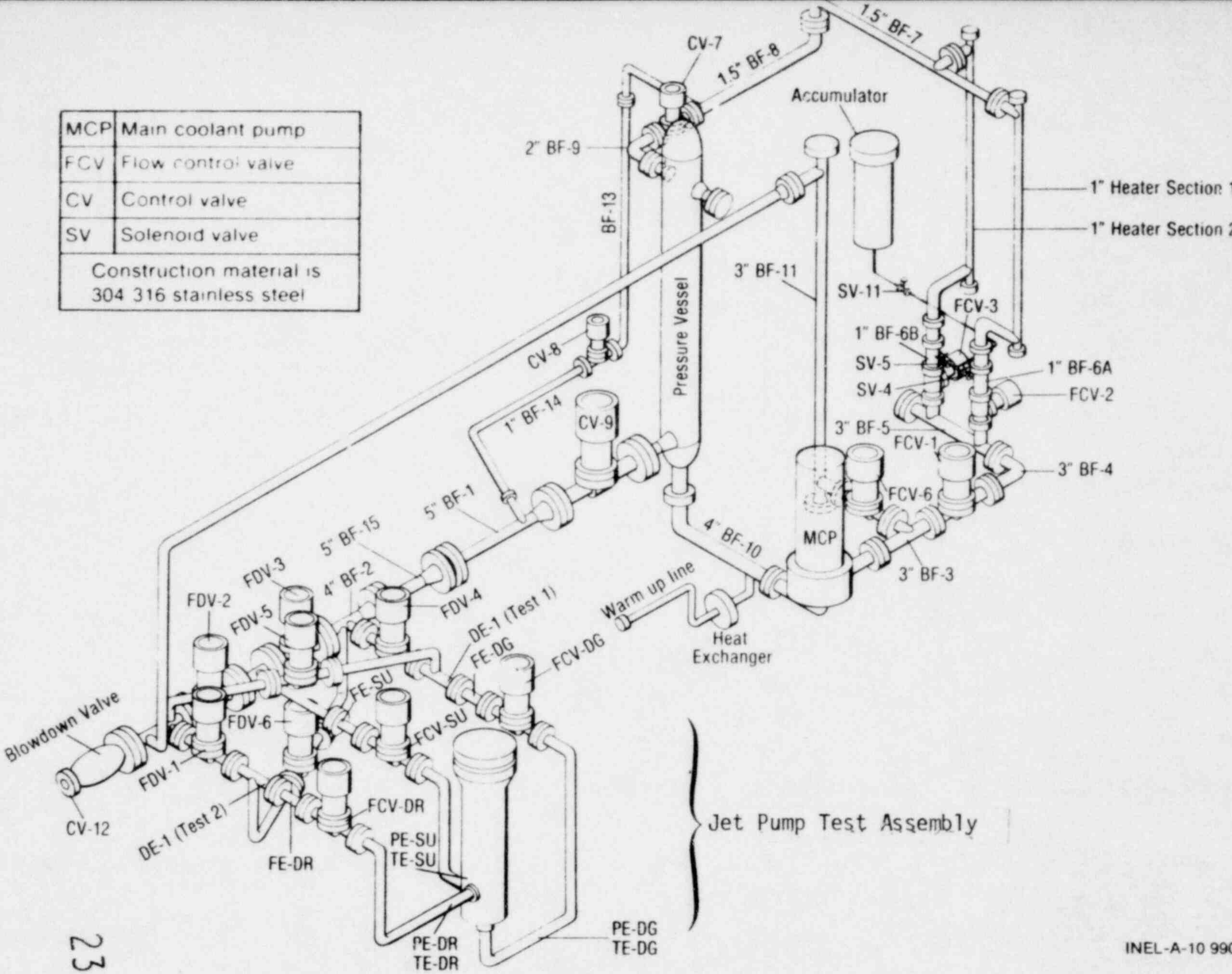

Fig. 2 Facility with test assembly.

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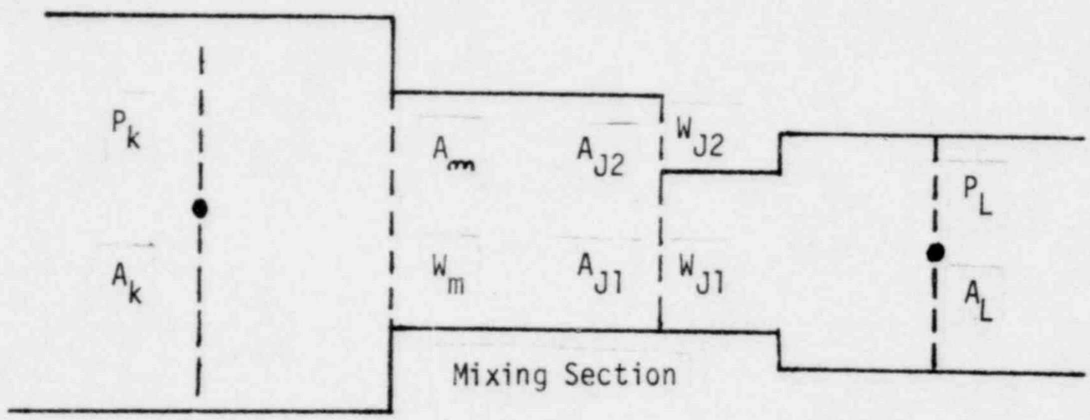

P = Pressure
A = Area
W = Mass Flow Rate

Fig. 3 RELAP4 two-stream mixing geometry.

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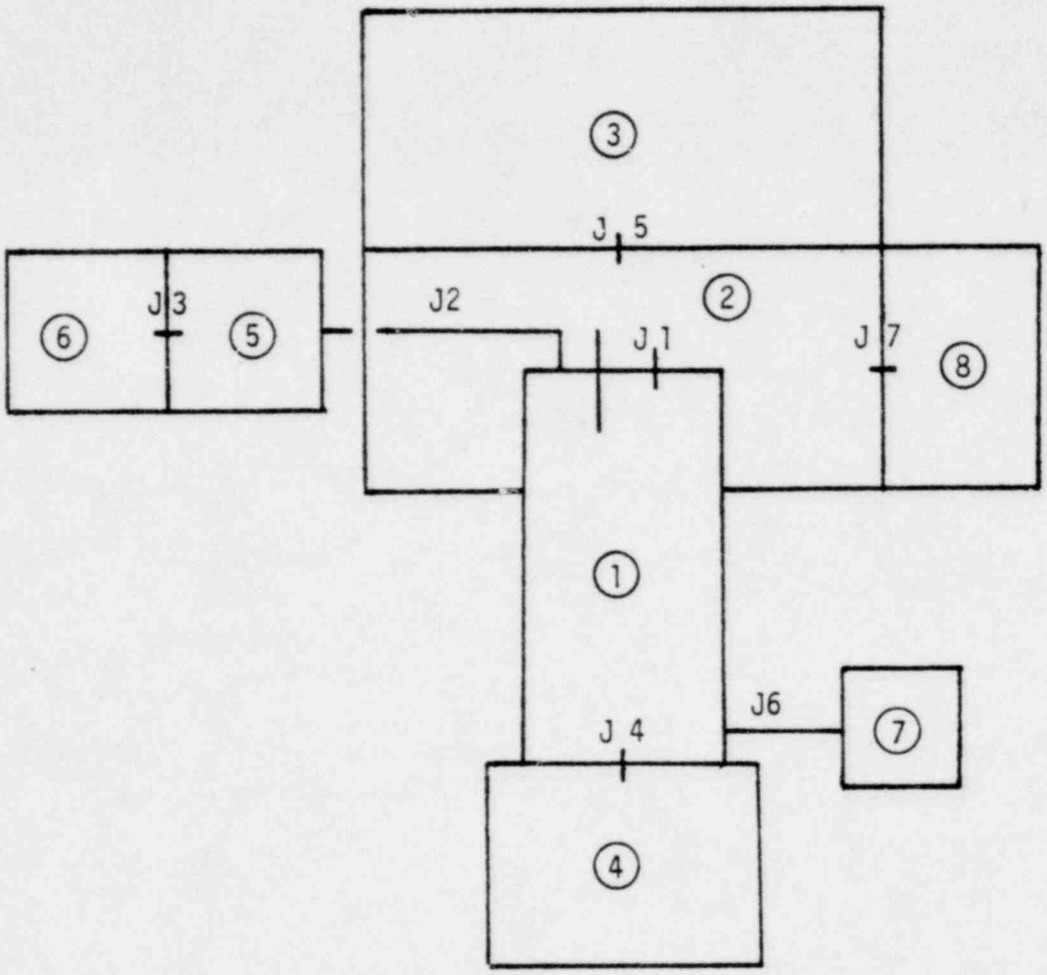

J = Junction
O = Volume
Volume 1 is the jet pump
Volumes 4, 6, and 8 are time-dependents
Volume 7 is a cushioning volume which
allowed faster computer running

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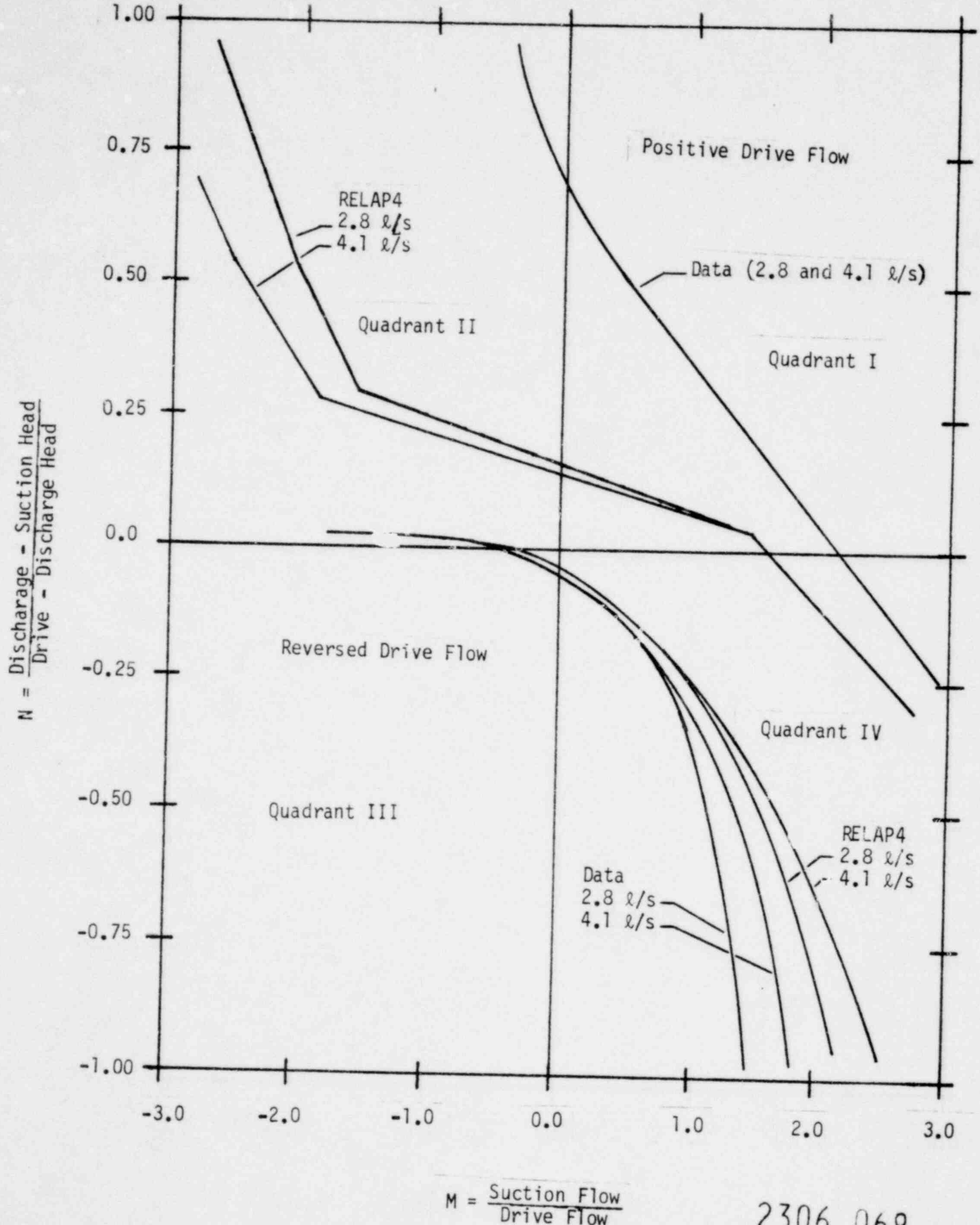
Fig. 4 RELAP4 steady state nodalization diagram.



2306 068

Fig. 5 M-N curve - current model and subscale data.

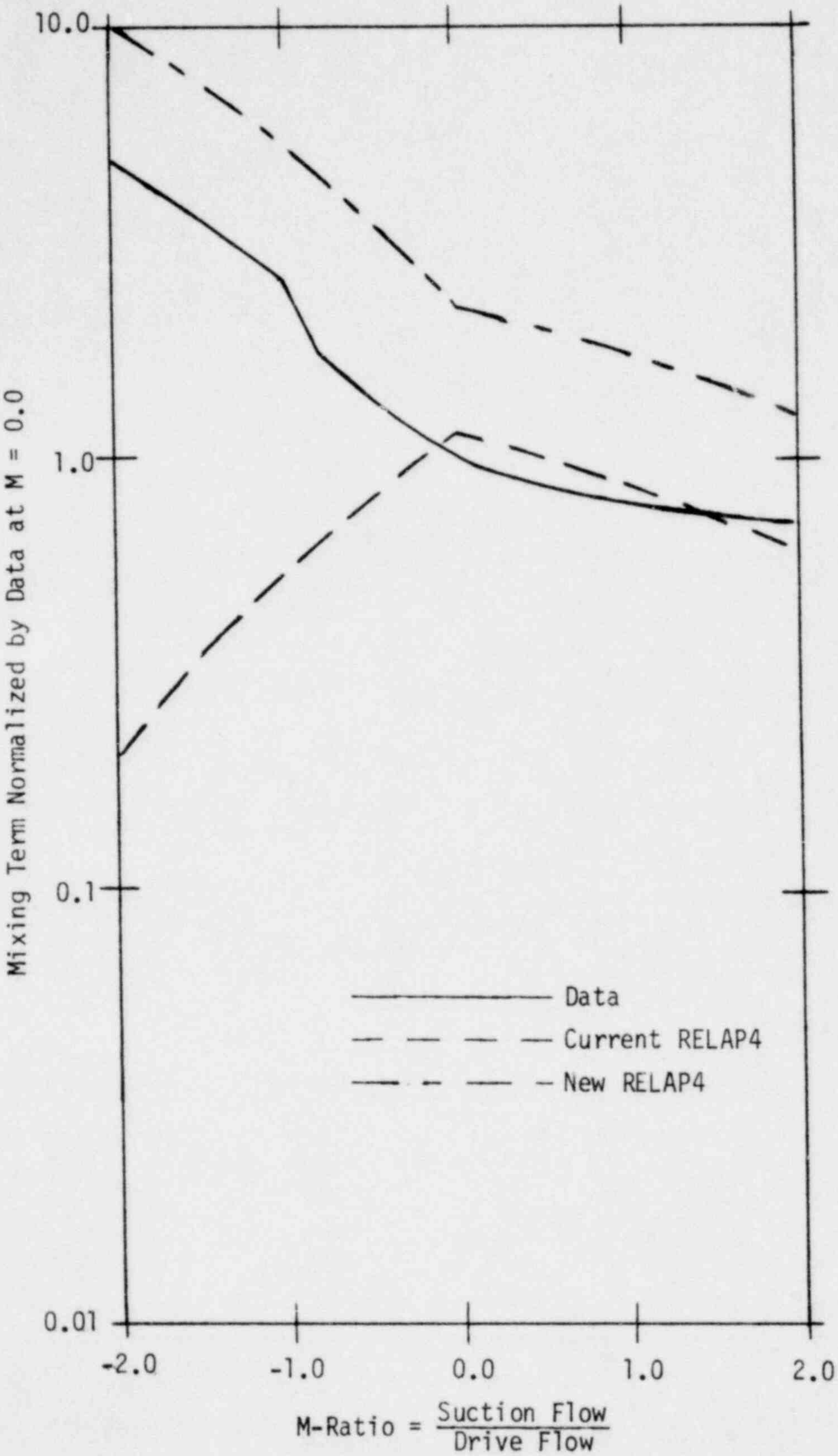


Fig. 6 Suction mixing term for positive drive flow.

2306 069

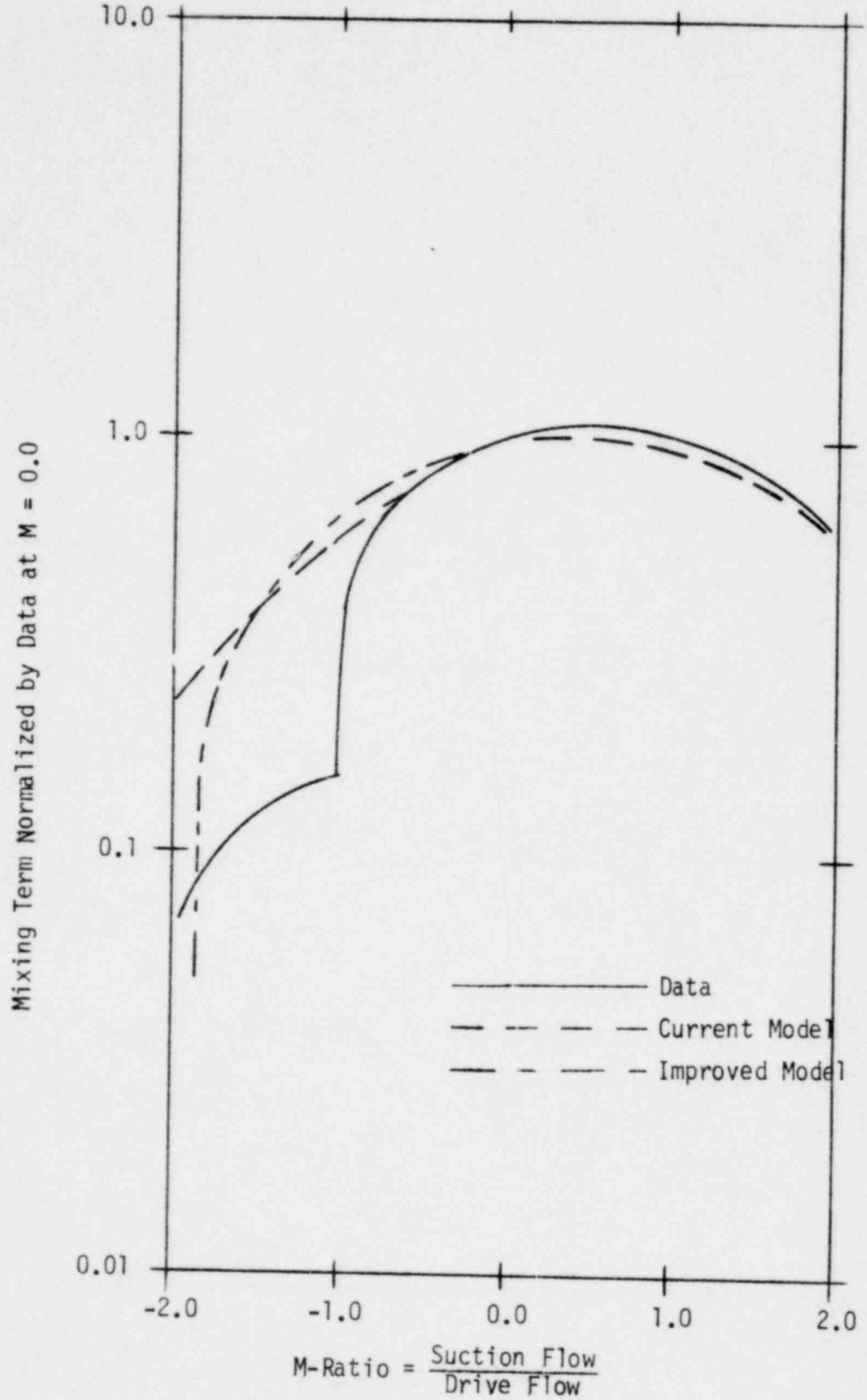


Fig. 7 Drive mixing term for positive drive flow.

2306 070

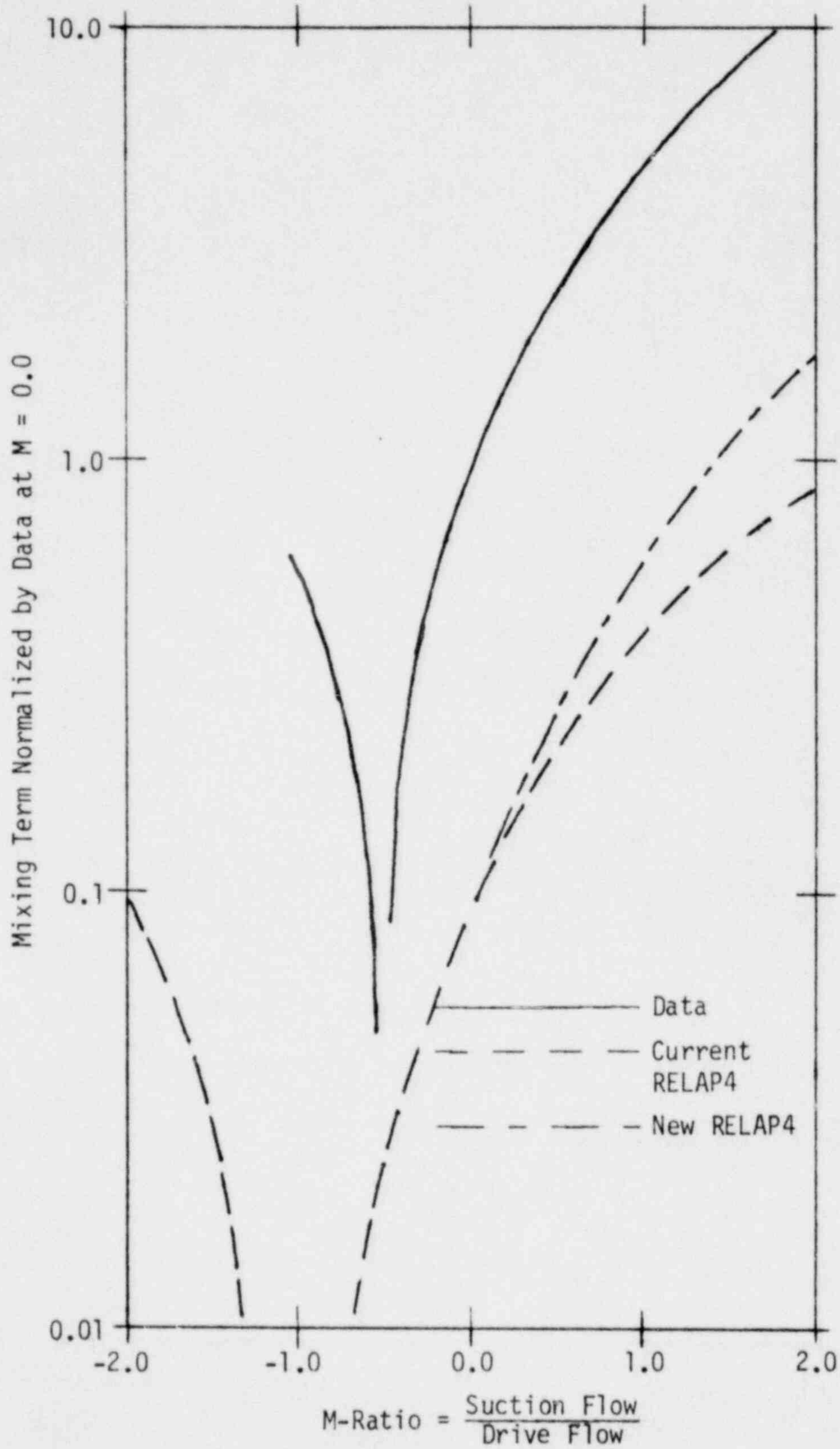


Fig. 8 Suction mixing term for negative drive flow

2306 071

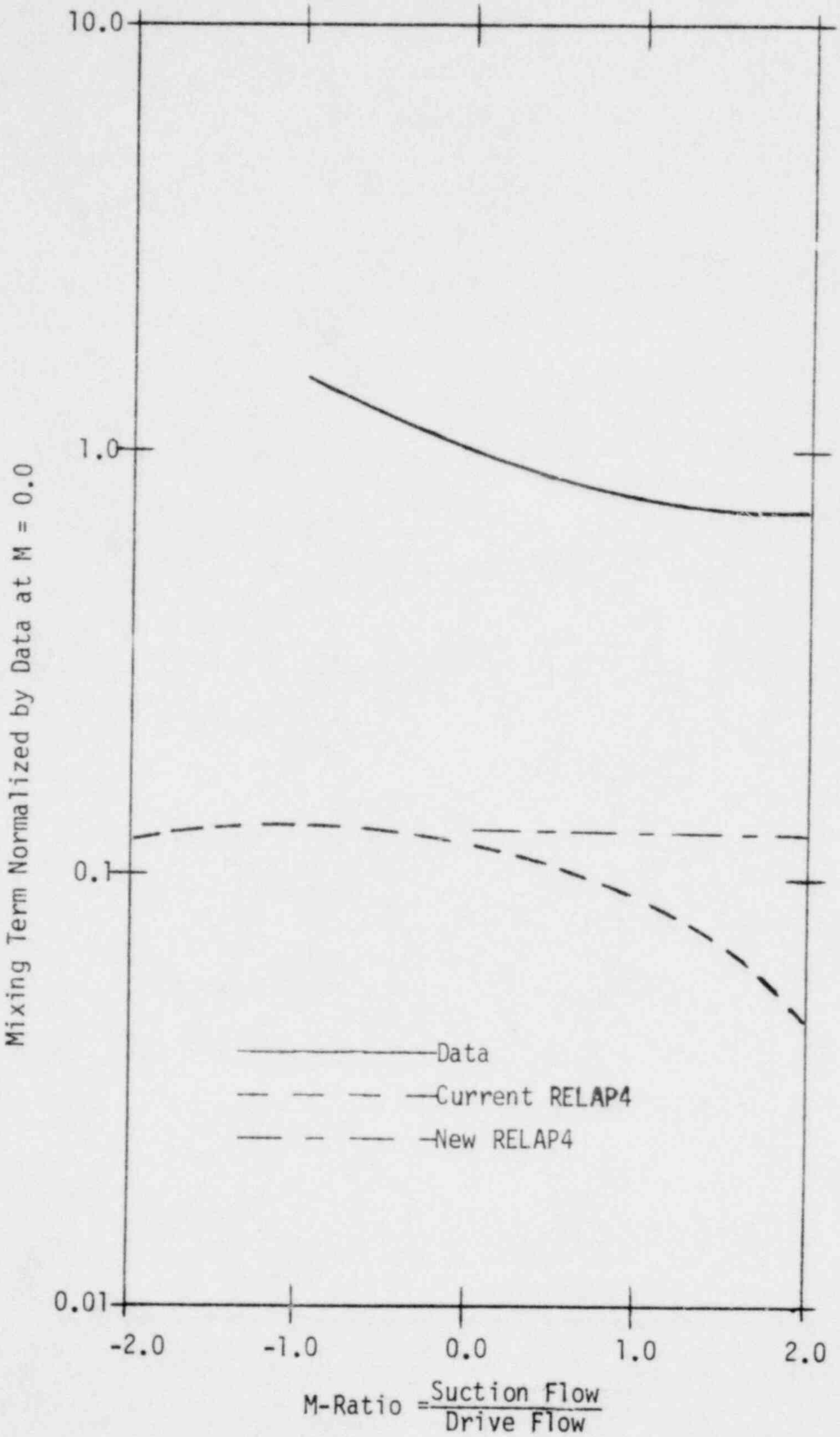
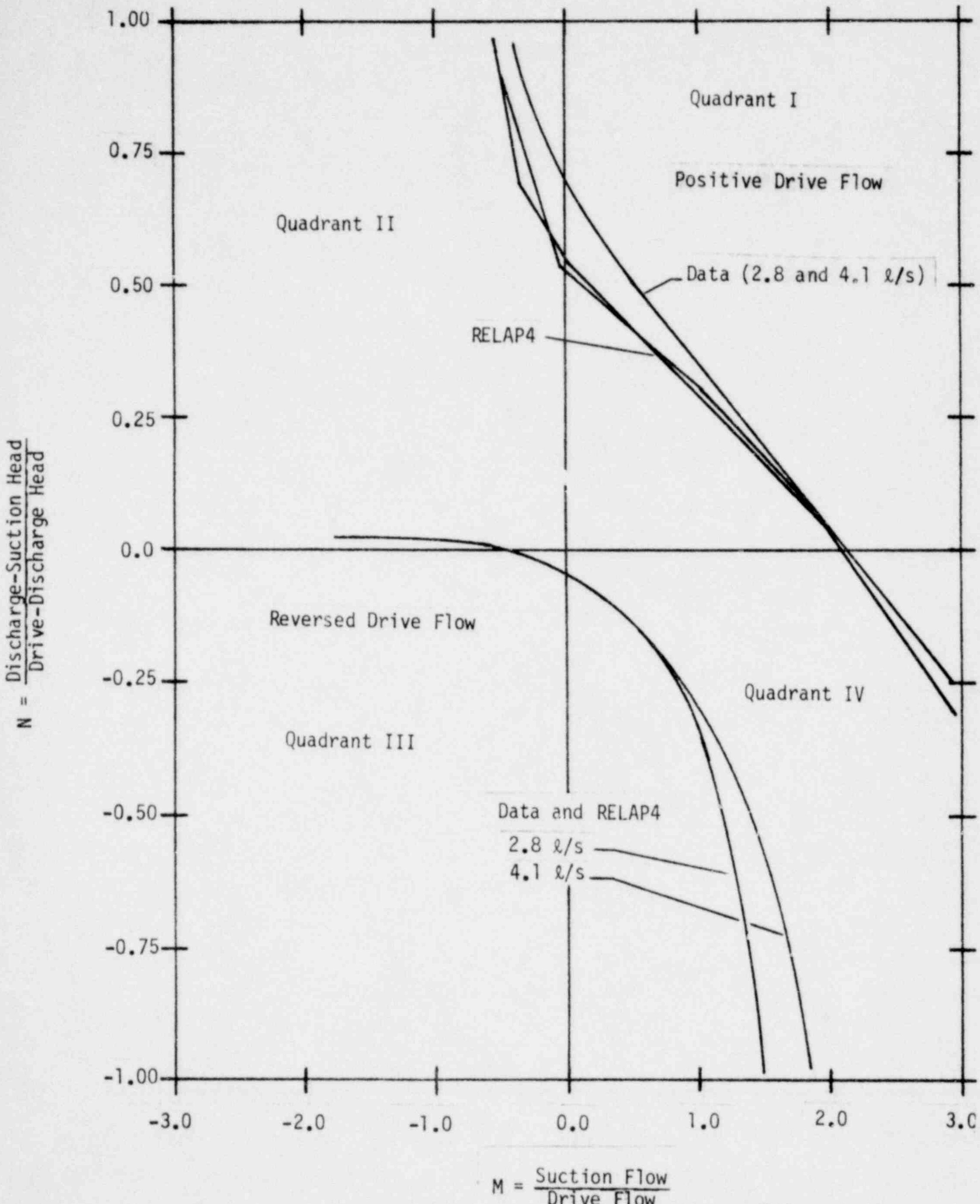


Fig. 9 Drive mixing term for negative drive flow.

2306 072



2306 073

Fig. 10 M-N Curve - improved model for subscale pump.

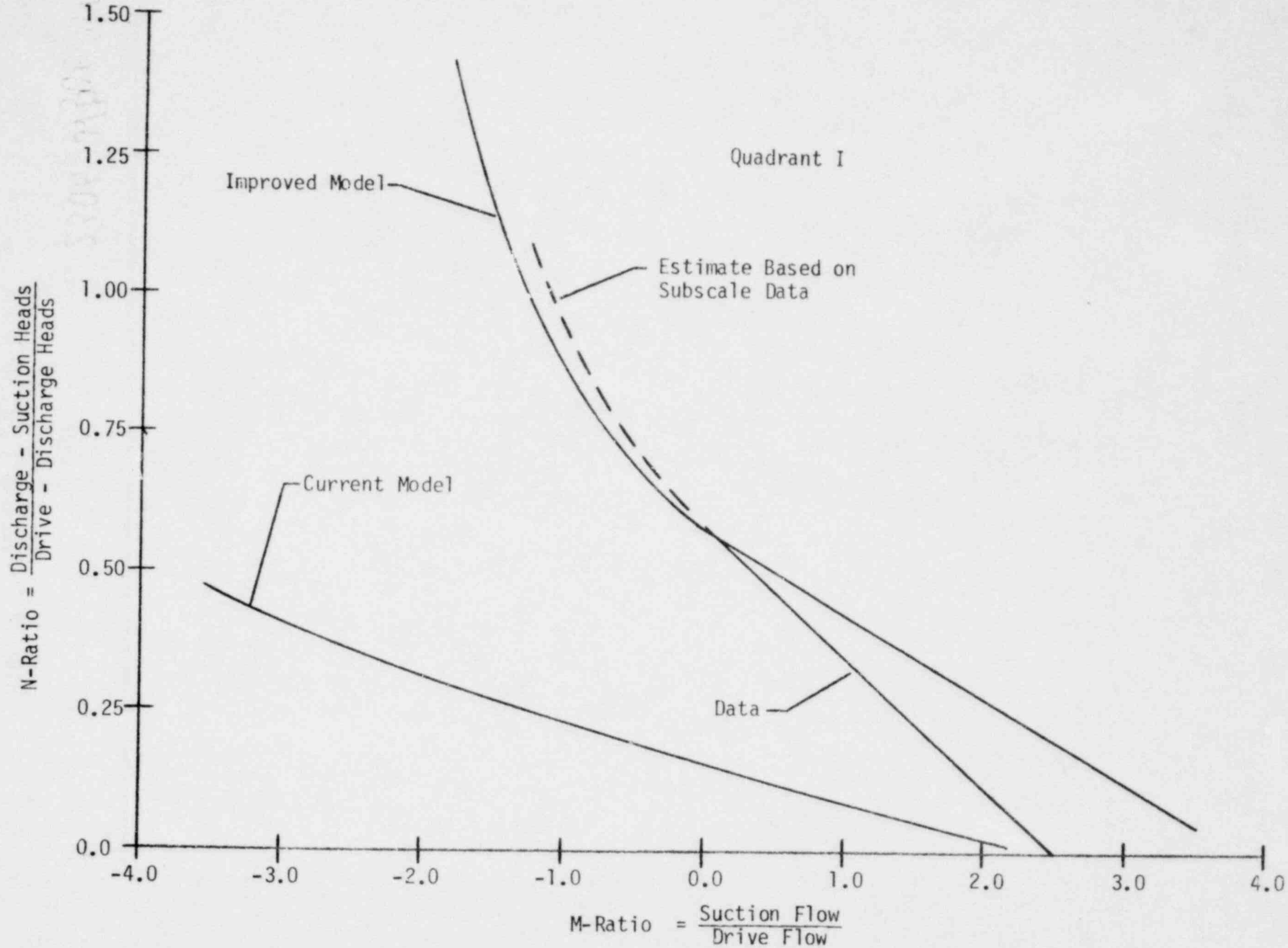


Fig. 11 M-N curve-improved model for full scale pump.

2306 074

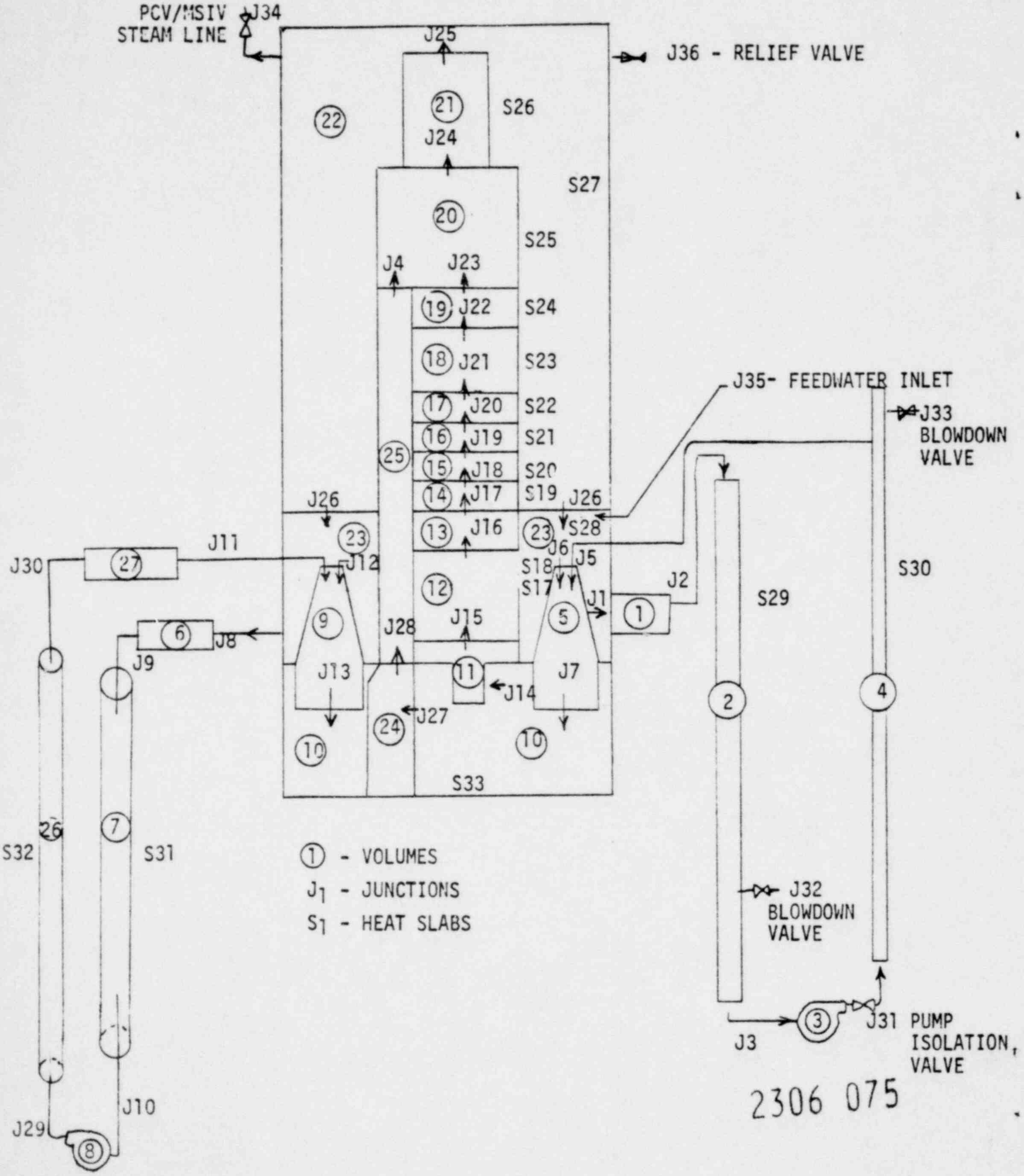


Fig. 12 TLTA RELAP4 nodalization diagram.

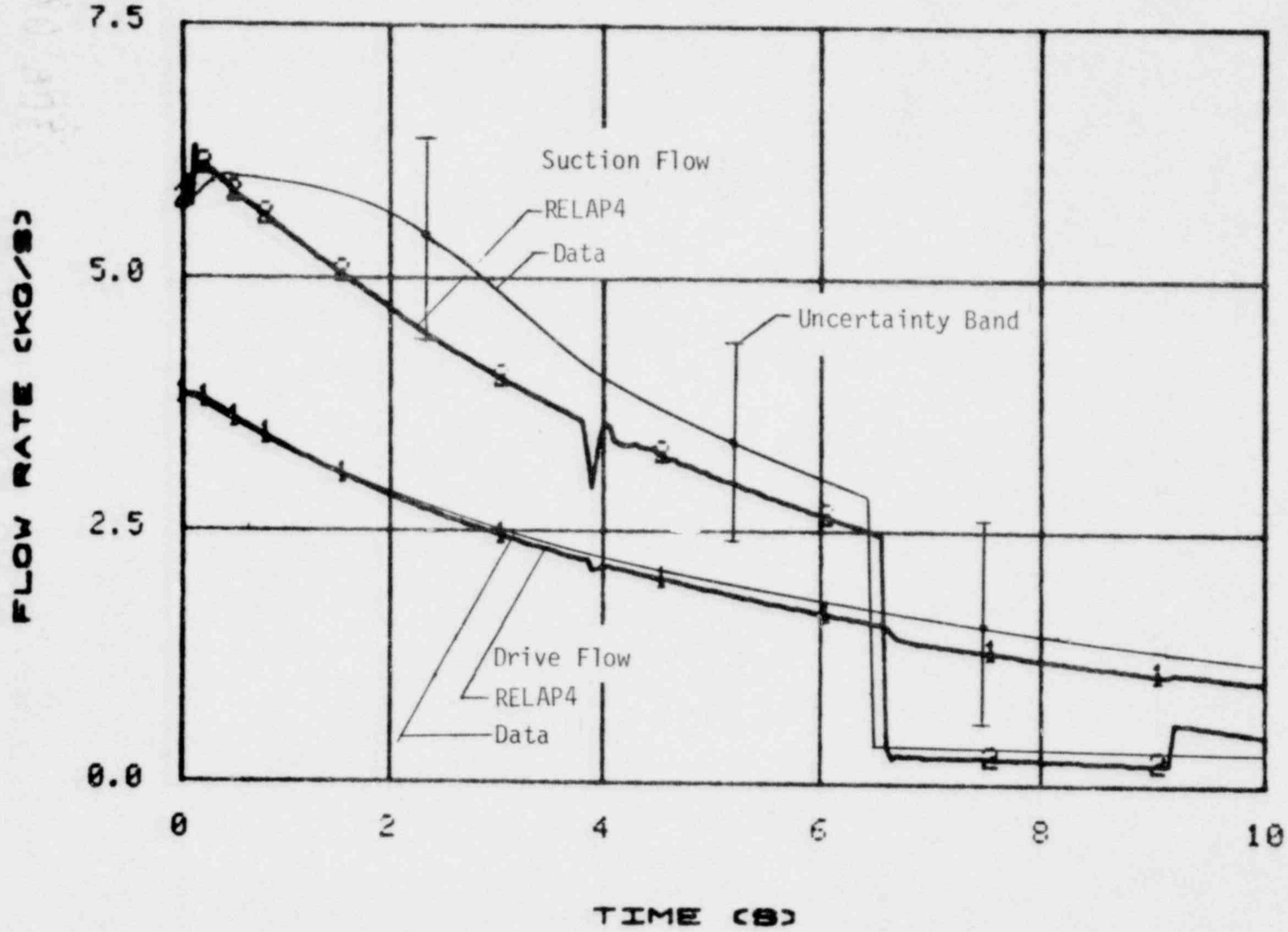


Fig. 13 TLTA intact loop jet pump behavior.

2306 076

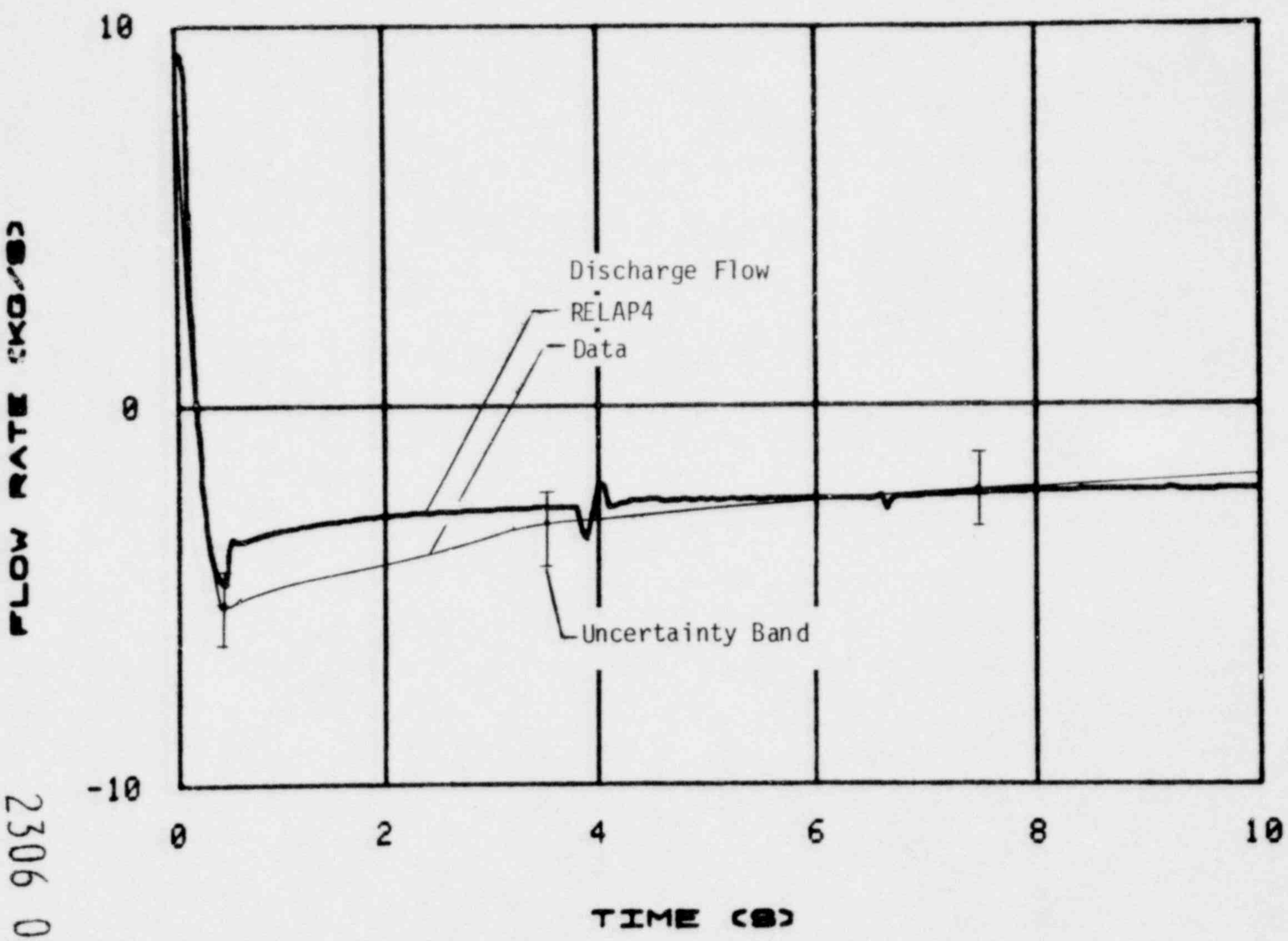


Fig. 14 TLTA broken loop jet pump behavior.

2306 077

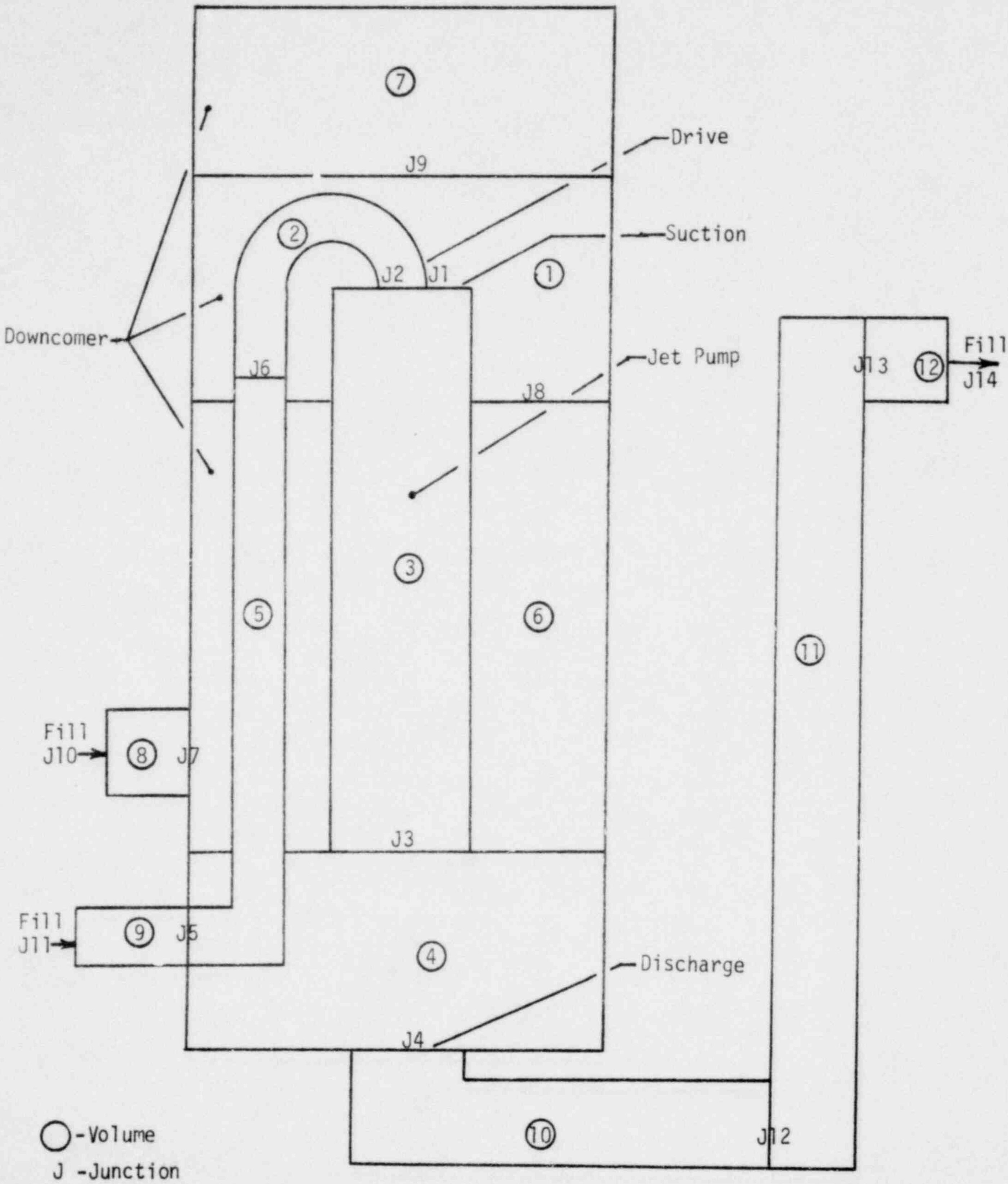


Fig. 15 Transient Test 1 RELAP4 nodalization diagram.

2306 078

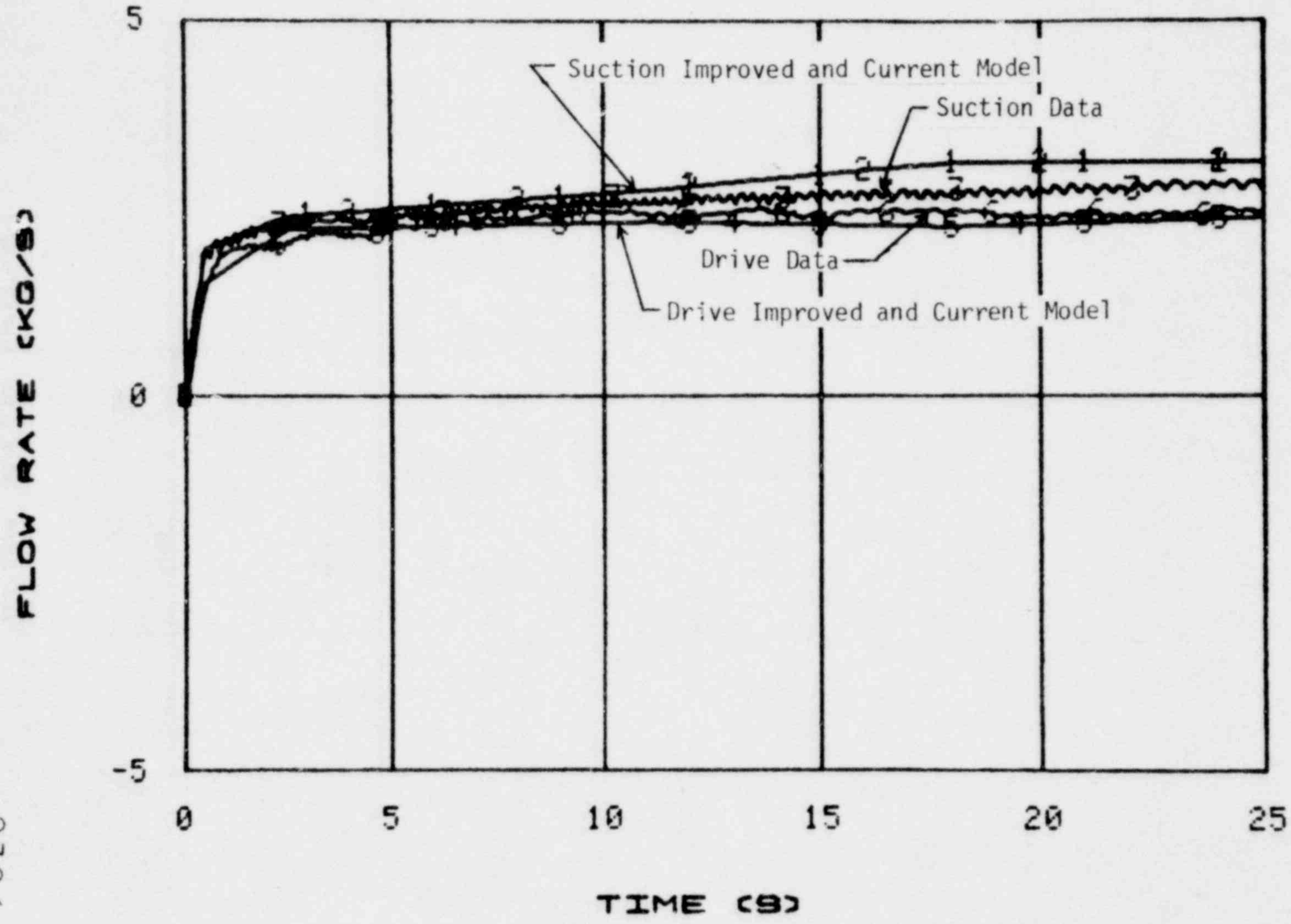


Fig. 16 Transient Test 1 flow into vessel.

2306 079

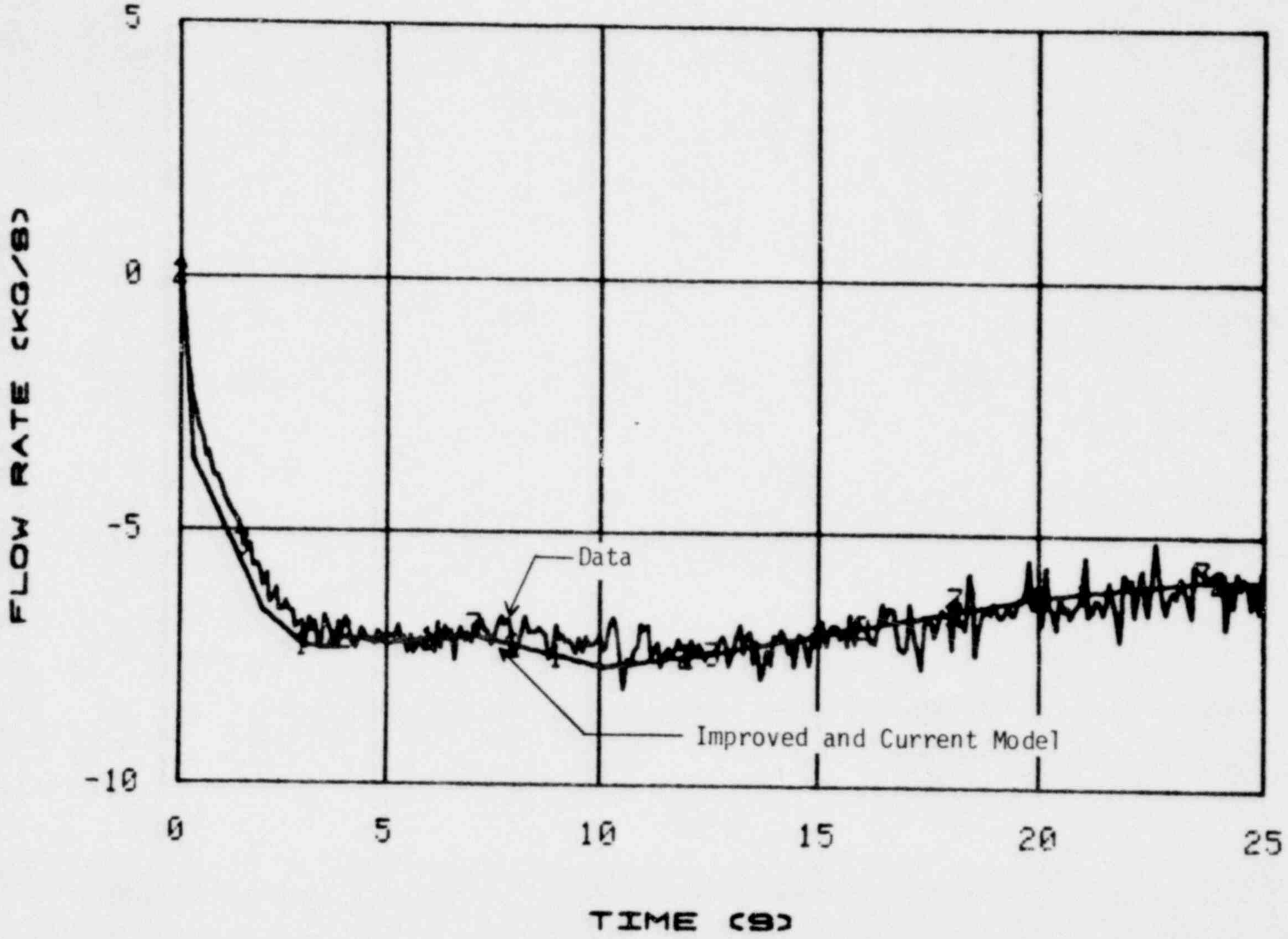


Fig. 17 Transient Test 1 flow out of vessel.

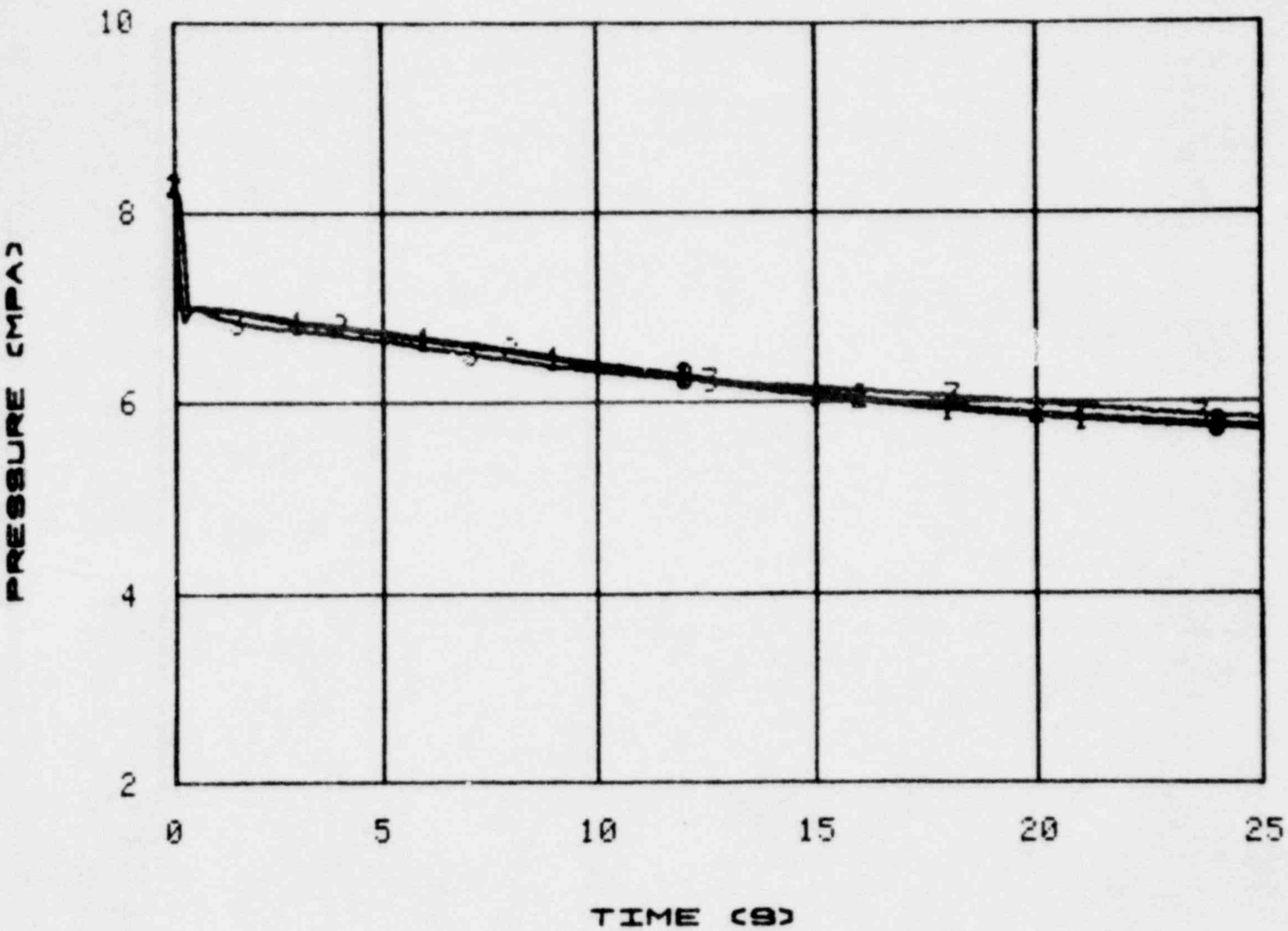


Fig. 18 Transient Test 1 discharge pressure.

2306 081

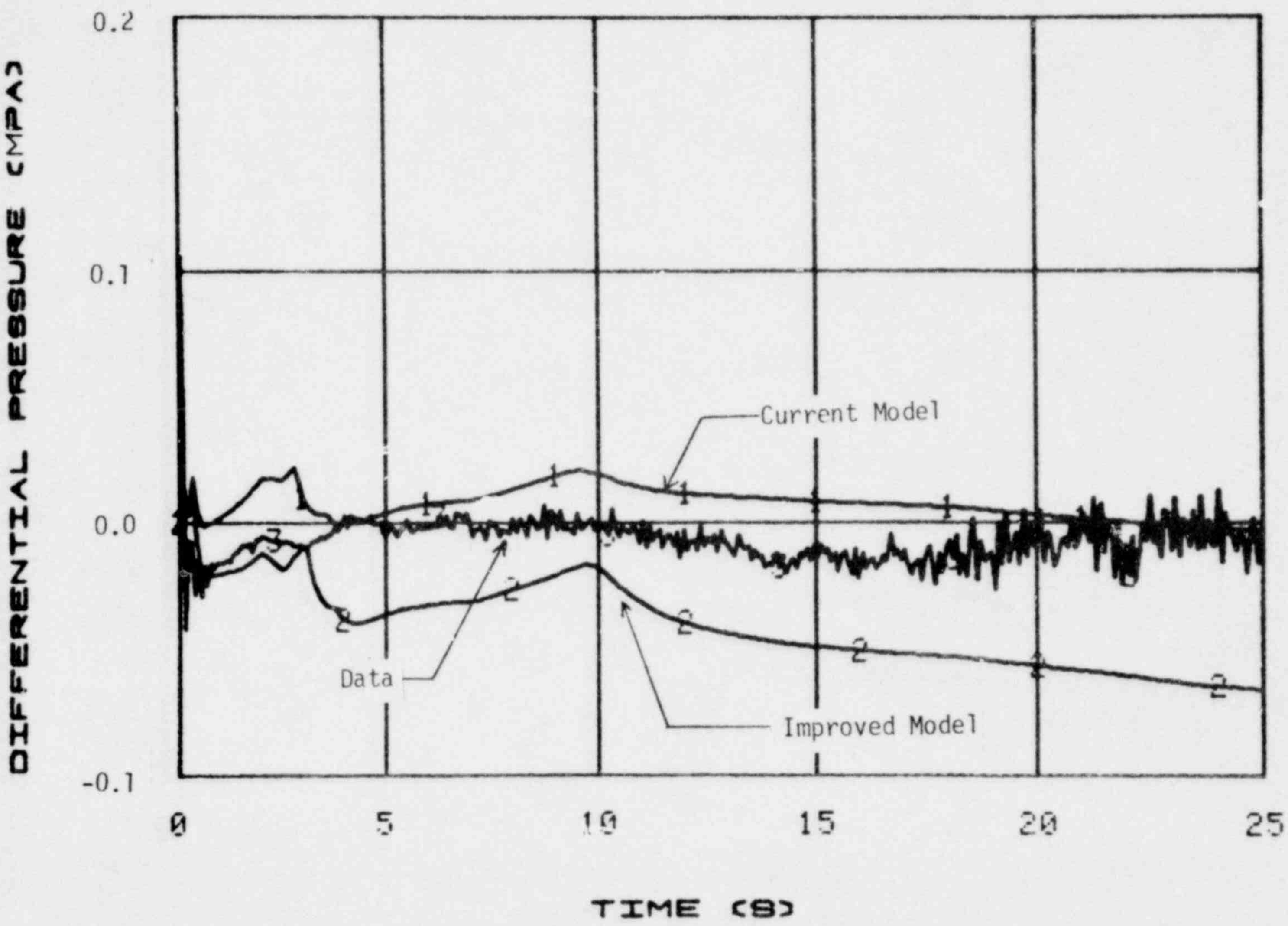


Fig. 19 Transient Test 1 differential pressure suction to discharge.

2306 082

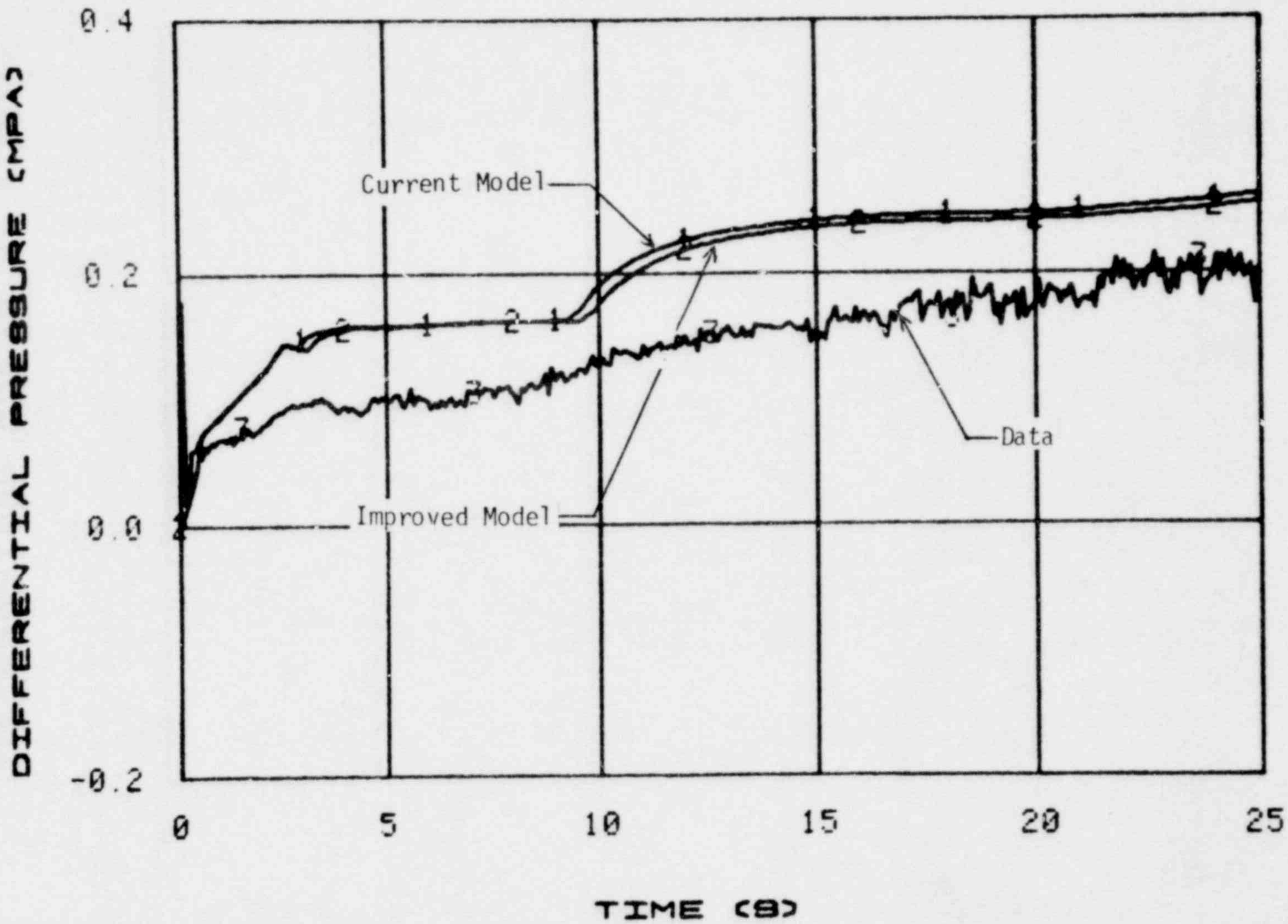


Fig. 20 Transient Test 1 differential pressure drive to discharge.

2306 083

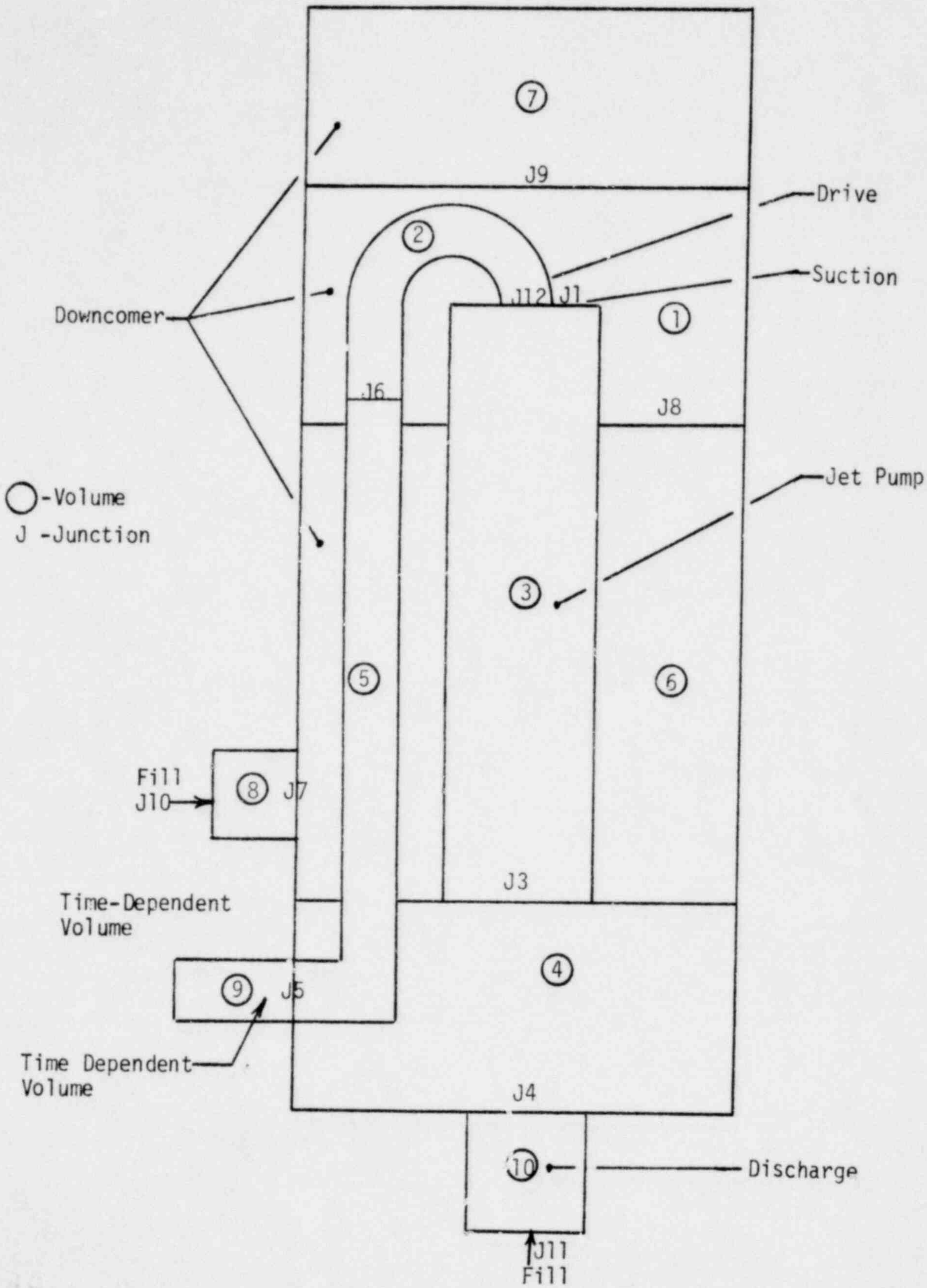


Fig. 21 Transient Test 2 RELAP4 nodalization diagram.

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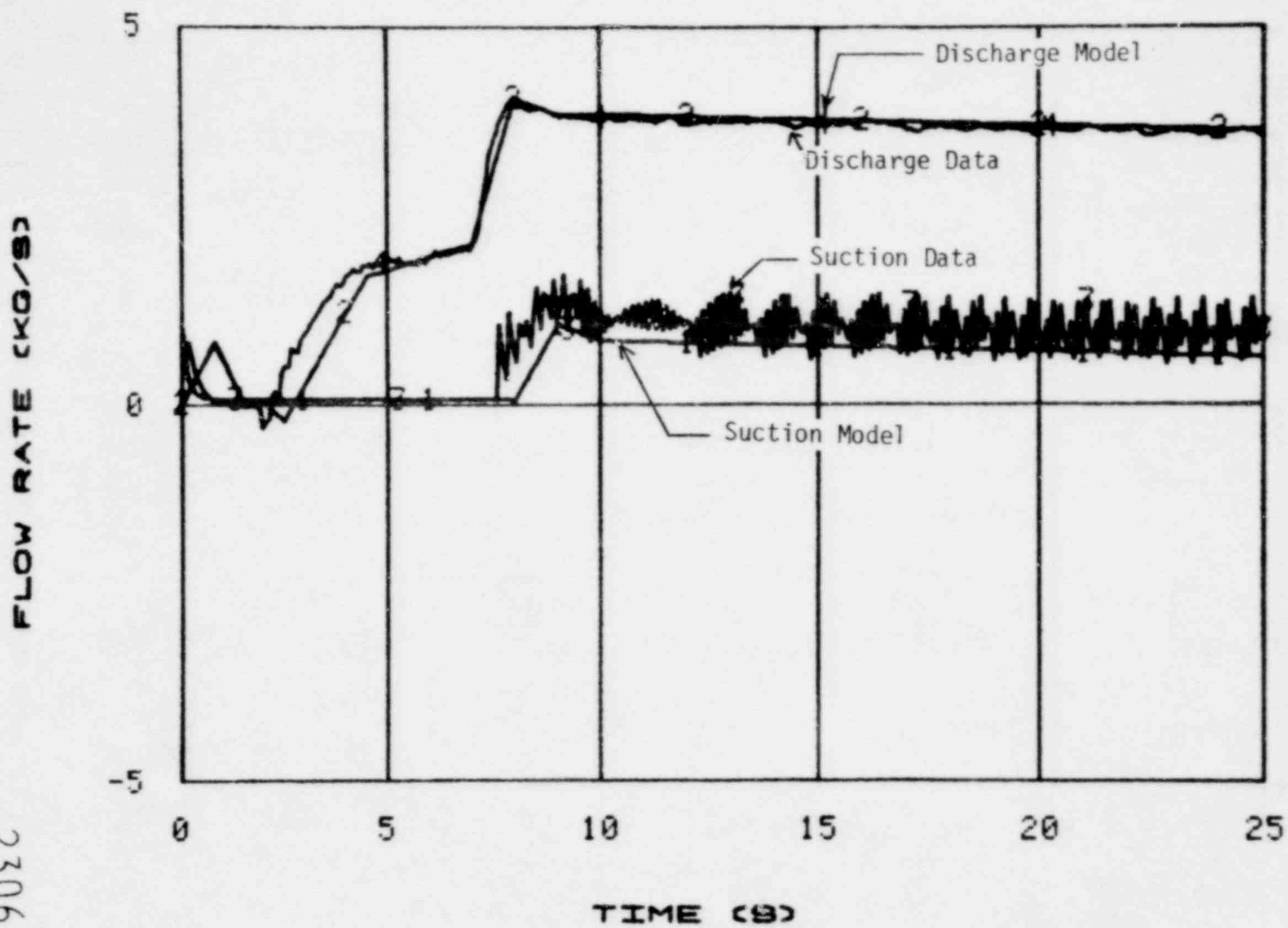

Fig. 22 Transient Test 2 flow into vessel.

2306 085

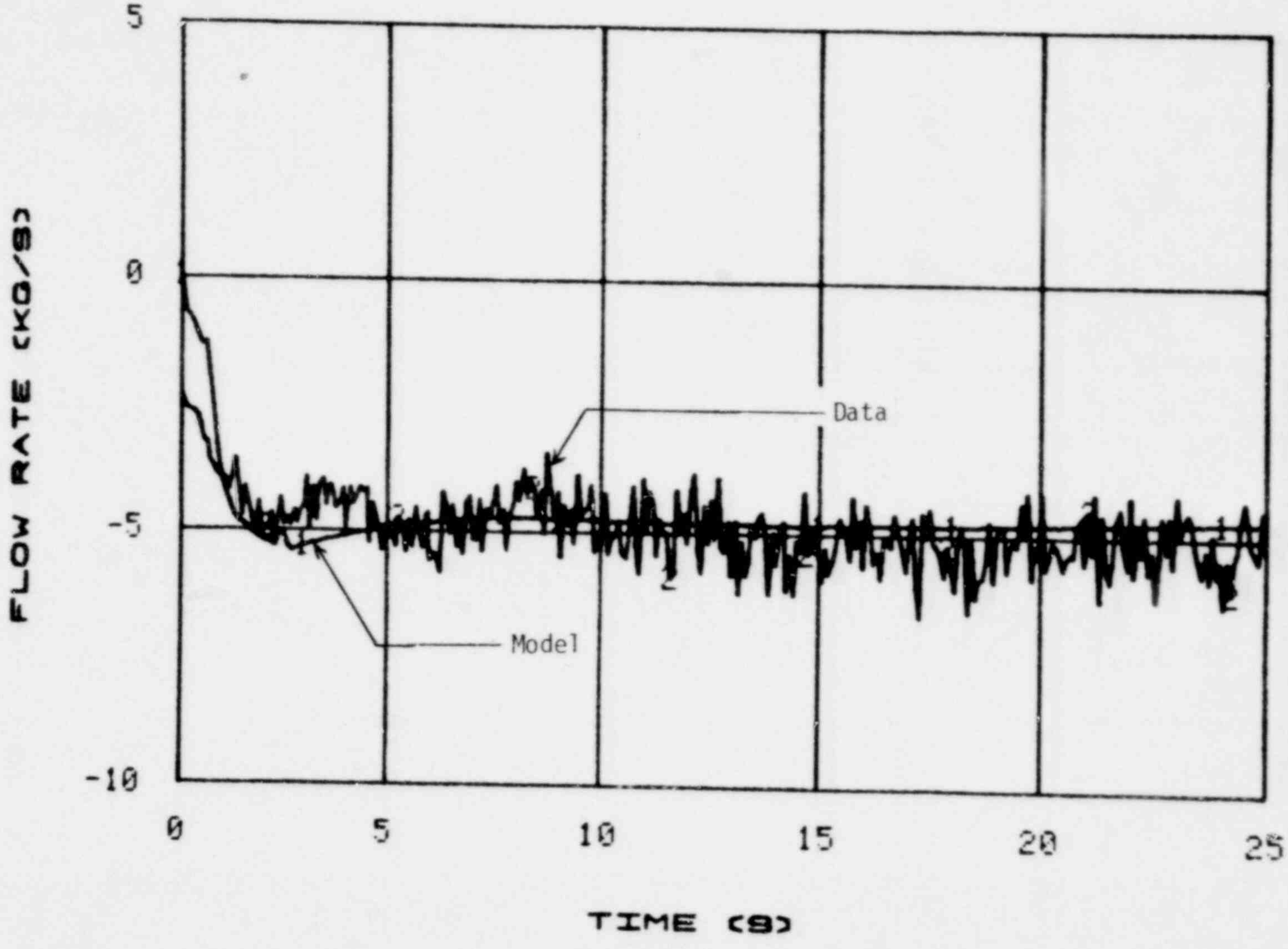

Fig. 23 Transient Test 2 flow out of vessel.

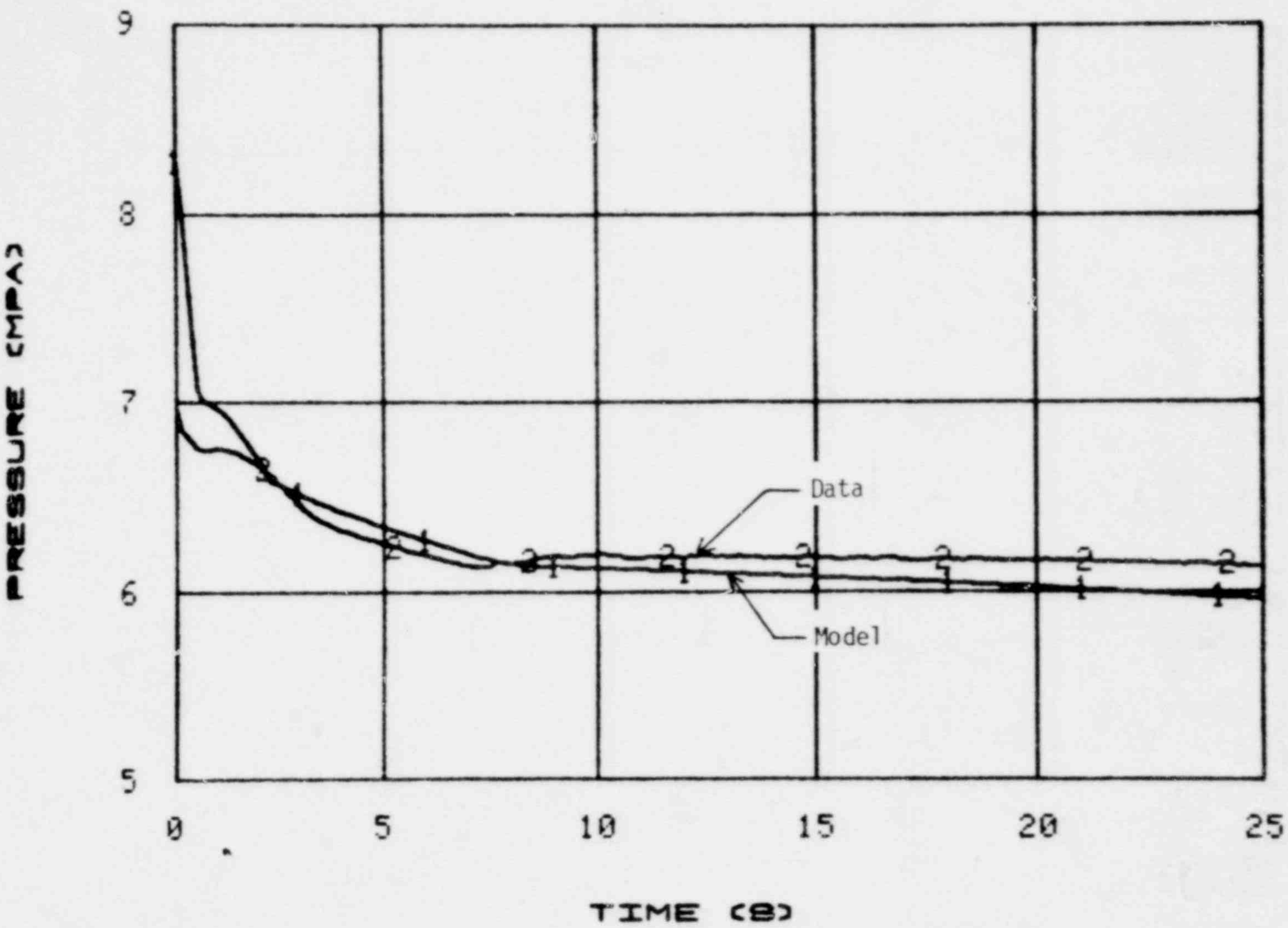

Fig. 24 Transient Test 2 suction pressure.

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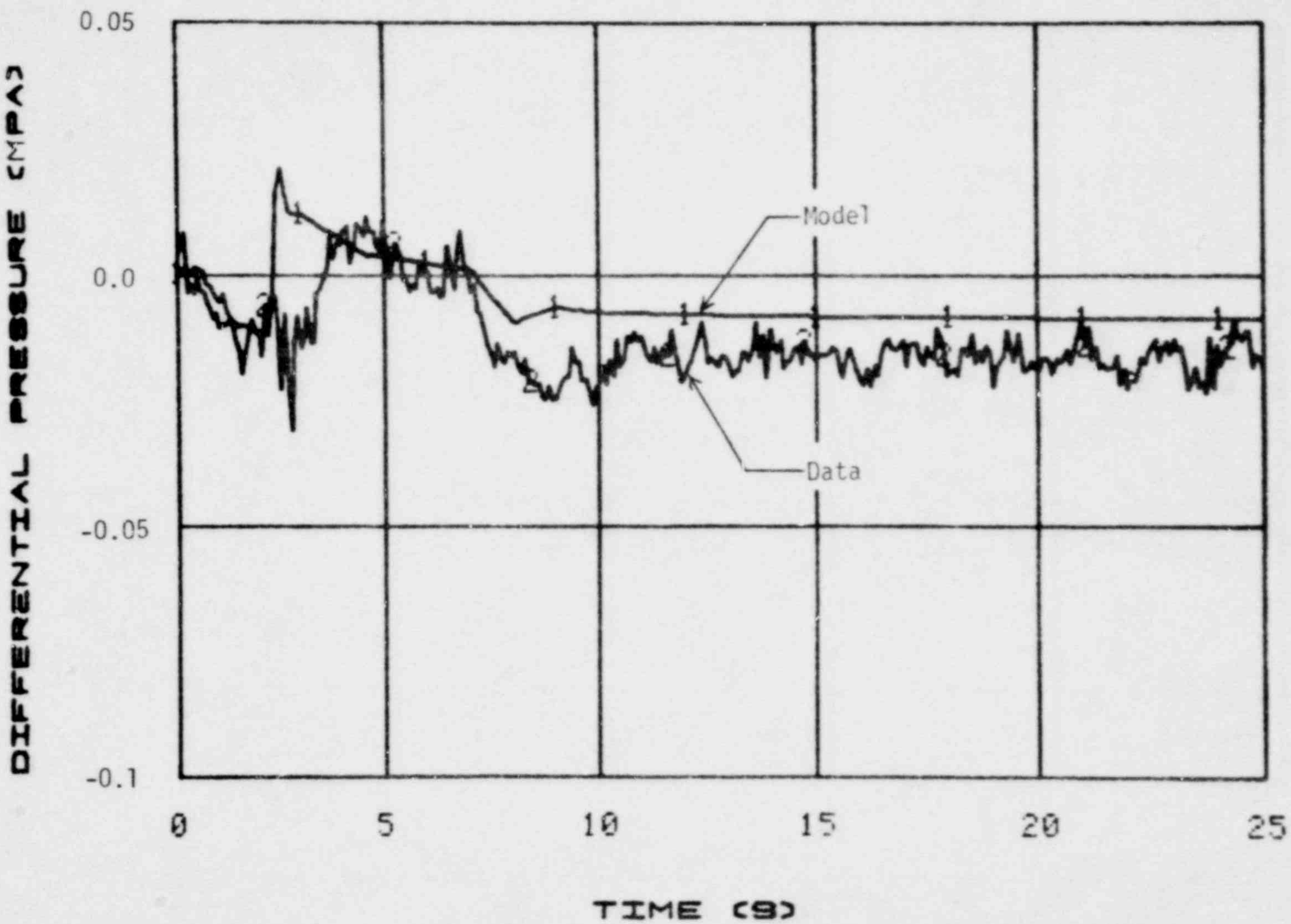

Fig. 25 Transient Test 2 differential pressure suction to discharge.

2306 088

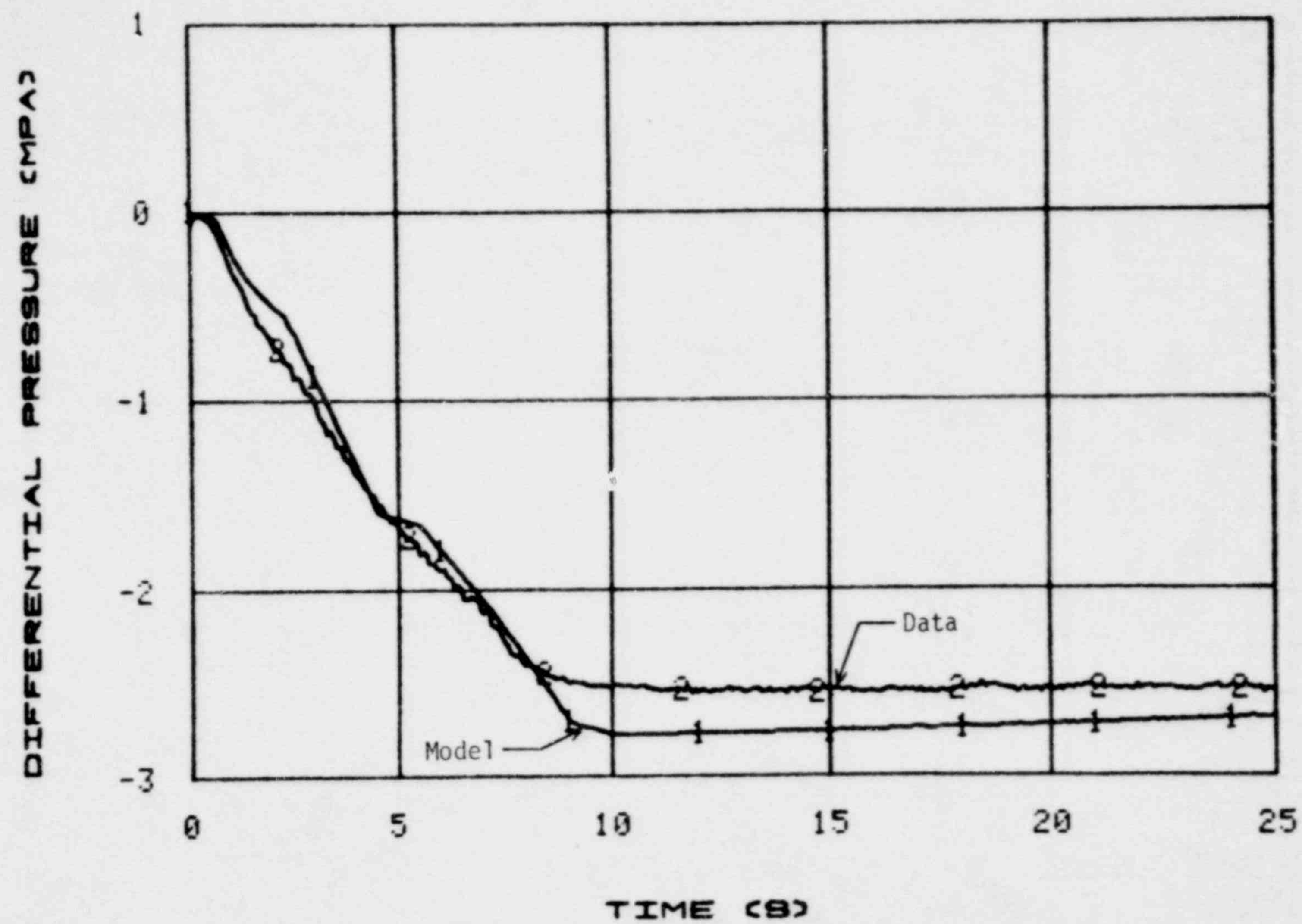

Fig. 26 Transient Test 2 differential pressure drive to discharge.

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APPENDIX A

TERMINOLOGY

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A brief description of jet pump terminology follows. Figure A-1 shows a schematic representation of a jet pump with the major components labeled. Jet pumps are characterized in the literature in terms of M-N curves, where:

$$M = \frac{W_2}{W_1}$$

$$N = \frac{\bar{P}_3 - \bar{P}_2}{\bar{P}_1 - \bar{P}_3}$$

$$\bar{P} = \frac{P}{\rho} + \frac{V^2}{2g_c}$$

W = mass flow rate

P = pressure

ρ = density

V = velocity

g_c = unit conversion factor

Subscripts:

1 = drive nozzle

2 = pump suction

3 = pump discharge

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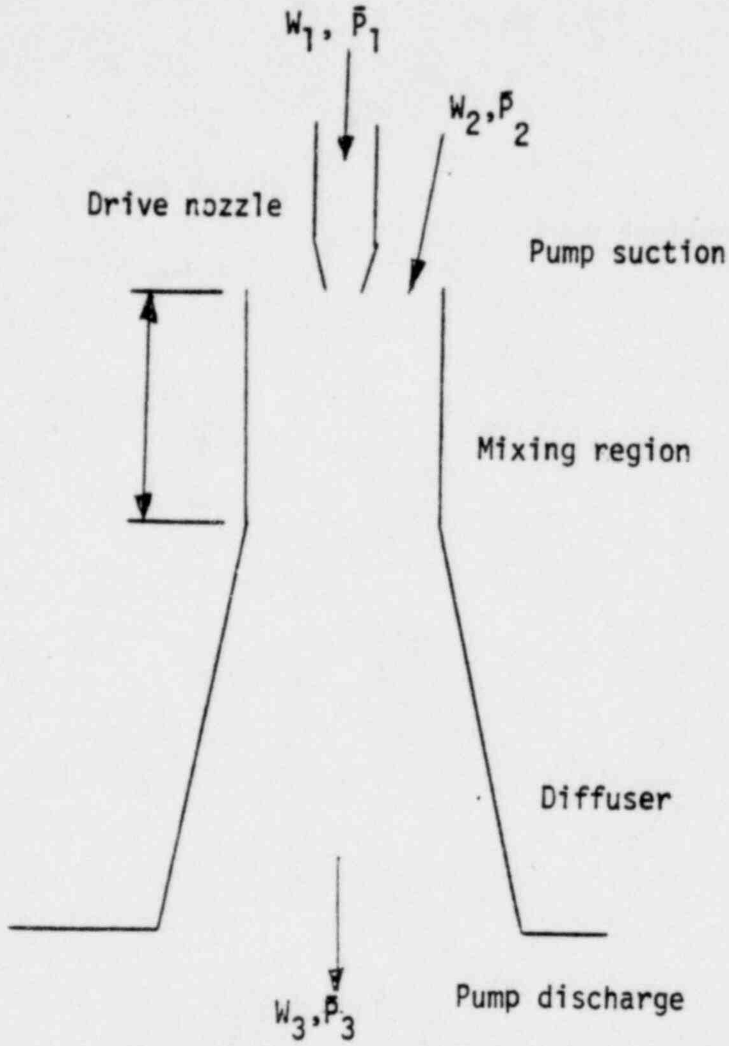

Fig. A-1 Jet pump schematic

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APPENDIX B

EXAMPLE CASE FOR CALCULATING THE JET PUMP FORM LOSS COEFFICIENTS

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An example of the method used to calculate the form loss coefficients is presented in this appendix. The particular case selected is for the reversed flow loss coefficient across the suction as shown in Figure B-1. The data for this case has no drive flow. Applying Bernoulli's equation from the throat to the outside of the suction gives the following equation

$$\frac{P_T}{\rho T} + \frac{V_T^2}{2g} + Z_T = \frac{P_s}{\rho s} + \frac{V_s^{\;2}}{2g} + K_{ST}\ \frac{V_{ST}^{\;2}}{2g} + f\,\frac{L}{D}\ \ \frac{V_T^{\;2}}{2g} \qquad \text{(B-1)}$$

P = pressure

V = velocity

Z = elevation

ρ = density

K_{ST} = reverse suction form loss coefficient.

Since $\rho_T = \rho_s$ and V_s 0.0 the equation reduces to

$$K_{ST} = (\overbrace{\frac{P_T}{\rho} + Z_T) - (\frac{P_s}{\rho} + Z_s}^{=DP\text{-}1}) + \frac{V_T^{\;2}}{2g} - \quad \frac{L}{D}\ \frac{V_T^{\;2}}{2g} \qquad \frac{V_{ST}^{\;2}}{2g} \qquad \text{(B-2)}$$

$$K_{ST} = (DP\text{-}1 + \ f\,\frac{V_T^{\;2}}{2g} - \quad f\,\frac{L}{D_T}\ \frac{V_T^{\;2}}{2g}) \Big/ \rho \qquad \frac{V_{ST}^{\;2}}{2g} \qquad \text{(B-3)}$$

DP-1 is measured directly, while the density and velocities can be determined from pressure, temperature, and volumetric flow measurements. Parameter values follow.

2306 094

$DP\text{-}1 = 33{,}100.\ \text{Pa}$

$V_T = 18.96\ \text{m/s}$

$V_{ST} = 25.12\ \text{m/s}$

$= 745\ \ \text{kg/m}^3$

$D = 0.029\ \text{m}$

$L = 0.102\ \text{m}$

$f = 0.022$ assuming smooth pipe

$$K_{ST} = \frac{\left(33{,}100. + 745.\ \frac{18.96^2}{*\,2.0} - 745.*0.022*\frac{0.102}{0.029} * \frac{18.96^2}{2}\right.}{745.*\frac{25.12^2}{2.0}}$$

$$K_{ST} = 0.67$$

The calculation is repeated for a number of different flow rates and performed for the cases where drive and suction velocities are equal. The results are averaged arriving at the value shown in the report.

For a pipe exit the loss coefficient based on the cross-sectional velocity is known to be 1.0. To convert K_{ST}, which is based on the higher velocity at the suction inlet, to an analogous value the velocity effect must be computed.

$$K = K_{ST}\ \left(\frac{A_T}{A_{ST}}\right)^2 = 0.67\ \left[\frac{4.6*10^{-4}\text{m}^2}{3.45*10^{-4}\ \text{m}^2}\right]^2$$

$$K = 1.19$$

The resulting coefficient is larger than 1.0, which is reasonable since the effects of the drive nozzle have not been taken into account.

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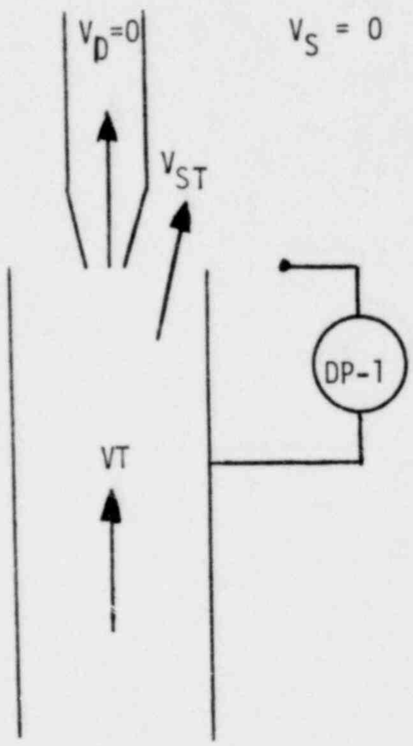

Fig. B-1 Reversed flow across suction.

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