

MASTER

**STEALTH: A Lagrange Explicit Finite-Difference
Code for Solids, Structural, and
Thermohydraulic Analysis.
Volume 7: Implicit Hydrodynamics**

NP-2080, Volume 7
Formerly NP-2080-CCM
Research Project 965-5

Computer Code Manual, June 1982

Prepared by

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Prepared by
Science Applications, Incorporated
La Jolla, California

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

Through RP307-1, EPRI has made STEALTH, the general-purpose and user-oriented explicit finite difference transient continuum mechanics computer code that is based on the technology developed and tested in the defense community, available to utilities and the industry at large. As part of the EPRI research program to develop advanced nonlinear analysis methodology and computer codes for nuclear design and licensing analysis, successful completion of the general-purpose version of the STEALTH code has been followed by reduced versions for "specific" applications such as soil-structure interaction, piping flow, and fluid-structure interaction. The current documentation updates expanded capabilities, modeling improvement, and additional qualifications that were accomplished since the publication of the original STEALTH manual, EPRI Computer Code Manual NP-260, in 1976.

PROJECT OBJECTIVE

The objective of the project is to develop a general, portable, modular, and machine-independent explicit finite difference code to address transient and quasi-static design situations such as water hammer, soil-structure interaction, missile impact, piping flow, and fluid-structure interaction. State-of-the-art capabilities are developed, and extensive qualifications are performed. It is intended that with extensive documentation and user-oriented modeling features, the code can be used by engineers with maximum efficiency and reliability.

PROJECT RESULTS

Since 1976, more than 100 copies of the STEALTH code have been distributed (through three releases) to both domestic and foreign organizations including utilities, vendors, architect-engineering firms,

and research institutions. Version 4-1A is the fourth release of the general-purpose STEALTH code in which three-dimensional capabilities are qualified and documented. In addition to the general-purpose code, special-purpose versions of STEALTH are developed using either mechanical-only or thermal-only subsets for efficient soil-structure interaction, piping flow, and fluid-structure interaction applications. EPRI Summary Report NP-2080-CCM-SY, STEALTH--Introduction and Guide, provides an overview of the design and documentation structures of the entire STEALTH family codes.

This project has been managed by C. Chan and H. T. Tang.

H. T. Tang, Project Manager
Nuclear Power Division

ABSTRACT

STEALTH is a family of computer codes that solve the equations of motion for a general continuum. These codes can be used to calculate a variety of physical processes in which the dynamic behavior of a continuum is involved. The versions of STEALTH described in this volume were designed for the calculation of problems involving low-speed fluid flow. They employ an implicit finite difference technique to solve the one- and two-dimensional equations of motion, written for an arbitrary coordinate system, for both incompressible and compressible fluids. The solution technique involves an iterative solution of the implicit, Lagrangian finite difference equations. Convection terms that result from the use of an arbitrarily-moving coordinate system are calculated separately. This volume provides the theoretical background, the finite difference equations, and the input instructions for the one- and two-dimensional codes; a discussion of several sample problems; and a listing of the input decks required to run those problems.

CONTENTS

<u>SECTION</u>		<u>PAGE</u>
1	INTRODUCTION	1.1
2	EQUATIONS OF MOTION	2.1
	2.1 Equations of Motion for a Continuum	2.1
	2.1.1 Conservation Equations	2.1
	2.1.2 Initial Conditions, Boundary Conditions, and Constitutive Relations	2.7
	2.2 Equations of Motion for 1D and 2D Fluid Flow	2.7
	2.2.1 Spatial Symmetries	2.8
	2.2.2 Constitutive Equations	2.9
	2.2.3 Conservation Equations for Incompressible Flow	2.10
3	NUMERICAL SOLUTION METHOD	3.1
	3.1 Introduction	3.1
	3.2 Time Differences	3.2
	3.3 General Solution Method	3.4
	3.3.1 Explicit Lagrangian Calculation	3.5
	3.3.2 Implicit Lagrangian Calculation	3.6
	3.3.3 Convection Phase	3.8
	3.4 Stability Considerations	3.12
4	ONE-DIMENSIONAL FINITE-DIFFERENCE EQUATIONS	4.1
	4.1 Introduction	4.1
	4.2 Calculational Sequence	4.1
	4.3 Explicit, Lagrangian Phase	4.7
	4.3.1 Momentum Equation	4.7
	4.3.2 Momentum Boundary Conditions	4.9
	4.4 Implicit, Lagrangian Phase	4.10
	4.4.1 Mass Equation	4.10
	4.4.2 Newton-Raphson Equation	4.13
	4.4.3 Momentum Equation	4.17
	4.4.4 Convergence	4.18
	4.4.5 Two-Sided Secant Iteration	4.19

CONTENTS (continued)

<u>SECTION</u>	<u>PAGE</u>
4.4.6 Artificial Viscosity	4.20
4.4.7 Viscous Stresses	4.22
4.4.8 Internal Energy Equation	4.24
4.5 Time Step Calculation	4.25
5 TWO-DIMENSIONAL FINITE-DIFFERENCE EQUATIONS	5.1
5.1 Introduction	5.1
5.2 Calculational Sequence	5.1
5.3 Explicit, Lagrangian Phase	5.8
5.3.1 Momentum Equations	5.8
5.3.2 Momentum Boundary Conditions	5.15
5.4 Implicit, Lagrangian Phase	5.16
5.4.1 Mass Equation	5.16
5.4.2 Newton-Raphson Equation	5.19
5.4.3 Momentum Equation	5.24
5.4.4 Convergence	5.27
5.4.5 Two-Sided Secant Iteration	5.28
5.4.6 Artificial Viscosity	5.29
5.4.7 Viscous Stresses	5.30
5.4.8 Internal Energy Equation	5.32
5.5 Time Step Calculation	5.34
5.6 Convection Phase	5.35
5.6.1 Mesh Velocity	5.36
5.6.2 Mass and Energy Convection	5.37
5.6.3 Momentum Convection	5.45
5.6.4 Momentum Boundary Conditions	5.51
5.6.5 Stress Calculations	5.52
5.7 Damping of Short Wavelength Instabilities	5.52

CONTENTS (continued)

<u>SECTION</u>		<u>PAGE</u>
6	INPUT INSTRUCTIONS FOR THE IMPLICIT FLUID MECHANICS VERSIONS OF THE STEALTH COMPUTER PROGRAMS	6.1
6.1	Introduction	6.1
6.1.1	Record Format	6.1
6.1.2	Manual Format	6.4
6.2	Index Space	6.6
6.3	Operational Considerations	6.11
6.3.1	Code Selection	6.11
6.3.1.1	Incompressible Flow Versions	6.11
6.3.1.2	Implicit, Compressible Flow Versions	6.12
6.3.2	Zoning Considerations	6.13
6.3.3	Time Step Considerations	6.15
6.3.4	Iteration Parameter Considerations	6.17
7	INPUT RECORDS	7.1
7.0	Problem Specification Phase.	7.001
7.1	Material Specification Phase	7.101
7.2	Grid Points Specification Phase.	7.201
7.3	Zone Specification Phase	7.301
7.4	Boundary Conditions Specifications Phase	7.401
7.5	Time Specification Phase	7.501
7.6	Edit Specification Phase	7.601
7.7	End of Input Data Deck	7.701
8	TEST AND EXAMPLE PROBLEMS	8.1
8.1	Introduction	8.1
8.2	Incompressible Flow Test Problems.	8.1
8.2.1	1D Incompressible Flow.	8.1
8.2.1.1	Problem Description.	8.1
8.2.1.2	Problem Set-Up	8.3
8.2.1.3	Results.	8.4
8.2.1.4	Input Decks.	8.7

CONTENTS (continued)

<u>SECTION</u>	<u>PAGE</u>
8.2.2 Calculation of the Generation of an Undular Bore .	8.7
8.2.2.1 Problem Description	8.7
8.2.2.2 Problem Set-Up.	8.11
8.2.2.3 Results	8.13
8.2.2.4 Input Deck.	8.13
8.2.3 Flow Over an Obstacle with a Rectangular Cross Section.	8.19
8.2.3.1 Problem Description	8.19
8.2.3.2 Problem Set-Up.	8.19
8.2.3.3 Results	8.22
8.2.3.4 Input Deck.	8.28
8.2.4 Calculation of the Growth of a Rayleigh-Taylor Instability.	8.28
8.2.4.1 Problem Description	8.28
8.2.4.2 Problem Set-Up.	8.40
8.2.4.3 Results	8.45
8.2.4.4 Input Decks	8.66
8.2.5 Calculation of Sloshing in a Large Fluid-Filled Tank Subjected to Horizontal Accelerations	8.70
8.2.5.1 Problem Description	8.70
8.2.5.2 Problem Set-Up.	8.72
8.2.5.3 Results	8.75
8.2.5.4 Input Decks	8.87
8.3 Implicit, Compressible Flow Test Problems	8.105
8.3.1 Pipe Blowdown.	8.105
8.3.1.1 Problem Description	8.105
8.3.1.2 Problem Set-Up.	8.106
8.3.1.3 Results	8.113
8.3.1.4 Input Decks	8.122

CONTENTS (continued)

<u>SECTION</u>	<u>PAGE</u>
8.3.2 Thermally Driven Cavity.	8.122
8.3.2.1 Problem Description	8.122
8.3.2.2 Problem Set-Up.	8.130
8.3.2.3 Results	8.132
8.3.2.4 Input Deck.	8.132
8.3.3 Calculations of Pressure Release Transients in Prototype PWR Geometries	8.139
8.3.3.1 Problem Description and Set-Up.	8.139
8.3.3.2 Results	8.151
8.3.3.3 Input Decks	8.226
8.3.4 Calculation of an Explosion in a Partially Water-Filled, Rigid Container.	8.226
8.3.4.1 Problem Description	8.226
8.3.4.2 Problem Set-Up.	8.240
8.3.4.3 Results	8.246
8.3.4.4 Input Deck.	8.265
APPENDIX FILES (FLS).	FLS.1
APPENDIX FUNCTIONS (FNC).	FNC.1
APPENDIX IDENTIFIERS (IDS).	IDS.1
APPENDIX MATERIAL MODELS (MAT).	MAT.1
APPENDIX MAXIMUMS (MAX)	MAX.1
APPENDIX MESSAGES (MSG)	MSG.1
REFERENCES.	REF.1

LIST OF FIGURES

<u>FIGURE</u>		<u>PAGE</u>
3.1a	Integration Volume for Mass Flux	3.11
3.1b	Integration Volume for Momentum Flux	3.11
4.1a	Diagram of 1D Displacement Mesh	4.2
4.1b	Diagram of 1D Stress Mesh	4.2
4.2a	Calculational Sequence for 1D Incompressible Flow Version of STEALTH	4.3
4.2b	Calculational Sequence for 1D Implicit, Compressible Flow Version of STEALTH	4.4
4.3	Graphical Representation of the Two-Sided Secant Iteration Method	4.21
5.1a	Diagram of 2D Displacement Mesh Showing Momentum Zone (dashed)	5.2
5.1b	Diagram of 2D Stress Mesh	5.2
5.2a	Calculational Sequence for 2D Incompressible Flow Version of STEALTH	5.3
5.2b	Calculational Sequence for 2D Implicit, Compressible Flow Version of STEALTH	5.4
5.3a	Location of Mass Fluxes	5.7
5.3b	Location of Momentum Fluxes	5.7
5.4	Schematic of the Procedure for Calculating Mass Convection	5.39
5.5	Schematic of the Procedure for Calculating Momentum Convection	5.46
5.6	Schematic of Alternating Error Pattern Leading to the Hourglass Instability	5.54
6.1	General Structure of a STEALTH Input Deck	6.3
6.2	Input Record Format	6.5

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
6.3	Input Record Documentation Format	6.7
6.4	One-Dimensional Index Conventions	6.9
6.5	Two-Dimensional Index Conventions	6.10
8.1	Velocity Profiles at Cycle 2 ($t = 50 \mu\text{sec}$) for 1D Planar, Cylindrical and Spherical Incompressible Flow	8.5
8.2	Velocity Profiles at Cycle 10 ($t = 250 \mu\text{sec}$) for 1D Planar, Cylindrical and Spherical Incompressible Flow	8.6
8.3	Pressure Profiles at Cycle 2 ($t = 50 \mu\text{sec}$) for 1D Planar, Cylindrical and Spherical Incompressible Flow	8.8
8.4	Initial Configuration for Undular Bore Problem	8.12
8.5	Mesh Configuration at Several Times for the Undular Bore Problem	8.14
8.6	Velocity Vector Plots at Several Times for the Undular Bore Problem	8.15
8.7	Free Surface Configuration at Several Times for the Undular Bore Problem	8.16
8.8	Configuration for Calculations of Incompressible Flow Over an Obstacle with a Rectangular Cross Section	8.20
8.9	Velocity Vector Plot at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Planar Obstacle with Rectangular Cross Section	8.24
8.10	Pressure Contour Plot at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Planar Obstacle with Rectangular Corss Section	8.25
8.11	Velocity Vector Plot at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Cylindrical Obstacle with Rectangular Cross Section	8.26
8.12	Pressure Contour Plot at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Cylindrical Obstacle with Rectangular Cross Section	8.27

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.13	Snapshot of Row 12 at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Planar Obstacle with Rectangular Cross Section	8.29
8.14	Snapshot of Row 15 at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Planar Obstacle with Rectangular Cross Section	8.30
8.15	Snapshot of Row 19 at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Planar Obstacle with Rectangular Cross Section	8.31
8.16	Snapshot of Row 35 at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Planar Obstacle with Rectangular Cross Section	8.32
8.17	Snapshot of Row 12 at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Cylindrical Obstacle with Rectangular Cross Section	8.33
8.18	Snapshot of Row 15 at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Cylindrical Obstacle with Rectangular Cross Section	8.34
8.19	Snapshot of Row 19 at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Cylindrical Obstacle with Rectangular Cross Section	8.35
8.20	Snapshot of row 35 at Cycle 19, time = 1.0850 for the Calculation of Flow Over a Cylindrical Obstacle with Rectangular Cross Section	8.36
8.21	Initial Configuration for Rayleigh-Taylor Instability Problem	8.41
8.22	Velocity Vector Plot at Cycle 1, time = 0.000100 for the Rayleigh-Taylor Instability Calculation	8.44
8.23	Mesh Configuration at Cycle 55, time = 0.025079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 2:1	8.46

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.24	Mesh Configuration at Cycle 105, time = 0.050079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 2:1	8.47
8.25	Mesh Configuration at Cycle 155, time = 0.075079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 2:1	8.48
8.26	Mesh Configuration at Cycle 205, time = 0.10008 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 2:1	8.49
8.27	Mesh Configuration at Cycle 255, time = 0.12508 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 2:1	8.50
8.28	Mesh Configuration at Cycle 305, time = 0.15008 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 2:1	8.51
8.29	Interface Configuration for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 2:1 . .	8.53
8.30	Mesh Configuration at Cycle 55, time = 0.025079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 10:1	8.54
8.31	Mesh Configuration at Cycle 105, time = 0.050079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 10:1	8.55
8.32	Mesh Configuration at Cycle 155, time = 0.075079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 10:1	8.56
8.33	Mesh Configuration at Cycle 205, time = 0.10008 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 10:1	8.57
8.34	Interface Configuration for 10:1 Density Ratio	8.58

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.35	Velocity Vector Plot at Cycle 55, time = 0.25079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 2:1	8.59
8.36	Velocity Vector Plot at Cycle 155, time = 0.075079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 2:1	8.60
8.37	Velocity Vector Plot at Cycle 305, time = 0.15008 for the Rayleigh-Taylor Instability Calculation with a Density ratio of 2:1	8.61
8.38	Velocity Vector Plot at Cycle 55, time = 0.025079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 10:1	8.62
8.39	Velocity Vector Plot at Cycle 105, time = 0.050079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 10:1	8.63
8.40	Velocity Vector Plot at Cycle 155, time = 0.075079 for the Rayleigh-Taylor Instability Calculation with a Density Ratio of 10:1	8.64
8.41	Spike and Bubble Amplitude as a Function of Time for the Rayleigh-Taylor Instability Calculation	8.65
8.42	Horizontal Acceleration Waveform Corresponding to the Boundary Condition used to Simulate Earthquake Excitation of Fluid Motion in a Storage Tank	8.71
8.43	Configuration used for Calculations of Fluid Sloshing in a Rectangular Tank	8.73
8.44	Mesh Configuration at Several Times for the Fluid Sloshing Calculation with a Simple Sine Wave Input	8.76
8.45	Velocity Field at Several Times for the Fluid Sloshing Calculation with a Simple Sine Wave Input	8.79
8.46	Contours of $p-p_o$ at Several Times for the Fluid Sloshing Calculation with a Simple Sine Wave Input	8.82

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.47	Surface Height History Adjacent to Left-Hand Wall for Fluid Sloshing Calculation with a Simple Sine Wave Input	8.85
8.48	Kinetic Energy History for the Fluid Sloshing Calculation with a Simple Sine Wave Input	8.86
8.49	Pressure Histories at Several Points Adjacent to the Walls for the Fluid Sloshing Calculation with a Simple Sine Wave Input	8.88
8.50	Surface Height History Adjacent to Left-Hand Wall for Fluid Sloshing Calculation with a Simulated Earthquake Boundary Condition	8.90
8.51	Pressure Histories at Several Locations for the Fluid Sloshing Calculation with a Simulated Earthquake Boundary Condition	8.91
8.52	Velocity Field at Several Times for the Fluid Sloshing Calculation with a Simulated Earthquake Boundary Condition	8.93
8.53	Contours of $p-p_0$ at several times for the Fluid Sloshing Calculation with a Simulated Earthquake Boundary Condition	8.96
8.54	Configurations for Pipe Depressurization Calculations Showing the 1D Problem Setup	8.107
8.55	Initial Configuration for the 2D Pipe Depressurization Calculations	8.109
8.56	Function for Pressure Boundary Condition	8.111
8.57	Comparison of Pressure Histories at Gauge Station 1 for the First 15 msec of the 1D Full Pipe Depressurization Calculations	8.114
8.58	Comparison of Pressure Histories at Gauge Station 3 for the First 15 msec of the 1D Full Pipe Depressurization Calculations	8.115
8.59	Comparison of Pressure Histories at Gauge Station 6 for the First 15 msec of the 1D Full Pipe Depressurization Calculations	8.116

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.60	Comparison of the Entire Pressure Histories at Gauge Station 1 for the 1D Full Pipe Depressurization Calculations	8.117
8.61	Comparison of the Entire Pressure Histories at Gauge Station 3 for the 1D Full Pipe Depressurization Calculations	8.118
8.62	Comparison of the Entire Pressure Histories at Gauge Station 6 for the 1D Full Pipe Depressurization Calculations	8.119
8.63	Comparison of Pressure Histories at Gauge Station 1 for the 1D Short Pipe Depressurization Calculations . .	8.121
8.64	Pressure Histories at Gauge Station 1 for Pipe Depressurization Calculations Performed with Other Codes	8.123
8.65	Configuration for Thermally Driven Cavity Problem . . .	8.131
8.66	Velocity Vector Field for the Thermally Driven Cavity Calculation at Cycle 81, $t = 0.51390$	8.133
8.67	Velocity Vector Field for the Thermally Driven Cavity Calculation at Cycle 147, $t = 0.10089$	8.134
8.68	Velocity Vector Field for the Thermally Driven Cavity Calculation at Cycle 213, $t = 0.15039$	8.135
8.69	Velocity Vector Field for the Thermally Driven Cavity Calculation at Cycle 280, $t = 0.20064$	8.136
8.70	Configuration for the Calculation of a Quarter Section of a Cylindrical Rarefaction	8.142
8.71	Configuration for the Calculation of a Half Section of a Cylindrical Rarefaction in a Region with Obstacles in the Flow	8.144
8.72	Configuration for the More Coarsely Zoned Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction	8.146

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.73	Configuration for the More Finely Zoned Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction	8.147
8.74	Configuration for the More Coarsely Zoned Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction	8.149
8.75	Configuration for the More Finely Zoned Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction	8.150
8.76	Calculation of a Quarter Section of a Cylindrical Rarefaction: Pressure Contours at Cycle 11, time = 0.55 . .	8.152
8.77	Calculation of a Quarter Section of a Cylindrical Rarefaction: Pressure Contours at Cycle 21, time = 1.05 . .	8.153
8.78	Calculation of a Quarter Section of a Cylindrical Rarefaction: Pressure Contours at Cycle 31, time = 1.55 . .	8.154
8.79	Calculation of a Quarter Section of a Cylindrical Rarefaction: Pressure Contours at Cycle 41, time = 2.05 . .	8.155
8.80	Calculation of a Quarter Section of a Cylindrical Rarefaction: Pressure Contours at Cycle 51, time = 2.25 . .	8.156
8.81	Calculation of a Quarter Section of a Cylindrical Rarefaction: Pressure Contours at Cycle 61, time = 3.05 . .	8.157
8.82	Calculation of a Quarter Section of a Cylindrical Rarefaction: Velocity Vectors at Cycle 11, time = 0.55 . .	8.158
8.83	Calculation of a Quarter Section of a Cylindrical Rarefaction: Velocity Vectors at Cycle 21, time = 1.05 . .	8.159
8.84	Calculation of a Quarter Section of a Cylindrical Rarefaction: Velocity Vectors at Cycle 31, time = 1.55 . .	8.160
8.85	Calculation of a Quarter Section of a Cylindrical Rarefaction: Velocity Vectors at Cycle 41, time = 2.05 . .	8.161
8.86	Calculation of a Quarter Section of a Cylindrical Rarefaction: Velocity Vectors at Cycle 51, time = 2.55 . .	8.162

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.87	Calculation of a Quarter Section of a Cylindrical Rarefaction: Velocity Vectors at Cycle 61, time = 3.05 . . .	8.163
8.88	Comparison of STEALTH and SOLA-ICE Calculations of a Cylindrical Rarefaction: Pressure Profiles Along a Radius Extending Directly Upward	8.165
8.89	Calculation of a Half Section of a Cylindrical Rarefaction in a Region with Obstacles in the Flow: Pressure Contours at Cycle 19, time = 0.52	8.167
8.90	Calculation of a Half Section of a Cylindrical Rarefaction in a Region with Obstacles in the Flow: Pressure Contours at Cycle 34, time = 1.00	8.168
8.91	Calculation of a Half Section of a Cylindrical Rarefaction in a Region with Obstacles in the Flow: Pressure Contours at Cycle 48, time = 1.53	8.169
8.92	Calculation of a Half Section of a Cylindrical Rarefaction in a Region with Obstacles in the Flow: Pressure Contours at Cycle 60, time = 2.04	8.170
8.93	Calculation of a Half Section of a Cylindrical Rarefaction in a region with Obstacles in the Flow: Pressure Contours at Cycle 70, time = 2.51	8.171
8.94	Calculation of a Half Section of a Cylindrical Rarefaction in a region with Obstacles in the Flow: Pressure Contours at Cycle 80, time = 3.04	8.172
8.95	Calculation of a Half Section of a Cylindrical Rarefaction in a region with obstacles in the flow: Velocity Vectors at Cycle 19, time = 0.52	8.173
8.96	Calculation of a Half Section of a Cylindrical Rarefaction in a Region with Obstacles in the Flow: Velocity Vectors at Cycle 34, time = 1.00	8.174
8.97	Calculation of a Half Section of a Cylindrical Rarefaction in a Region with Obstacles in the Flow: Velocity Vectors at Cycle 48, time = 1.53	8.175
8.98	Calculation of a Half-Section of a Cylindrical Rarefaction in a region with Obstacles in the Flow: Velocity Vectors at Cycle 60, time = 2.04	8.176

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.99	Calculation of a Half Section of a Cylindrical Rarefaction in a Region with Obstacles in the Flow: Velocity Vectors at Cycle 70, time = 2.51	8.177
8.100	Calculation of a Half Section of a Cylindrical Rarefaction in a Region with Obstacles in the Flow: Velocity Vectors at Cycle 80, time = 3.04	8.178
8.101	Comparison of STEALTH and SOLA-ICE Calculations of a Cylindrical Rarefaction with Obstacles in the Flow: Pressure Profiles Along a Horizontal Line 0.4 m Below the Bottom Surface of the Rectangular Obstacle	8.179
8.102	Comparison of STEALTH and SOLA-ICE Calculations of a Cylindrical Rarefaction with Obstacles in the Flow: Pressure Profiles Along a Horizontal Line 0.4 m Above the Top Surface of the Rectangular Obstacle	8.180
8.103	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Pressure Contours at Cycle 11, time = 0.55	8.182
8.104	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Pressure Contours at Cycle 21, time = 1.05	8.183
8.105	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Pressure Contours at Cycle 31, time = 1.55	8.184
8.106	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Pressure Contours at Cycle 41, time = 2.05	8.185
8.107	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Pressure Contours at Cycle 51, time = 2.55	8.186
8.108	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Pressure Contours at Cycle 61, time = 3.05	8.187
8.109	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Velocity Vectors at Cycle 11, time = 0.55	8.188

LIST OF FIGURES (Continued)

<u>FIGURE</u>		<u>PAGE</u>
8.110	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Velocity Vectors at Cycle 21, time = 1.05	8.189
8.111	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Velocity Vectors at Cycle 31, time = 1.55	8.190
8.112	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Velocity Vectors at Cycle 41, time = 2.05	8.191
8.113	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Velocity Vectors at Cycle 51, time = 2.55	8.192
8.114	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Coarse Zoning: Velocity Vectors at Cycle 61, time = 3.05	8.193
8.115	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Pressure Contours at Cycle 11, time = 0.55	8.194
8.116	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Pressure Contours at Cycle 21, time = 1.05	8.195
8.117	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Pressure Contours at Cycle 31, time = 1.44	8.196
8.118	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Pressure Contours at Cycle 41, time = 2.05	8.197
8.119	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Pressure Contours at Cycle 51, time = 2.55	8.198
8.120	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Pressure Contours at Cycle 61, time = 3.05	8.199
8.121	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Velocity Vectors at Cycle 11, time = 0.55	8.200

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.122	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Velocity Vectors at Cycle 21, time = 1.05	8.201
8.123	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-downcomer Junction - Fine Zoning: Velocity Vectors at Cycle 31, time = 1.55	8.202
8.124	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Velocity Vectors at Cycle 41, time = 2.05	8.203
8.125	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Velocity Vectors at Cycle 51, time = 2.55	8.204
8.126	Calculation of a Rarefaction in a Geometry Similar to a Cold Leg-Downcomer Junction - Fine Zoning: Velocity Vectors at Cycle 61, time = 3.05	8.205
8.127	Comparison of STEALTH and SOLA-ICE Calculations of a Rarefaction in a Cold Leg-Downcomer Junction Geometry: Pressure Profiles Along a Vertical Line 0.18 m to the Right of the Symmetry Axis (1/2 Radius of Channel) . . .	8.207
8.128	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Coarse Zoning: Pressure Contours at Cycle 26, time = 1.04	8.209
8.129	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Coarse Zoning: Pressure Contours at Cycle 51, time = 2.04	8.210
8.130	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Coarse Zoning: Pressure Contours at Cycle 76, time = 3.04	8.211
8.131	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Coarse Zoning: Pressure Contours at Cycle 101, time = 4.04	8.212
8.132	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Coarse Zoning: Pressure Contours at Cycle 126, time = 5.04	8.213

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.133	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Coarse Zoning: Pressure Contours at Cycle 151, time = 6.04	8.214
8.134	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Coarse Zoning: Pressure Contours at Cycle 176, time = 7.04	8.215
8.135	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Coarse Zoning: Pressure Contours at Cycle 201, time = 8.04	8.216
8.136	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Coarse Zoning: Pressure Contours at Cycle 226, time = 9.04	8.217
8.137	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Fine Zoning: Pressure Contours at Cycle 26, time = 1.04	8.218
8.138	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Fine Zoning: Pressure Contours at Cycle 51, time = 2.04	8.219
8.139	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Fine Zoning: Pressure Contours at Cycle 76, time = 3.04	8.220
8.140	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Fine Zoning: Pressure Contours at Cycle 101, time = 4.04	8.221
8.141	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Fine Zoning: Pressure Contours at Cycle 126, time = 5.04	8.222
8.142	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Fine Zoning: Pressure Contours at Cycle 151, time = 6.04	8.223
8.143	Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction - Fine Zoning: Pressure Contours at Cycle 176, time = 7.04	8.224

LIST OF FIGURES (Continued)

<u>FIGURE</u>		<u>PAGE</u>
8.144	Comparison of the More Coarsely Zoned STEALTH Calculation and the SOLA-ICE Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction: Pressure Profiles Along Vertical Lines on Either Side of Obstacle	8.225
8.145	Comparison of the More Finely Zoned STEALTH Calculation and the SOLA-ICE Calculation of a Rarefaction in a Narrow Channel with a Central Obstruction: Pressure Profiles Along Vertical Lines of Either Side of Obstacle	8.227
8.146	COVA 1 Experiment Configuration	8.241
8.147	Initial Mesh Configuration Used for the APRICOT 3 Calculation	8.242
8.148	Mesh Configuration and Velocity Field at Several Times for the APRICOT 3 Calculation	8.247
8.149	Location of the Zones that were Monitored in the APRICOT 3 Calculation for Comparison with the COVA 1 Experimental Results	8.253
8.150	Comparison of Peak Pressures at Gage Locations on the Vessel Floor	8.254
8.151	Comparison of Peak Pressures at Gage Locations on the Vessel Wall	8.255
8.152	Comparison of Wave Arrival Times at Gage Locations on the Vessel Floor	8.256
8.153	Comparison of Wave Arrival Times at Gage Locations on the Vessel Wall	8.257
8.154	Comparison of Pressure Histories Near the Location of Gage 3 for the Explicit and Implicit Calculations of APRICOT 3	8.259
8.155	Comparison of Pressure Histories Near the Location of Gage 5 for the Explicit and Implicit Calculations of APRICOT 3	8.260
8.156	Comparison of Pressure Histories Near the Location of Gage 6 for the Explicit and Implicit Calculations of APRICOT 3	8.261

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
8.157	Comparison of Pressure Histories Near the Location of Gage 11 for the Explicit and Implicit Calculations of APRICOT 3	8.262
8.158	Comparison of Peak Pressures at Gage Locations on the Vessel Ceiling	8.263
8.159	Comparison of Wave Arrival Times at Gage Locations on the Vessel Ceiling	8.264

LIST OF TABLES

<u>TABLE</u>		<u>PAGE</u>
7.0	Summary of PRB Phase Input Records and Input Variables . .	7.009
7.1	Summary of MAT Phase Input Records and Input Variables . .	7.109
7.2	Summary of GPT Phase Input Records and Input Variables . .	7.209a
7.3	Summary of ZON Phase Input Records and Input Variables . .	7.309
7.4	Summary of BDY Phase Input Records and Input Variables . .	7.409
7.5	Summary of TIM Phase Input Records and Input Variables . .	7.509
7.6	Summary of EDT Phase Input Records and Input Variables . .	7.609a
8.1	Input Deck for 1D Planar Incompressible Flow	8.9
8.2	Modifications to 1D Incompressible Flow Data Deck for Cylindrical Symmetry	8.10
8.3	Modifications to 1D Incompressible Flow Data Deck for Spherical Symmetry	8.10
8.4	Data Deck for Undular Bore Calculation	8.17
8.5	Initial Transient Pressure and Final Steady-State Pressure at Several Stations	8.23
8.6	Data Deck for Calculation of Flow Over a Planar Obstacle with a Rectangular Cross Section	8.37
8.7	Modifications for Cylindrical Symmetry	8.39
8.8	Data Deck for Taylor Instability Calculation with 2:1 Density Ratio	8.67
8.9	Modifications to the Taylor Instability Data Deck for 10:1 Density Ratio	8.69
8.10	Data Deck for Fluid Sloshing Calculation with a Simple Sine Wave Input	8.99
8.11	Data Deck for Fluid Sloshing Calculation with a Simulated Earthquake Boundary Condition	8.103
8.12	Initial Conditions at Gauge Locations for Specified Enthalpy Distribution	8.112

LIST OF TABLES (continued)

<u>TABLE</u>		<u>PAGE</u>
8.13	Data Deck for 1D Full Pipe Depressurization Calculation with Uniform Enthalpy Distribution	8.124
8.14	Data Deck for 1D Short Pipe Depressurization Calculation with Uniform Enthalpy Distribution	8.125
8.15	Data Deck for 2D Lagrangian Short Pipe Depres- surization Calculation with Uniform Enthalpy Distribution	8.126
8.16	Data Deck for 2D Eulerian Short Pipe Depres- surization Calculation with Uniform Enthalpy Distribution	8.128
8.17	Data Deck for the Thermally Driven Cavity Calculation . .	8.137
8.18	Data Deck for the Calculation of a Cylindrical Rarefaction	8.228
8.19	Data Deck for the Calculation of a Cylindrical Rarefaction with Obstacles in the Flow	8.230
8.20	Data Deck for the More Coarsely Zoned Calculation of a Rarefaction in a Cold Leg-Downcomer Junction Geometry	8.232
8.21	Data Deck for the More Finely Zoned Calculation of a Rarefaction in a Cold Leg-Downcomer Junction Geometry . .	8.234
8.22	Data Deck for the More Coarsely Zoned Calculation of a Rarefaction in a Narrow Channel Containing a Central Obstruction	8.236
8.23	Data Deck for the More Finely Zoned Calculation of a Rarefaction in a Narrow Channel Containing a Central Obstruction	8.238
8.24	Gage Locations for COVA 1 Experiments and APRICOT 3 Calculations	8.251

SECTION 1

INTRODUCTION

This volume describes a subset of the STEALTH family of computer codes that has been developed specifically for the solution of fluid dynamics problems. Whereas the other STEALTH codes utilize an explicit finite-difference technique for solution of the equations of motion, in the codes described here an implicit solution method is used. This means that these codes are generally more suitable for the calculation of problems involving low speed flow or other problems involving small strain-rate phenomena.

This set of codes is made up of six separate codes. Two of the codes solve the 1D and 2D equations of motion for an inviscid, incompressible fluid. Two others also solve the equations of motion for an incompressible fluid, but include the full viscous stress tensor. The final two codes solve the equations of motion for a viscous, compressible fluid and include the simultaneous calculation of heat conduction. The 1D codes can treat systems exhibiting one-dimensional planar, cylindrical or spherical symmetry, while the 2D codes can handle two-dimensional planar or cylindrical symmetry.

In order to facilitate the use of these codes by those already familiar with the STEALTH family of codes, an attempt has been made to conform as closely as possible to the format and conventions used in other versions of the STEALTH codes. Where possible, the finite-difference techniques used in other versions of STEALTH were retained; however, a number of new ideas were incorporated into these codes which have required some fairly major modifications to the original codes. These modifications were also made to conform to the basic STEALTH format as closely as possible.

The original STEALTH codes solve the equations of motion for a general continuum using an explicit, Lagrangian finite-difference method. This method is based primarily on technology developed for the HEMP code by researchers at the Livermore National Laboratory (LNL) (Reference 1). The codes described here, on the other hand, solve the equations of motion, written for an arbitrary coordinate system, using an implicit finite-difference method. While retaining many of the original features taken from HEMP, these codes also incorporate some of the technology developed at the Los Alamos Scientific Laboratory (LASL) for the numerical solution of fluid mechanics problems.

The general solution method used here to solve the equations of motion for incompressible flow had its origins in the MAC code (Reference 2) and, more recently, has been utilized in the development of the SOLA family of codes (Reference 3). The solution method for compressible flow was derived from the ICE methodology (Reference 4) which has also been incorporated into the SOLA family (Reference 5). To facilitate incorporation of these solution methods into the STEALTH framework, some ideas were taken from the YAQUI (Reference 6) and SAQUI (Reference 7) codes. In particular, the concept of separating the convection terms from the equations of motion and splitting the calculation into three separate phases (explicit-Lagrangian, implicit-Lagrangian, and convection), as described in Section 4, came from these two codes. This method allows us to utilize many of the original features of the STEALTH codes in the initial Lagrangian phases and to evaluate in a separate phase the convection terms which arise from the use of a non-Lagrangian coordinate system. Using this three phase approach has the further advantage of facilitating the incorporation of either the incompressible flow solution method or the ICE methodology for compressible flow by permitting the insertion of the appropriate logic into the second Lagrangian phase while leaving the other phases unchanged.

The technique used in the final convection phase utilizes the ALE (Arbitrary Lagrangian-Eulerian) methodology (Reference 8) developed at LASL and incorporated into the YAQUI code. This method, which computes the convection terms for an arbitrarily moving coordinate system (as opposed to the usual fixed Eulerian coordinate system), originated with the Generalized Coordinate System method developed for the AFTON codes (Reference 9).

In this volume, a complete description of the equations of motion and the numerical solution methods for the implicit fluid mechanics versions of STEALTH are given. These can be found in Sections 2 and 3. The actual finite-difference equations for the 1D and 2D computer codes are provided in Sections 4 and 5. In many cases where material contained in other volumes of the STEALTH documentation would be duplicated, the reader is referred to those other volumes. Any concepts, equations, etc., unique to the implicit versions of code, however, are discussed in detail.

Instructions for the use of these codes are provided in Sections 6 and 7. Since the input is essentially standard for all versions of the STEALTH codes, most of the material found in this section comes directly from the user instructions for the other versions. This is found in Sections 6 and 7 of Volume 1. However, a few new input records have been added, and a few new variables have been added to previously existing input records. A thorough discussion of the input as it pertains to the implicit versions is given, and a tutorial discussion on the use of these versions is also provided.

Section 8 provides a discussion of some sample and verification problems. Some of these are intended to demonstrate the general capabilities and limitations of the codes, while others are simple problems that can be used to check out the codes and to become familiar with their use.

As with any complex computer codes like these, it is inevitable that previously undiscovered bugs will exist and that features will have been omitted that some users would find useful. Therefore, on the following two pages forms are provided which may be used to report bugs or to suggest changes.

STEALTH SUSPECTED ERROR REPORT

Please complete this form and return to:

Nuclear Safety and Analysis Dept., Attn: H. T. Tang
Electric Power Research Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, California 94304

STEALTH 1D ☐ 2D ☐ 3D ☐ Version No. _____

Compressible ☐ Incompressible ☐ System _____

Machine _____ Telephone _____

Name _____

Address _____

Description: (Please be complete. Append relevant decks,
listings, core dumps, etc.)

S T E A L T H

READER'S COMMENT FORM

Please complete this form and return:

Nuclear Safety and Analysis Dept., Attn: H. T. Tang
Electric Power Research Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, California 94304

Your comments and suggestions about this computer code manual may help to improve its usefulness; this form will be sent to the author for appropriate action. Possible topics for comment are: clarity; accuracy; completeness; organization; index; figures; examples; legibility.

SECTION 2

EQUATIONS OF MOTION

2.1 EQUATIONS OF MOTION FOR A CONTINUUM

The general equations of motion for a continuum are derived in Section 2 of Volume 1. These are the fundamental equations upon which all versions of the STEALTH codes are based. The various versions of the STEALTH codes merely represent different numerical solution techniques applied either to those equations directly or to some approximation for those equations. In this section, we start with these general equations of motion and develop the forms solved in the incompressible flow and implicit, compressible flow versions of the codes.

2.1.1 Conservation Equations. The behavior of a physical system can be described by the laws for conservation of mass, momentum, and energy. The mathematical representation of the law of conservation of mass in a fixed Cartesian coordinate system may be written in vector notation^{*} as

$$\frac{\partial \rho}{\partial t} = - \nabla \cdot (\rho \underline{v}), \quad (2.1a)$$

and in tensor notation^{*} as

$$\frac{\partial \rho}{\partial t} = - \frac{\partial}{\partial x_j} (\rho v_j). \quad (2.1b)$$

^{*}Conventions used are the same as used in Section 2 of Volume 1.

The equation for conservation of momentum in the same coordinate system is, in vector notation,

$$\frac{\partial}{\partial t}(\rho \underline{v}) = -\nabla \cdot \underline{v}(\rho \underline{v}) + (\nabla \cdot \underline{s}) - (\nabla p) + \rho \underline{g}, \quad (2.2a)$$

or in tensor notation,

$$\frac{\partial}{\partial t}(\rho v_i) = -\frac{\partial}{\partial x_j}(\rho v_j v_i) + \frac{\partial}{\partial x_j} s_{ji} - \frac{\partial}{\partial x_j} p \delta_{ij} + \rho g_i. \quad (2.2b)$$

Finally, the equation for conservation of energy is

$$\begin{aligned} \frac{\partial}{\partial t} \left(\rho \hat{u} + \frac{1}{2} \rho v^2 \right) = & -\nabla \cdot \underline{v} \left(\rho \hat{u} + \frac{1}{2} \rho v^2 \right) - \nabla \cdot \dot{\underline{h}} \\ & + \nabla \cdot (\underline{s} \cdot \underline{v}) - \nabla \cdot p \underline{v} + \rho \underline{v} \cdot \underline{g} + U^{\sim} \end{aligned} \quad (2.3a)$$

or

$$\begin{aligned} \frac{\partial}{\partial t} \left(\rho \hat{u} + \frac{1}{2} \rho v^2 \right) = & -\frac{\partial}{\partial x_i} v_i \left(\rho \hat{u} + \frac{1}{2} \rho v^2 \right) - \frac{\partial}{\partial x_i} \dot{h}_i \\ & + \frac{\partial}{\partial x_j} s_{ji} v_i - \frac{\partial}{\partial x_i} p v_i + \rho v_i g_i + U^{\sim} . \end{aligned} \quad (2.3b)$$

In these equations, the following notation is used:

- $\underline{v}$ = material velocity relative to a fixed reference frame,
 ρ = mass density,
 $\underline{s}$ = deviatoric stress or viscous stress* tensor (tension is positive)
 p = hydrostatic pressure,
 $\underline{g}$ = acceleration of gravity,
 $\hat{u}$ = internal energy per unit mass,
 $\dot{\underline{h}}$ = heat conduction flux,
 U''' = energy source/sink per unit volume.

It is often convenient to reduce the equation for conservation of energy, Eq.(2.3), to an internal energy equation by subtracting out the mechanical energy. This can be achieved by manipulation of the three conservation equations as described in Section 2.1.2, Volume 1, and results in the following internal energy equation:

$$\frac{\partial}{\partial t}(\rho \hat{u}) = -(\nabla \cdot \underline{v})\rho \hat{u} - \nabla \cdot \dot{\underline{h}} + (\underline{s} : \nabla \underline{v}) - p(\nabla \cdot \underline{v}) + U''', \quad (2.4a)$$

$$\frac{\partial}{\partial t}(\rho \hat{u}) = - \frac{\partial}{\partial x_i}(\rho \hat{u} v_i) - \frac{\partial}{\partial x_i} \dot{h}_i + s_{ij} \frac{\partial}{\partial x_j} v_i - p \frac{\partial}{\partial x_i} v_i + U'''. \quad (2.4b)$$

The above equations, Eqs.(2.1-2.4), are written in an Eulerian coordinate system, i.e., a reference system fixed in space. They can be

*For viscous fluids this tensor may not be the deviatoric stress tensor (which can be represented by a traceless matrix) since it may contain the bulk viscosity as well as the shear viscosity terms.

converted to a coordinate system that moves with the material, a Lagrangian coordinate system, by introducing the concept of the "material" derivative,

$$\frac{D}{Dt} () = \frac{\partial}{\partial t} () + \underline{v} \cdot \nabla ().$$

In this equation, the term on the left is the time derivative in a coordinate system moving with the material. It is expressed in terms of quantities in a fixed coordinate system by the terms on the right. Rearranging Eqs.(2.1), (2.2), and (2.4) and using the above expression for the time derivative, we obtain the following Lagrangian equations of motion. For conservation of mass, we have

$$\frac{D}{Dt} \rho = - (\nabla \cdot \underline{v}) \rho \quad (2.5a)$$

or

$$\frac{D}{Dt} \rho = - \rho \frac{\partial}{\partial x_j} v_j. \quad (2.5b)$$

This equation simply states that the mass is constant in a given Lagrangian volume element and that the change in density is only a function of the change in relative volume of that element. For conservation of momentum, we have

$$\rho \frac{D}{Dt} \underline{v} = \nabla \cdot \underline{s} - \nabla p + \rho \underline{g} \quad (2.6a)$$

or

$$\rho \frac{D}{Dt} v_i = \frac{\partial}{\partial x_j} s_{ji} - \frac{\partial}{\partial x_j} p \delta_{ij} + \rho g_i, \quad (2.6b)$$

and the Lagrangian internal energy equation becomes

$$\rho \frac{D}{Dt} \hat{u} = - \nabla \cdot \dot{\underline{h}} + (\underline{s} : \nabla \underline{v}) - p(\nabla \cdot \underline{v}) + \dot{U} \quad (2.7a)$$

or

$$\rho \frac{D}{Dt} \hat{u} = - \frac{\partial}{\partial x_i} \dot{h}_i + s_{ij} \frac{\partial}{\partial x_j} v_i - p \frac{\partial}{\partial x_i} v_i + \dot{U}. \quad (2.7b)$$

It should be noted that the principal difference between the Lagrangian and Eulerian equations of motion is the presence of the convection term on the right hand side of the Eulerian equations. This has the form $-(\nabla \cdot \underline{v})A$, where A represents mass, momentum, or energy. For example, in the Lagrangian momentum equation, Eq.(2.6), the rate of change of momentum of a fluid element is simply equal to the forces acting on that element. In an Eulerian coordinate system since there is motion of the fluid relative to the coordinate system, an additional term is necessary to account for the change in the momentum due to fluid flowing into and out of the volume element. This is what we have called the convection term. As another example, in the case of the equation for conservation of mass, the mass of a Lagrangian fluid element is constant, so that in the Eulerian mass equation the change in mass is entirely due to the convection term.

The reason for emphasizing this point is that distinguishing between the Lagrangian and Eulerian forms of the equations of motion in this way provides the basis for the Arbitrary-Lagrangian-Eulerian (ALE) methodology (Reference 8) that is used in the versions of the STEALTH codes described here. We noted that the convection terms in the Eulerian equations arise from the fact that the fluid is moving at a velocity $\underline{v}$ relative to a fixed reference frame and that the convection term disappears if the relative velocity between the fluid and the coordinate system is zero (Lagrangian). We can also write a more general set of equations for a coordinate system

which is moving at some arbitrary velocity relative to the fluid. If we call this relative velocity $\underline{w}$, where

$$\underline{w} = \underline{v} - \underline{v}_{cs}$$

($\underline{v}_{cs}$ is the velocity of the coordinate system relative to a fixed frame of reference), then the new equations are obtained simply by replacing the fluid velocity $\underline{v}$ with the relative velocity $\underline{w}$ in the convection terms. The resulting equations for an arbitrary coordinate system are

$$\frac{\partial \rho}{\partial t} = -(\nabla \cdot \underline{w})\rho \quad (2.8)$$

for conservation of mass,

$$\frac{\partial}{\partial t}(\rho \underline{v}) = -(\nabla \cdot \underline{w})\rho \underline{v} + (\nabla \cdot \underline{s}) - (\nabla p) + \rho \underline{g} \quad (2.9)$$

for conservation of momentum, and

$$\frac{\partial}{\partial t}(\rho \hat{u}) = -(\nabla \cdot \underline{w})\hat{u} - \nabla \cdot \underline{\dot{h}} + (\underline{s} : \nabla \underline{v}) - p(\nabla \cdot \underline{v}) + U'' \quad (2.10)$$

for internal energy, or

$$\begin{aligned} \frac{\partial}{\partial t} \left(\rho \hat{u} + \frac{1}{2} \rho v^2 \right) &= -(\nabla \cdot \underline{w}) \left(\rho \hat{u} + \frac{1}{2} \rho v^2 \right) + \nabla \cdot \underline{\dot{h}} \\ &+ \nabla \cdot (\underline{s} \cdot \underline{v}) - \nabla \cdot p \underline{v} + \rho \underline{v} \cdot \underline{g} + U'' \end{aligned} \quad (2.11)$$

for conservation of total energy.

In the basic ALE methodology, the solution of the above equations is achieved in two steps. The first step involves a solution of the Lagrangian equations, i.e., the above equations without the convection terms. This is followed by a second step in which the convection terms are evaluated. This applies to all the various physical approximations and numerical solution methods to which the ALE methodology may be applied, e.g., incompressible flow, explicit compressible flow, implicit compressible flow. In fact, one of the reasons for separating the equations in this way is to allow these physical approximations or numerical solution methods to be applied to the Lagrangian equations alone while calculating the convection terms separately. Therefore, in discussing simplifications to the fundamental equations in Section 2.2, we will restrict our discussions to the Lagrangian equations.

2.1.2 Initial Conditions, Boundary Conditions, and Constitutive Relations. To complete the specification of a physical system, initial conditions, boundary conditions, and constitutive relations are required. The reader is referred to the discussion of these topics provided in Sections 2.1.3 - 2.1.5 of Volume 1.

2.2 EQUATIONS OF MOTION FOR 1D AND 2D FLUID FLOW

Section 2.2 of Volume 1 provides a detailed discussion of the reduction of the fundamental continuum mechanics equations to simpler forms. The reader is referred to that section if more detail is desired than is provided here. For the versions of the STEALTH codes described in this volume, we are interested in simplifications of three types. One is a spatial simplification that results from natural symmetries exhibited in many instances by physical systems. The second is a simplification of the constitutive equations which describe the material response characteristics. The third is a simplification of the conservation equations that results from assumptions concerning the dominant phenomena

occurring in the physical systems. Quite often these last two simplifications may be interrelated.

In the case of the implicit, compressible flow versions, spatial simplifications are made to obtain the equations for one-dimensional and two-dimensional motions. In addition, the constitutive equations are reduced to those describing a viscous fluid. For the incompressible flow versions the same spatial simplifications are made; however, in this case a simplification to the constitutive equations to describe the incompressibility of the fluid also results in a simplification of the conservation equations. These are all described below.

In these discussions we have omitted consideration of heat conduction. Heat conduction is not included in the incompressible flow versions while for the implicit, compressible flow versions the heat conduction calculation is identical to that done in the other versions of STEALTH. A discussion of those equations is provided in Volume 1 of the STEALTH documentation.

2.2.1 Spatial Symmetries. As discussed in Section 2.2.2 of Volume 1, physical systems often exhibit natural symmetries. In many cases, gradients in two of the three orthogonal directions are zero so that motions take place in only one direction. In this case we say the system exhibits one-dimensional symmetry. Generally, only three types of one-dimensional symmetry are considered, although others could exist. If in a rectangular (x,y,z) coordinate system, the gradients in the y and z directions are zero so that all motions are in the x direction, the system exhibits one-dimensional planar symmetry. Similarly, if, in a cylindrical (r,θ,z) or a spherical (r,θ,ϕ) coordinate system, the gradients in the θ and z or in the θ and ϕ directions are zero and all motions are in the r direction, the system exhibits one-dimensional cylindrical or spherical symmetry, respectively.

If gradients in only one direction are zero so that motions take place in two directions, i.e., in a plane, the system exhibits two-dimensional symmetry. The two most common types of two-dimensional symmetry are (1) planar, in which gradients in the z direction of a rectangular (x,y,z) coordinate system are zero, and (2) cylindrical, in which gradients in the θ direction of a cylindrical (r, θ ,z) coordinate system are zero. In the first case, motions take place in the x-y plane, while in the second case motions are in the r-z plane. These three one-dimensional symmetries and two two-dimensional symmetries are treated by all versions of the STEALTH code, including those described here.

2.2.2 Constitutive Equations. The equations of motion as presented in Section 2.1 apply to a general continuum, i.e., to a solid, liquid or gas, which may undergo many different types of deformation, e.g., elastic response, plastic flow, viscous flow. The type of behavior is modeled by the constitutive equations that are used to complete the set of equations of motion. In the explicit versions of STEALTH the constitutive equations that are included are fairly general, i.e., they include the types of material behavior listed above as well as several others. In the versions of the code described here, however, we have restricted ourselves to a simpler set of constitutive equations that apply specifically to fluids. Only two types of constitutive equations are considered: the pressure equation of state and the viscous stress equations.

For a viscous, compressible fluid, both types of constitutive equations are required. The equation of state for the pressure is of the form

$$p = p(\hat{u}, \rho) . \quad (2.12)$$

This may be a simple ideal gas equation of state or may have a more complicated form. In general the same forms that are applicable for the

explicit versions of STEALTH are applicable here. A description of these forms may be found in Appendix Material Models (MAT).

The set of equations for the viscous stresses is of the form

$$s_{ij} = \zeta \left(\frac{\partial}{\partial x_i} v_j + \frac{\partial}{\partial x_j} v_i \right) + \lambda \left(\frac{\partial}{\partial x_k} v_k \right) \delta_{ij} . \quad (2.13)$$

Here ζ is the coefficient of shear viscosity, and $\lambda = \kappa - 2/3\zeta$, where κ is the coefficient of dilatational viscosity. These equations, Eqs.(2.12) and (2.13), define the stress variables p and $\underline{s}$, in the equations of motion and provide closure for the set of equations.

For an inviscid, incompressible fluid, we can simplify the constitutive equations even further. Since we are assuming in this case that the effects of viscosity are negligible, we can write $\underline{s} = 0$ and can eliminate terms involving the viscous stress tensor from the equations of motion. In this case the total stress tensor reduces to the pressure.

The assumption of incompressibility also effects the constitutive equations. This assumption implies that the bulk modulus, $\rho \frac{\partial p}{\partial \rho}$, is infinite and that the pressure specified by the pressure equation of state is indeterminate. Therefore, we omit consideration of a pressure equation of state, and instead solve a modified set of conservation equations as explained below.

2.2.3 Conservation Equations for Incompressible Flow. Assuming that the fluid is incompressible results in the following simplifications to the Lagrangian mass equation, Eq.(2.5),

$$\frac{D}{Dt} \rho = 0 \quad \text{or} \quad \nabla \cdot \underline{v} = 0.$$

This has several consequences. As we said, a constitutive equation for the pressure is no longer needed to complete the set of equations; the bulk modulus is infinite, and, therefore, the sound speed is also infinite. In addition, the internal energy equation becomes decoupled from the momentum equation in most cases. Since we have eliminated the pressure equation of state, the Lagrangian momentum equation, Eq.(2.6), contains no internal energy-dependent variables as long as the viscous stresses are considered to be energy independent. Because these two equations are decoupled, we can omit consideration of the energy equation completely, and, therefore, no longer need to consider heat conduction effects.

The resulting set of Lagrangian equations for incompressible flow consists of the incompressibility condition,

$$\nabla \cdot \underline{v} = 0 , \quad (2.14)$$

and the momentum equation for inviscid fluids,

$$\rho \frac{D}{Dt} \underline{v} = - \nabla p + \rho \underline{g} , \quad (2.15)$$

or for viscous fluids,

$$\rho \frac{D}{Dt} \underline{v} = \nabla \cdot \underline{\underline{s}} - \nabla p + \rho \underline{g} . \quad (2.6a)$$

This set of partial differential equations is elliptic as opposed to the original equations which were hyperbolic (wave equation).^{*} Because of this,

^{*}When viscosity terms are included, the incompressible flow equations are mixed elliptic-parabolic while the compressible flow equations are mixed hyperbolic-parabolic. However, the elliptic and hyperbolic features tend to dominate unless unusually large viscosity coefficients are used.

a different solution method is required from the explicit time integration used in most other versions of STEALTH. Elliptic partial differential equations describe a system in which there is instantaneous communication between all points in the space domain (infinite sound speed) as compared with hyperbolic equations where there is a finite sphere of influence corresponding to the finite sound speed. As opposed to the explicit time integration method used for the numerical solution of the hyperbolic equations, which relies on the finite sound speed, the numerical solution method for elliptic equations must permit instantaneous communication. As a result, the solution methods turn out to be similar to implicit time integration methods used for hyperbolic equations. These also permit instantaneous communication throughout the space domain even though information is actually propagated with a finite sound speed. It turns out, therefore, that we are able to use essentially the same solution method for all versions of the STEALTH codes that we are discussing here. The actual solution method used is discussed in detail in the next section.

SECTION 3

NUMERICAL SOLUTION METHOD

3.1 INTRODUCTION

In discussing the finite-difference methods used to solve the equations of motion for a continuum, it is convenient to consider time differences and spatial differences separately. To illustrate, consider a simplified form of the Lagrange momentum equation,

$$\frac{\partial}{\partial t} \underline{v} = - \frac{1}{\rho} \nabla p. \quad (3.1)$$

By spatial differences, we mean the finite-difference representation for ∇p . If we had considered the Eulerian version of the same equation, the finite-difference approximation for the divergence of velocity contained in the convection term would also be termed a spatial difference. By time differences, we mean the finite-difference representation for the time derivative in the above equation, $\frac{\partial}{\partial t} \underline{v}$.

Section 3.12 of Volume 1 contains a discussion of the surface integral approach used to derive the spatial differences used in STEALTH. The same approach has been followed for the versions of STEALTH described in this volume; therefore no discussion of space differencing methods will be provided here. The time differencing method, however, is different from that used in other versions of the STEALTH codes. Therefore, a detailed discussion of that aspect of the solution is provided below.

3.2 TIME DIFFERENCES

Finite difference representations for first-order time derivatives, such as appear in Eq.(3.1), are usually categorized as forward, backward, or centered differencing and as explicit or implicit. In the explicit category, both forward and centered differences are included while backward and centered differences can fall into the implicit category. This is explained below.

An explicit, forward-differenced approximation to Eq.(3.1) can be written

$$\left(\frac{\partial}{\partial t} \underline{v} \right)^n = \left(\underline{v}^{n+1} - \underline{v}^n \right) / \Delta t^{n+1/2} = - \frac{1}{\rho^n} \left[\nabla p^n \right]. \quad (3.2)$$

Here, the time derivative at time n is represented by a difference between quantities at times $n+1$ and n , i.e., by a difference that is forward in time. The brackets around the pressure gradient are meant to indicate a spatial difference representation for that term rather than writing out the full equation. In solving Eq.(3.2), we solve for updated velocities $\underline{v}^{n+1}$ for each point in the space mesh in terms of known quantities at the earlier time ($\underline{v}^n$ and p^n).

The explicit, centered-differenced approximation is similar:

$$\left(\frac{\partial}{\partial t} \underline{v} \right)^n = \left(\underline{v}^{n+1/2} - \underline{v}^{n-1/2} \right) / \Delta t^n = - \frac{1}{\rho^n} \left[\nabla p^n \right]. \quad (3.3)$$

In this case, the time derivative at time n is represented by a difference in quantities over a time interval centered at time n . Once again, updated velocities are calculated from known quantities at an earlier time.

However, this method requires additional initial conditions. As initial conditions for Eq.(3.2), we need only $\underline{v}$ and p at $t=0$. For Eq.(3.3) we also need to know the time derivative at $t=0$, in order to calculate $\underline{v}^{-1/2}$. In general this information is not known, so in practice $\underline{v}^{-1/2}$ is approximated by $\underline{v}^0$, and very small time steps are used initially to minimize any error introduced by this approximation. The explicit, centered differencing method is used in the explicit versions of the STEALTH codes.

An implicit, backward-differenced approximation to Eq.(3.1) is as follows:

$$\left(\frac{\partial}{\partial t} \underline{v}\right)^{n+1} = \left(\underline{v}^{n+1} - \underline{v}^n\right) / \Delta t^{n+1/2} = \frac{1}{\rho^{n+1}} \left[\nabla p^{n+1} \right]. \quad (3.4)$$

Here, the time derivative is at time $n+1$ and is represented by a difference in quantities over a time interval that is backward in time. The important point to note, and the thing that makes this method implicit, is that updated velocities and updated pressures are solved for simultaneously. This requires the simultaneous solution of this equation, along with an additional equation which gives p^{n+1} in terms of $\underline{v}^{n+1}$, for each point in the space mesh. For incompressible flow, this latter equation is derived from the incompressibility condition $\nabla \cdot \underline{v}^{n+1} = 0$. For compressible flow the pressure equation of state, $p = p(\hat{u}, \rho)$, is used along with a finite difference representation for the equation for conservation of mass, Eq.(2.5a), which provides ρ^{n+1} as a function of $\underline{v}^{n+1}$.

Finally, an implicit, centered-differenced approximation can be written

$$\left(\frac{\partial}{\partial t} \underline{v}\right)^{n+1/2} = \left(\underline{v}^{n+1} - \underline{v}^n\right) / \Delta t^{n+1/2} = - \frac{1}{\rho^{n+1}} \left[\nabla \left(p^{n+1} + p^n \right) / 2 \right]. \quad (3.5)$$

The advantage of implicit methods over explicit ones is related to stability. For explicit methods to achieve stability the integration time step is restricted to a small value (essentially the time it takes for a sound signal to cross a zone). Implicit methods, on the other hand, are more stable and usually permit the use of much larger time steps. In fact, many implicit schemes, particularly those employing backward differencing, as in Eq.(3.4), may be unconditionally stable in principle. Implicit, centered-differenced methods such as Eq.(3.5), however, are often unstable without the addition of special stabilizing terms.

The codes described in this volume all use an implicit solution method. The compressible flow versions are intended for problems involving relatively slow flow where advantage can be taken of the larger time steps allowed by implicit methods. The incompressible flow versions necessarily require an implicit solution method. As we said in the previous section, the equations of motion for inviscid, incompressible flow are elliptic. Since the solution of these equations requires the simultaneous solution, for each point in the space mesh, of the momentum equation along with the incompressibility condition, the solution method has to be of an implicit type as described above. In all the versions of STEALTH described in this volume, the solution method corresponds to the implicit, backward-differenced method of Eq.(3.4).

3.3 GENERAL SOLUTION METHOD

In Section 2.1.1 we described how the ALE solution methodology involves splitting the solution into two phases, one for the Lagrangian equations and one for the convection terms. In solving the Lagrangian equations for both incompressible and compressible flow, we further divide that part of the solution into two phases, meaning that the overall solution methodology is a three-step process. These steps are as follows.

The first step is an explicit solution of the Lagrange momentum equation using a forward-differencing approximation as in Eq.(3.2). With the exception of the time-centering of some of the variables in the codes, this ends up being identical to the solution of the momentum equation performed in the explicit versions of STEALTH.

The results from this explicit phase are then used as the first approximation in an iterative solution of the implicit equations, which is accomplished in the second phase. The results from the explicit phase are used in order to maximize the efficiency of the iterative solution by providing a good first guess.

Completion of the second phase completes the solution of the Lagrange equations. In the third and final phase, the convection terms are calculated in order to complete the solution of the full set of equations for a general coordinate system. As an option, this final phase can be omitted; this results in a purely Lagrangian calculation. As an option for the compressible flow codes only, the second phase can be omitted, resulting in an explicit calculation. This can be done either with or without the final phase. Each of these phases is discussed in more detail below, and the actual finite-difference equations for each phase are given in Sections 4 and 5.

3.3.1 Explicit Lagrangian Calculation. The explicit integration of the Lagrangian momentum equation follows the same method used in the explicit versions of STEALTH and described in Volume 1 of the STEALTH documentation. The only difference is in the time centering of the velocities to reflect the difference between the forward differencing, Eq.(3.2), used here and the centered differencing, Eq.(3.3), used in explicit STEALTH. The space differencing methods are identical between the two versions, i.e., a surface integral approach is used to derive the finite-difference approximations. See Section 3.1.2 of Volume 1 for more detail.

3.3.2 Implicit Lagrangian Calculation. In this phase an iterative solution of the backward-differenced Lagrangian momentum equation, the mass equation, and (in the case of the compressible flow codes) the pressure equation of state is accomplished using the velocity field resulting from the explicit phase as an initial guess. This is accomplished for the incompressible flow versions as follows.

The objective is to calculate a new velocity field from the momentum equation that satisfies the mass equation for incompressible flow (often called the incompressibility condition)

$$\nabla \cdot \underline{v} \rightarrow 0.$$

This is accomplished using a Newton-Raphson iteration as follows.

The first step is to calculate the velocity divergence,

$$D = \nabla \cdot \underline{v},$$

using a finite-difference representation developed from a surface integral approach. Next, a pressure increment for each cell is calculated from the Newton-Raphson equation,

$$\delta p = - \omega D / D',$$

where $D' = \partial D / \partial p$ and ω is a relaxation factor. This pressure increment is then used to calculate a change in velocity, $\underline{v}$, for each grid point adjacent to the cell, using the modified momentum equation,

$$\delta \underline{v} = - \frac{\Delta t}{\rho^n} \left[\nabla (\delta p) \right]. \quad (3.6)$$

Here again, the brackets denote a finite-difference approximation for the gradient. New pressures and velocities are then calculated by adding the respective increments to the values for those variables that existed at the beginning of the iteration cycle. This is repeated for each cell in the mesh so that the total $\delta \underline{v}$ for each mesh point is actually the sum of the individual velocity increments resulting from the δp 's in all the adjacent cells.

If the velocity field resulting from this sweep through the mesh satisfies the condition $D < \epsilon$, where ϵ is some small number specified by input, then this phase of the calculation is complete. If any cell exists with $D > \epsilon$, then the process is repeated until convergence is achieved.

For the compressible flow versions the approach is similar. In this case we are attempting to calculate simultaneously updated pressures and velocities that satisfy both the Lagrange momentum equation and the pressure equation of state. To do that two different pressures are defined; the pressure used in the momentum equation we denote by p while the pressure given by the equation of state we call p' . To calculate p' we integrate the Lagrangian mass equation, Eq.(2.5a), (the velocities obtained from the explicit phase are used in the finite difference representation for $\nabla \cdot \underline{v}$) to obtain an updated density which is then used in the equation of state.

Next we calculate the quantity

$$W = p - p' ,$$

where initially p is the pressure used in the explicit momentum equation. To converge to the correct solution we require that $W \rightarrow 0$. To accomplish this we calculate a pressure increment, as we did for the incompressible flow versions, from the Newton-Raphson equation,

$$\delta p = -\omega W/W' ,$$

where $W' = \partial W / \partial p = 1 - \partial p' / \partial p$. Again, this pressure increment is used in the modified momentum equation, Eq.(3.6), to calculate a change in the grid point velocity for each grid point adjacent to the cell. Then the same procedure as is used in the incompressible versions is used here to update p and $\underline{v}$, and the process is repeated until $W < \epsilon$ for all cells in the mesh.

For the incompressible flow versions, after the implicit solution of the Lagrange momentum equation has been completed we are ready to proceed with the convection phase. For the compressible flow versions, first we need to calculate the Lagrangian energy equation, Eq.(2.7). An explicit solution of this equation, similar to that used in the explicit versions of STEALTH, is used. In the problems for which these codes are intended, the energy equation is only weakly coupled to the momentum equation through the equation of state so that no instabilities or significant inaccuracies are introduced by solving the energy equation explicitly.

3.3.3 Convection Phase. In this phase, the convection terms for the full set of equations for a general coordinate system are calculated. So far, through the second phase, we have solved the Lagrangian equations,

$$\frac{D}{Dt} \rho = - (\nabla \cdot \underline{v}) \rho \quad (=0 \text{ for incompressible flow}), \quad (3.7)$$

$$\frac{D}{Dt}(\rho \underline{v}) = \nabla \cdot \underline{\underline{s}} - \nabla p + \rho \underline{g}, \quad (3.8)$$

$$\frac{D}{Dt}(\rho \hat{u}) = -\nabla \cdot \dot{\underline{h}} + (\underline{\underline{s}} : \nabla \underline{v}) - p(\nabla \cdot \underline{v}) + U^{\sim}. \quad (3.9)^*$$

*Omitted for incompressible flow.

To complete the solution for a general coordinate system we include the convection terms as explained in Section 2.1.1. Thus, we have

$$\frac{\partial \rho}{\partial t} = \frac{D}{Dt} \rho - (\nabla \cdot \underline{w}) \rho, \quad (3.10)$$

$$\frac{\partial}{\partial t}(\rho \underline{v}) = \frac{D}{Dt}(\rho \underline{v}) - (\nabla \cdot \underline{w})(\rho \underline{v}), \quad (3.11)$$

and

$$\frac{\partial}{\partial t}(\rho \hat{u}) = \frac{D}{Dt}(\rho \hat{u}) - (\nabla \cdot \underline{w})(\rho \hat{u}), \quad (3.12)$$

where $\underline{w} = \underline{v} - \underline{v}_{cs}$ is the relative velocity between the fluid and the coordinate system.

In some cases it may be more desirable to calculate convection of total energy rather than internal energy in order to insure strict conservation of total energy during the convection phase. In this case the total specific energy

$$\epsilon_L = \rho \hat{u} + \frac{1}{2} \rho v^2 \quad (3.13)$$

is calculated at the end of the Lagrangian phase. Changes to it from the convection terms are then calculated from

$$\epsilon = \epsilon_L - (\nabla \cdot \underline{w}) (\rho \hat{u} + \frac{1}{2} \rho v^2) \Delta t. \quad (3.14)$$

Finally, the internal energy is calculated at the end of convection phase by subtracting the new kinetic energy [calculated from the velocities obtained from Eq.(3.11)] from the new total energy. This method,

Eqs.(3.13)-(3.14), is not generally used, although it may be included in special versions of the codes. In general, Eq.(3.12) is used to calculate energy convection.

The divergence terms in the above equations are expressed in finite-difference form using the surface integral approach as follows. From Gauss' theorem, we can write the following equation:

$$(\nabla \cdot \underline{w})A = \lim_{\Delta V \rightarrow 0} \frac{1}{\Delta V} \int_S A(\underline{w} \cdot \underline{n})dS, \quad (3.15)$$

where the integration is over the surface S surrounding some small volume ΔV . Applying this to the mass flux equation, Eq.(3.10), or to the energy flux equations, Eqs.(3.12) or (3.14), we select ΔV to be the volume of a cell as shown in Figure 3.1a. By integrating Eq.(3.15) (with A replaced by ρ or $\rho \hat{u}$) over that volume, we are calculating the mass or energy flowing across the surfaces of that cell. In calculating the momentum flux equation, Eq.(3.11), we integrate over the dashed volume shown in Figure 3.1b. This is the same volume used for evaluation of the pressure gradient in the Lagrange momentum equation. By integrating Eq.(3.15) over this volume (with A replaced by $\rho \underline{v}$), we calculate the momentum flux between the center grid point and the diagonally adjacent grid points. Using this method, there is no momentum exchange between the center grid point and the grid points directly adjacent to it (above and below or on either side). This is the same method employed by the YAQUI code developed at the Los Alamos Scientific Laboratory (Reference 4).

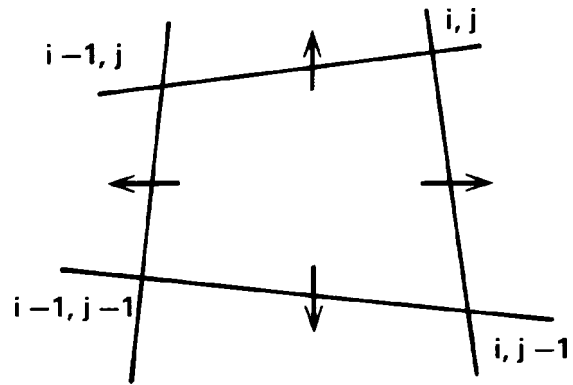


Figure 3.1a. Integration volume for mass flux.

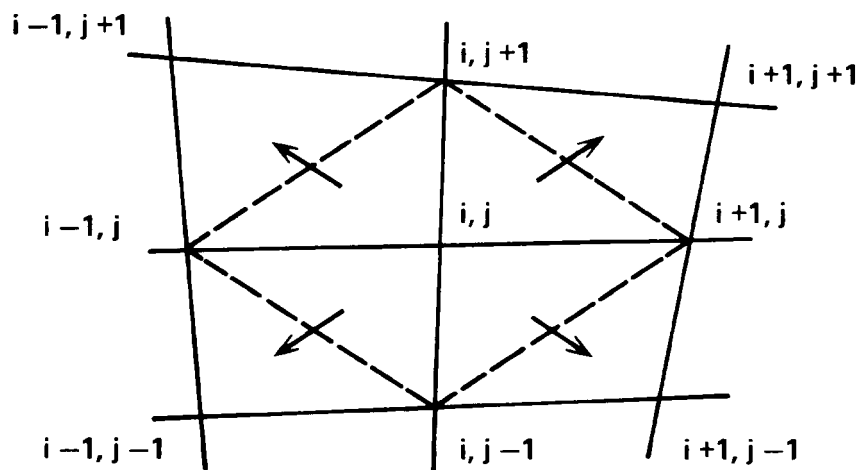


Figure 3.1b. Integration volume for momentum flux.

3.4 STABILITY CONSIDERATIONS

In Section 3.2, we discussed explicit and implicit time differencing schemes and noted the differences in stability between the two. Explicit methods, such as the one used in other versions of STEALTH, are stable only if the time step is restricted to a small value governed by the time it takes a sound signal to cross a zone. Implicit methods, on the other hand, are usually more stable and permit larger time steps. In fact, for many implicit methods, including the backward differencing method employed here, the 1D Lagrangian equations can be shown to be unconditionally stable for linear problems. This allows the use of large time steps limited only by accuracy considerations, i.e., by the time resolution required for the solution.

Experience has shown, however, that most implicit methods, particularly in 2D, do not turn out to be unconditionally stable even though idealized analyses suggest that they may be. They do permit the use of much larger time steps than could be used for equivalent explicit methods, but for very large time steps instabilities sometimes occur. Fortunately, accuracy considerations usually dictate the use of a smaller time step than would lead to instabilities.

In the method employed here, several factors can lead to instabilities. First of all, if the strain rates become large, the use of large time steps can lead to unphysical zone distortions, i.e., zones which turn inside out. This type of instability is slow-growing compared to the exponentially growing instabilities which can occur with explicit methods, and they can usually be controlled by the addition of artificial damping terms (see Section 5.6). However, there are stability considerations associated with these terms as well.

A second source of instability is related to the iterative method used to solve the implicit equations. The initial guess for the iteration is provided by the solution of the explicit momentum equation. If the time step is too large, the explicit solution may be a sufficiently bad first guess to cause an unstable iteration. In this case, the iteration diverges, and a solution is not obtained. This problem is most severe when the fluid equation of state is highly nonlinear, but can be helped by using a two-sided secant method for the iteration rather than the Newton-Raphson method. This is discussed in a later section.

These sources of instability apply to the solution of the Lagrangian equations of motion. When the convection terms are added, further stability considerations arise. Since the method employed here assumes that mass, momentum and energy exchanges occur only between adjacent zones, the time step must be restricted so that the fluid cannot move more than one zone width per time step. It turns out that this restriction usually also eliminates the stability problem in the Lagrangian phase related to zones turning inside out. Therefore it has been used for an automatic time step calculation to replace the one used in the explicit versions of STEALTH. Whereas the explicit versions use the time step criterion

$$\Delta t < \Delta \ell / c \quad ,$$

where $\Delta \ell$ is the width of a zone and c is the sound speed, in these versions we use

$$\Delta t < \Delta \ell / |v| \quad .$$

Although this criterion does not absolutely guarantee stability for the implicit codes (particularly in the case of a highly non-linear equation of state), it has been found to be reliable in most cases. Furthermore, accuracy considerations generally dictate the use of a smaller time step

than would be required for stability so that quite often the automatic time step calculation is not needed. Some guidelines for selecting the time step based on accuracy are provided in Section 6.3.3.

SECTION 4

ONE-DIMENSIONAL FINITE-DIFFERENCE EQUATIONS

4.1 INTRODUCTION

The finite-difference equations representing the one-dimensional equations of motion for a fluid are solved using two staggered meshes - a displacement mesh and a stress mesh. This is the same approach as is used in the other versions of STEALTH described in Volume 1. The displacement mesh is made up of grid points which define geometric quantities such as shapes, interfaces, boundaries, etc. The equation for conservation of momentum is solved in the displacement mesh to calculate the vector quantities, acceleration ($\ddot{x}$), velocity ($\dot{x}$), and position (x), which are said to be centered in space at the grid points. Actually, the first-order finite difference method used here assumes that these quantities are constant (average values) over some volume encompassing the grid point as shown (dashed) in Figure 4.1a. This region is sometimes referred to as the momentum zone or momentum cell.

The stress mesh is made up of zones encompassing the volume between grid points. Scalar and tensor quantities such as pressure, internal energy, density, and viscous stresses are calculated in this mesh and are said to be centered at the zone centers as shown in Figure 4.1b. These quantities also are assumed to be constant over the zone volume.

4.2 CALCULATIONAL SEQUENCE

The one-dimensional equations of motion for a fluid are solved in two steps. These are shown schematically in Figure 4.2a and b. Figure 4.2a applies to the incompressible flow version while Figure 4.2b applies to the implicit, compressible flow version. In both cases the explicit, Lagrangian momentum equation is solved first using the stress (or pressure)

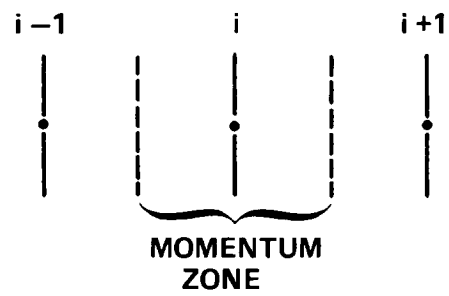


Figure 4.1a. Diagram of 1D displacement mesh.

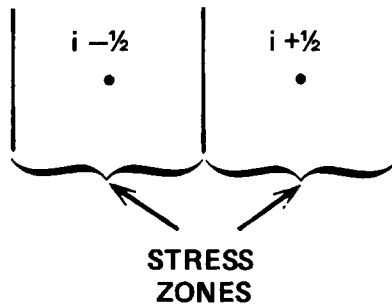


Figure 4.1b. Diagram of 1D stress mesh.

CALCULATIONAL SEQUENCE **1D INCOMPRESSIBLE FLOW VERSION**

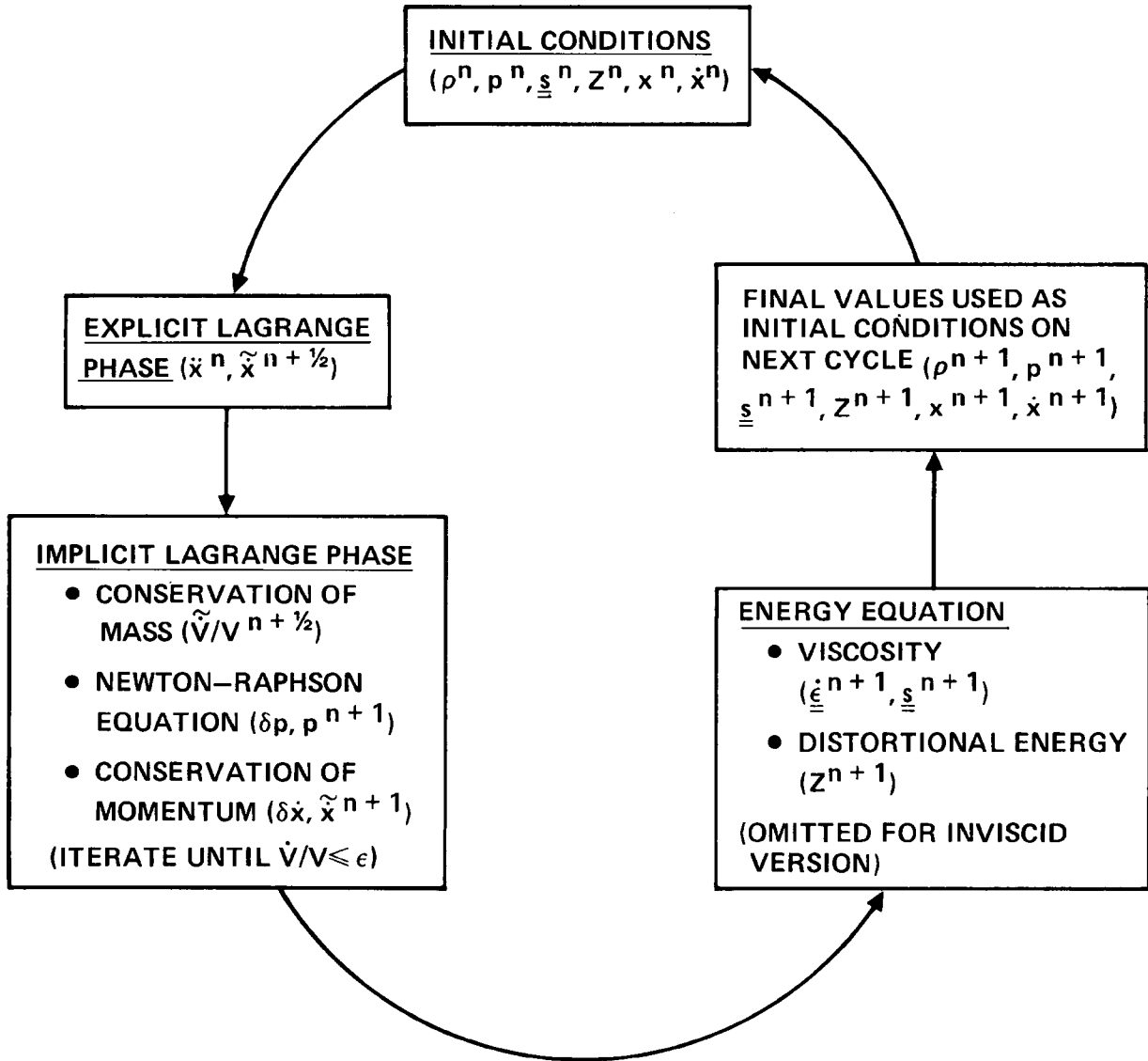


Figure 4.2a. Calculational sequence for 1D incompressible flow version of STEALTH.

CALCULATIONAL SEQUENCE **1D IMPLICIT, COMPRESSIBLE FLOW VERSION**

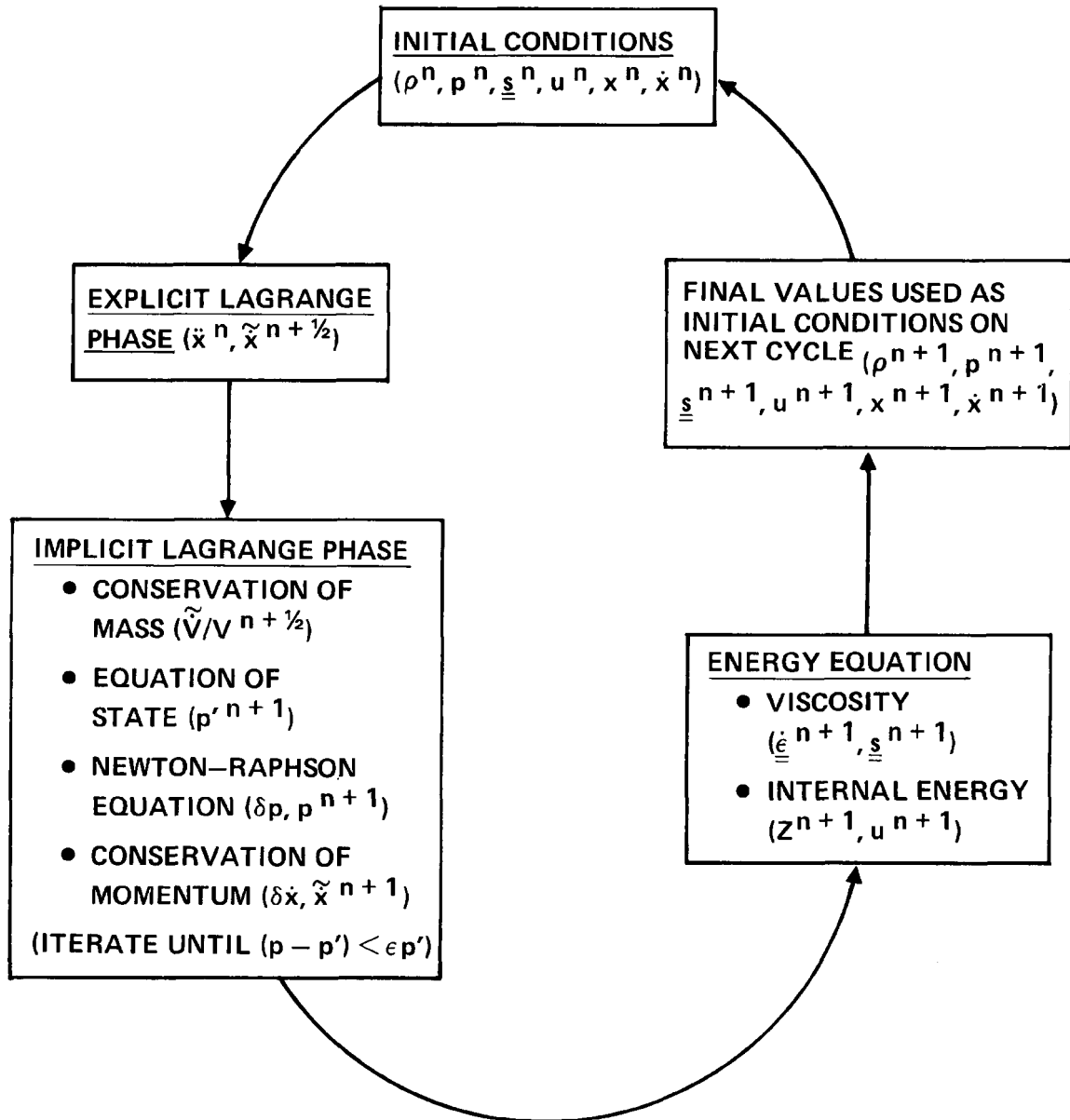


Figure 4.2b. Calculational sequence for 1D implicit, compressible flow version of STEALTH.

and density distributions existing at the beginning of the cycle. The resulting velocities are temporary (indicated by the tilde) and are arbitrarily given time centering $n+\frac{1}{2}$ to indicate that they represent intermediate values somewhere between the initial time n at the start of the cycle and the final time $n+1$.

Next an iteration is performed to solve simultaneously the implicit equations for each zone in the mesh. The principal difference between the two versions described here is in this implicit phase. In both versions the velocities resulting from the explicit Lagrangian phase are used as initial conditions for this iteration, and these velocities are used to calculate the volume strain rate (equal to the divergence of velocity). In the incompressible flow version we are attempting to find a solution such that this quantity is approximately zero. Therefore if this quantity is larger than some small number (specified by input), then the Newton-Raphson equation is used to calculate a pressure increment for each zone, and a modified form of the momentum equation is used to calculate the resulting change in velocity for the two grid points adjoining each zone. The pressure and velocity increments are added to the old values of pressure and velocity for each zone and this entire process is repeated until convergence is achieved, i.e., until $\dot{V}/V \geq \epsilon$ for all zones.

In the implicit, compressible flow version we are looking for a solution such that the pressure p used in the momentum equation and the new velocities obtained from that equation are centered at the same point in time. An equivalent condition is as follows. We can define another pressure variable p' which is obtained from the equation of state using an updated relative volume based on the new velocity field. Then an implicit solution is obtained when the two pressures, p and p' , are equal. Therefore, we define a variable $W = p - p'$ and use a Newton-Raphson

equation in conjunction with a modified form of the momentum equation, the same as was done for incompressible flow, to calculate new pressures and velocities.

When these iterations have converged, we have a new set of pressures, velocities and relative volumes at time $n+1$. At this point the solution of the Lagrangian equations of motion for an inviscid, incompressible fluid is complete. For the compressible flow and viscous, incompressible flow versions, however, we have the additional tasks of solving the Lagrange internal energy equation (including heat conduction for the compressible flow version) and of calculating the updated viscous stresses based on the new velocity field.*

In previous sections we discussed the solution of the equations for a general coordinate system using the ALE method. In problems involving one-dimensional motions, this method does not usually offer any significant advantages over a purely Lagrangian calculation, so it is not used here. The principal advantages of the ALE method come in the solution of two-dimensional problems which will be discussed in Section 5.

In the following sections, the complete finite-difference equations corresponding to the above calculational sequence are provided.

*The internal energy equation is solved for the viscous, incompressible flow version to keep track of viscous energy dissipation for editing purposes only. This is not a necessary part of the calculation since the momentum and energy equations are decoupled in the incompressible flow approximation as long as the viscosity coefficients are energy independent.

4.3 EXPLICIT, LAGRANGIAN PHASE

4.3.1 Momentum Equation. The equation for conservation of momentum for a general fluid was given for a Lagrangian coordinate system in Section 2.2.2, Eq.(2.13). That equation, written for one independent space variable (plane, cylindrical, and spherical symmetries), is*

$$\ddot{x} = \frac{1}{\rho} \frac{\partial \sigma_{xx}}{\partial x} + f \frac{1}{\rho} \left[\frac{\sigma_{xx} - \sigma_{yy}}{x} \right], \quad (4.1a)$$

where

$$f = \begin{cases} 0 & \text{for plane symmetry} \\ 1 & \text{for cylindrical symmetry} \\ 2 & \text{for spherical symmetry.} \end{cases}$$

For inviscid, incompressible flow this reduces to*

$$\ddot{x} = - \frac{1}{\rho} \frac{\partial p}{\partial x}. \quad (4.1b)$$

Following the method described in Section 4.2.2 of Volume 1 and using the space centering conventions illustrated in Figures 4.1a and b, we can write the finite-difference form of Eq.(4.1a) as

$$\ddot{x}_i^n = \left(\frac{2}{\alpha_{i-\frac{1}{2}}^n + \alpha_{i+\frac{1}{2}}^n} \right) \left(\left(\sigma_{xx} \right)_{i+\frac{1}{2}}^n - \left(\sigma_{xx} \right)_{i-\frac{1}{2}}^n \right) + f \left(\frac{\beta_{i-\frac{1}{2}}^n + \beta_{i+\frac{1}{2}}^n}{2} \right), \quad (4.2a)$$

*In planar symmetry, a gravitational constant may be added to the acceleration defined by Eqs.(4.1a) and (4.1b).

where

$$\alpha_{i-\frac{1}{2}}^n = \rho_{i-\frac{1}{2}}^n \left(x_i^n - x_{i-1}^n \right), \quad (4.3a)$$

$$\alpha_{i+\frac{1}{2}}^n = \rho_{i+\frac{1}{2}}^n \left(x_{i+1}^n - x_i^n \right), \quad (4.3b)$$

$$\beta_{i-\frac{1}{2}}^n = \frac{1}{\rho_{i-\frac{1}{2}}^n} \left[\frac{\left(\sigma_{xx} \right)_{i-\frac{1}{2}}^n - \left(\sigma_{yy} \right)_{i-\frac{1}{2}}^n}{\left(x_i^n + x_{i-1}^n \right) / 2} \right], \quad (4.3c)$$

$$\beta_{i+\frac{1}{2}}^n = \frac{1}{\rho_{i+\frac{1}{2}}^n} \left[\frac{\left(\sigma_{xx} \right)_{i+\frac{1}{2}}^n - \left(\sigma_{yy} \right)_{i+\frac{1}{2}}^n}{\left(x_{i+1}^n + x_i^n \right) / 2} \right]. \quad (4.3d)$$

Similarly, the finite difference form of Eq.(4.1b) is

$$\ddot{x}_i^n = \left(\frac{-2}{\alpha_{i-\frac{1}{2}}^n + \alpha_{i+\frac{1}{2}}^n} \right) \left(p_{i+\frac{1}{2}}^n - p_{i-\frac{1}{2}}^n \right). \quad (4.2b)$$

Evaluation of Eqs.(4.2) provides the acceleration of grid point i at time n . The velocity is then determined from an explicit, forward differenced integration,

$$\tilde{x}_i^{n+1/2} = \tilde{x}_i^n + \ddot{x}_i^n \Delta t^{n+1/2}. \quad (4.4)$$

As we said previously, the new velocity is arbitrarily centered at time $n+1/2$ to show that it is a temporary value obtained prior to completing the implicit solution for the final velocity at time $n+1$.

The time step $\Delta t^{n+1/2}$ used in Eq.(4.4) is a constant* specified by input. Because all time integrations in these versions of STEALTH take place over the interval $n \rightarrow n+1$, only this time step is used. This is in contrast to other versions of the codes which employ an explicit centered integration (see Section 3.2) and, therefore, must use two different time steps, Δt^n and $\Delta t^{n+1/2}$.

4.3.2 Momentum Boundary Conditions. Section 4.2.3 of Volume 1 provides a detailed discussion of momentum boundary conditions for the 1D STEALTH codes. That discussion is directly applicable to these versions of the codes. That discussion will not be repeated here, but rather the reader is referred to the discussion in Volume 1.

* An automatic time step calculation based on stability considerations has been incorporated into the codes. However, accuracy considerations generally dictate a smaller time step than would be required for stability. In that case a constant time step is used, although some programmed variation is allowed. See Sections 3.4 and 6.3.3 for more details.

4.4 IMPLICIT, LAGRANGIAN PHASE

4.4.1 Mass Equation. The general continuity equation or conservation of mass equation for one-dimensional symmetries is

$$\frac{\dot{V}}{V} = \nabla \cdot \dot{\mathbf{x}} = \frac{\partial \dot{\mathbf{x}}}{\partial \mathbf{x}} + f \frac{\dot{\mathbf{x}}}{\mathbf{x}}, \quad (4.5)$$

where

$$f = \begin{cases} 0 & \text{for plane symmetry} \\ 1 & \text{for cylindrical symmetry} \\ 2 & \text{for spherical symmetry.} \end{cases}$$

In writing the finite-difference representation for this equation, several options are open to us within the general STEALTH differencing format. First, the quantity $\dot{V}/V$ can be calculated directly from the change in true volume $\mathcal{V}$ calculated from coordinates. Second the individual terms in Eq.(4.5) can be treated separately, i.e., the individual strain rates can be calculated separately with the volume strain rate calculated as the sum of those individual components. The third option is to evaluate $\nabla \cdot \dot{\mathbf{x}}$ directly using the surface integral approach. In the versions of the code described in Volume 1, a method essentially equivalent to the third option is used. This is described in Section 4.2.4 of that volume. The same method is used here yielding the following equations for the three one-dimensional symmetries:

Plane Symmetry

$$\left(\frac{\tilde{V}}{V} \right)_{i-1/2}^{n+1/2} = \frac{\rho_{i-1/2}^n}{m_{i-1/2}^n} \left(\tilde{x}_i^{n+1/2} - \tilde{x}_{i-1}^{n+1/2} \right). \quad (4.6a)$$

Cylindrical Symmetry

$$\left(\frac{\tilde{v}}{\bar{v}}\right)_{i-l_2}^{n+l_2} = \frac{\rho_{i-l_2}^n}{m_{i-l_2}^n} 2\pi \left(x_i^n \tilde{x}_i^{n+l_2} - x_{i-1}^n \tilde{x}_{i-1}^{n+l_2} \right). \quad (4.6b)$$

Spherical Symmetry

$$\begin{aligned} \left(\frac{\tilde{v}}{\bar{v}}\right)_{i-l_2}^{n+l_2} = \frac{\rho_{i-l_2}^n}{m_{i-l_2}^n} 4\pi \left\{ \left[\left(x_i^n\right)^2 \tilde{x}_i^{n+l_2} - \left(x_{i-1}^n\right)^2 \tilde{x}_{i-1}^{n+l_2} \right] \right. \\ \left. + \left[\left(\tilde{x}_i^{n+l_2}\right)^3 - \left(\tilde{x}_{i-1}^{n+l_2}\right)^3 \right] \frac{(\Delta t^{n+l_2})^2}{12} \right\}. \quad (4.6c) \end{aligned}$$

In these equations the positions, densities, and masses are centered at time n in contrast to the velocities which are centered at the advanced times. This is done to simplify the actual computerized solution of these equations. For low speed flow problems of the type for which these versions of the codes were intended, the error introduced by this approximation is negligible because the positions and densities change very little in one cycle.

In Eq. (4.6) the mass $m_{i-l_2}^n$ enters the calculation. This is calculated at the beginning of the cycle from the true volume $\mathcal{V}$ of the zone according to the equation,

$$m_{i-l_2}^n = \rho_{i-l_2}^n \mathcal{V}_{i-l_2}^n, \quad (4.7)$$

where the true volume is calculated as described in Section 4.2.4 of Volume 1.

The result of Eq.(4.6) can be integrated to determine the change in relative volume,

$$\Delta V_{i-1/2}^{n+1/2} = V_{i-1/2}^n \Delta t^{n+1/2} (\tilde{V}/V)_{i-1/2}^{n+1/2} \quad (4.8)$$

This becomes approximately a backward-differenced equation as $(\tilde{V}/V)^{n+1/2}$ approaches the final value of $(\tilde{V}/V)^{n+1}$. Backward differencing is used here so that this calculation will be compatible with the eventual calculation of the updated positions from the velocities. That calculation also uses backward differencing (described in 4.4.3). Next, we calculate the change in compression,

$$\Delta C_{i-1/2}^{n+1/2} = -\Delta V_{i-1/2}^{n+1/2}, \quad (4.9)$$

and the new compression

$$C_{i-1/2}^{n+1} = C_{i-1/2}^n + \Delta C_{i-1/2}^{n+1/2}. \quad (4.10)$$

The new relative volume is

$$V_{i-1/2}^{n+1} = 1 - C_{i-1/2}^{n+1}, \quad (4.11)$$

and the new density is

$$\rho_{i-\frac{1}{2}}^{n+1} = \rho_{i-\frac{1}{2}}^0 / V_{i-\frac{1}{2}}^{n+1}. \quad (4.12)$$

This method of computing relative volume and density by using the calculation of compression as an intermediate step is done to minimize round-off error. This is discussed in Section 4.2.4 of Volume 1.

4.4.2 Newton-Raphson Equation. For the incompressible flow versions, the objective of the implicit phase of the calculation is to calculate a velocity field such that $\dot{\tilde{V}}/V \simeq 0$. This is done by means of a Newton-Raphson iteration. If the volume strain rate calculated as described in the previous section exceeds some specified small number ϵ , then a pressure increment δp is calculated from a Newton-Raphson equation. This is then used in a form of the momentum equation to calculate a new velocity field. This process is repeated until

$$(\tilde{V}/V)_{i-\frac{1}{2}}^{n+1} \leq \epsilon. \quad (4.13)$$

The Newton-Raphson equation for the pressure increment is

$$\delta p_{i-\frac{1}{2}} = -\omega \left[(\tilde{V}/V)_{i-\frac{1}{2}}^{n+1} \right] / \left[\frac{\partial (\tilde{V}/V)_{i-\frac{1}{2}}}{\partial p_{i-\frac{1}{2}}} \right], \quad (4.14)$$

where ω is the relaxation factor used to accelerate the convergence of the iteration. The acceptable range for ω is $1 \leq \omega < 2$; for $\omega \geq 2$, an unstable iteration results.

The derivative in the denominator of Eq.(4.14) can be evaluated as follows:

$$\frac{\partial(\tilde{V}/V)_{i-1/2}}{\partial p_{i-1/2}} = \frac{\partial(\tilde{V}/V)_{i-1/2}}{\partial \dot{x}_i} \frac{\partial \dot{x}_i}{\partial p_{i-1/2}} + \frac{\partial(\tilde{V}/V)_{i-1/2}}{\partial \dot{x}_{i-1}} \frac{\partial \dot{x}_{i-1}}{\partial p_{i-1/2}} \quad (4.15)$$

The derivatives of the velocity strain rate, derived from Eq.(4.6), are then given by

Plane Symmetry

$$\frac{\partial(\tilde{V}/V)_{i-1/2}}{\partial \dot{x}_i} = \frac{\rho_{i-1/2}^n}{m_{i-1/2}^n}, \quad (4.16a)$$

$$\frac{\partial(\tilde{V}/V)_{i-1/2}}{\partial \dot{x}_{i-1}} = - \frac{\rho_{i-1/2}^n}{m_{i-1/2}^n}, \quad (4.16b)$$

Cylindrical Symmetry

$$\frac{\partial(\tilde{V}/V)_{i-1/2}}{\partial \dot{x}_i} = \frac{\rho_{i-1/2}^n}{m_{i-1/2}^n} 2\pi x_i^n, \quad (4.16c)$$

$$\frac{\partial(\tilde{V}/V)_{i-1/2}}{\partial \dot{x}_{i-1}} = - \frac{\rho_{i-1/2}^n}{m_{i-1/2}^n} 2\pi x_{i-1}^n, \quad (4.16d)$$

Spherical Symmetry

$$\frac{\partial (\tilde{V}/V)_{i-\frac{1}{2}}}{\partial \dot{x}_i} = \frac{\rho_{i-\frac{1}{2}}^n}{m_{i-\frac{1}{2}}^n} 4\pi \left[\left(x_i^n \right)^2 + \frac{1}{4} \tilde{x}_i^{n+\frac{1}{2}} \left(\Delta t^{n+\frac{1}{2}} \right)^2 \right], \quad (4.16e)$$

$$\frac{\partial (\tilde{V}/V)_{i-\frac{1}{2}}}{\partial \dot{x}_{i-1}} = - \frac{\rho_{i-\frac{1}{2}}^n}{m_{i-\frac{1}{2}}^n} 4\pi \left[\left(x_{i-1}^n \right)^2 + \frac{1}{4} \tilde{x}_{i-1}^{n+\frac{1}{2}} \left(\Delta t^{n+\frac{1}{2}} \right)^2 \right], \quad (4.16f)$$

and the derivatives of the velocities in terms of the pressure, derived from the momentum equation, Eq.(4.2), are

$$\begin{aligned} \frac{\partial \dot{x}_i}{\partial p_{i-\frac{1}{2}}} &= \frac{2\Delta t^{n+\frac{1}{2}}}{\alpha_{i-\frac{1}{2}}^n + \alpha_{i+\frac{1}{2}}^n}, \\ \frac{\partial \dot{x}_{i-1}}{\partial p_{i-\frac{1}{2}}} &= - \frac{2\Delta t^{n+\frac{1}{2}}}{\alpha_{i-\frac{3}{2}}^n + \alpha_{i-\frac{1}{2}}^n}. \end{aligned} \quad (4.17)$$

For the implicit, compressible flow versions, the objective is to calculate a velocity field such that the pressure p (used in the momentum equation) is equal to the equation of state pressure p' , calculated using $\dot{V}/V$ determined from that velocity field. Therefore we define the variable

$$w_{i-\frac{1}{2}}^{n+1} = p_{i-\frac{1}{2}}^{n+1} - (p')_{i-\frac{1}{2}}^{n+1}, \quad (4.18)$$

where p^{n+1} is the pressure used in the momentum equation and $(p')^{n+1}$ is the equation of state pressure

$$(\hat{p})_{i-\frac{1}{2}}^{n+1} = p' \left(v_{i-\frac{1}{2}}^{n+1}, u_{i-\frac{1}{2}}^n \right). \quad (4.19)$$

If W exceeds some small value, then, as in the case of the incompressible flow version, a pressure increment calculated from a Newton-Raphson equation is used in a form of the momentum equation to calculate a new velocity field.

The Newton-Raphson equation for the implicit, compressible flow version is

$$\delta p_{i-\frac{1}{2}} = -\omega W_{i-\frac{1}{2}}^{n+1} / \left(\frac{\partial W_{i-\frac{1}{2}}}{\partial p_{i-\frac{1}{2}}} \right). \quad (4.20)$$

In this case, although the usual range for ω is $1 \leq \omega < 2$, in some cases it may turn out that $\omega < 1$ gives acceptable results. This is discussed further in Section 6.3.4.

The derivative in the denominator of Eq.(4.19) can be evaluated as follows:

$$\frac{\partial W_{i-\frac{1}{2}}}{\partial p_{i-\frac{1}{2}}} = 1 - \frac{\partial \hat{p}_{i-\frac{1}{2}}}{\partial p_{i-\frac{1}{2}}} = 1 - \frac{\partial \hat{p}_{i-\frac{1}{2}}}{\partial (\tilde{V}/V)_{i-\frac{1}{2}}} \frac{\partial (\tilde{V}/V)_{i-\frac{1}{2}}}{\partial p_{i-\frac{1}{2}}}. \quad (4.21)$$

In this equation, the derivative of $\tilde{V}/V$ with respect to p is evaluated from Eq.(4.15) while the derivative of $\hat{p}'$ with respect to $\tilde{V}/V$ is calculated from the equation of state, Eq.(4.19).

Once the pressure increment has been calculated using either Eq.(4.14) or Eq.(4.20), the pressure is updated,

$$p_{i-\frac{1}{2}}^{n+1}(\text{new}) = p_{i-\frac{1}{2}}^{n+1}(\text{old}) + \delta p_{i-\frac{1}{2}} . \quad (4.22)$$

In the first iteration cycle, the old pressure in Eq.(4.22) is the pressure that existed at the start of the time step, i.e.,

$$p_{i-\frac{1}{2}}^{n+1}(\text{old}) = p_{i-\frac{1}{2}}^n .$$

thereafter, $p_{i-\frac{1}{2}}^{n+1}$ is updated by $\delta p_{i-\frac{1}{2}}$ on each iteration cycle until convergence is achieved.

4.4.3 Momentum Equation. Once a pressure increment for a zone has been calculated from the Newton-Raphson equation, it is then used in a modified form of the momentum equation, Eq.(4.2), to calculate new velocities. In Eq.(4.2), the acceleration of a grid point produced by the pressures in the two adjacent zones is calculated. In this phase, however, we calculate the change in velocity of the two grid points adjacent to each zone produced by the pressure increment in that zone. This procedure is used primarily for computational convenience. The net effect is the same as is achieved in Eq.(4.2) since by sweeping through the mesh we pick up the contributions to the grid point velocity change from the pressure increments in the two adjacent zones.

The velocity changes are calculated from the modified momentum equation as follows:

$$\begin{aligned}\tilde{\dot{x}}_i &= \frac{2\Delta t^{n+1/2}}{\alpha_{i-1/2}^n + \alpha_{i+1/2}^n} \delta p_{i-1/2}, \\ \tilde{\dot{x}}_{i-1} &= - \frac{2\Delta t^{n+1/2}}{\alpha_{i-3/2}^n + \alpha_{i-1/2}^n} \delta p_{i-1/2}.\end{aligned}\quad (4.23)$$

As we did in the case of the mass equation (4.6), the positions and densities in Eq.(4.19) are centered at time n . This is indicated by the time centering of the α 's. Using positions at time n is done for computational convenience and introduces a negligible error because the positions and densities change very little in one cycle.

Once the velocity increments are calculated, a new set of velocities can then be calculated as follows,

$$\begin{aligned}\tilde{x}_i^{n+1/2}(\text{new}) &= \tilde{x}_i^{n+1/2}(\text{old}) + \tilde{\dot{x}}_i, \\ \tilde{x}_{i-1}^{n+1/2}(\text{new}) &= \tilde{x}_{i-1}^{n+1/2}(\text{old}) + \tilde{\dot{x}}_{i-1}.\end{aligned}\quad (4.24)$$

4.4.4 Convergence. The iterative process described above is repeated until either the volume strain rate or the pressure difference approaches zero, i.e., until

$$(\tilde{V}/V)_{i-1/2}^{n+1/2} \leq \epsilon$$

or

$$w_{i-1/2}^{n+1} \leq \epsilon \left(p_{i-1/2}^{n+1} \right),$$

where ϵ is a small number (input constant); the actual value used for ϵ is

problem-dependent. When convergence is reached, the velocities and pressures have achieved their $n+1$ values so that we can write

$$\dot{x}_i^{n+1} = \tilde{\dot{x}}_i^{n+\frac{1}{2}}.$$

The new positions are then calculated from a backward differenced integration:

$$x_i^{n+1} = x_i^n + \dot{x}_i^{n+1} \Delta t^{n+\frac{1}{2}}. \quad (4.25)$$

A centered integration could have been used here, but experience has shown that it does not result in a substantial increase in accuracy and that it can have an adverse effect on stability.

At this point a new set of pressures, velocities, positions and densities at time $n+1$ have been obtained. For the inviscid, incompressible flow version, this completes one cycle of the Lagrangian calculation. These variables are then used as initial conditions for the next time step. For the viscous, incompressible flow version and the compressible flow version, however, we still need to calculate the remaining variables that are centered in the stress mesh. This includes the calculation of the individual strain rates and the viscous stresses in both versions and the artificial viscosity as well as the solution of the Lagrangian internal energy equation (including heat conduction) in the compressible flow version. This is described below in Sections 4.4.6 - 4.4.8. However, first we discuss a modification to the implicit iteration for highly nonlinear problems.

4.4.5 Two-Sided Secant Iteration. In some cases in which the fluid exhibits highly nonlinear behavior (e.g., near the saturated liquid phase line in a steam-water phase transition) the Newton-Raphson iteration method may converge slowly or may even diverge. In these situations a two-sided secant method provides more rapid convergence.

This method is shown graphically in Figure 4.3. In this figure the pressure difference $W = p - p'$ is plotted on the ordinate with the pressure p on the abscissa. The solid curve represents the function $W(p)$ for which we are trying to find the point $W = 0$. Three points in the W, p plane are required; points 1 and 2 must bound the solution $W = 0$, and point 3 must lie between them. Secants are constructed through points 1 and 3 and points 2 and 3 which intersect the $W = 0$ axis at p_A and p_B , respectively. The new pressure p_{new} is then calculated to be the average of these two pressures, and the pressure increment δp is calculated from the difference between this pressure and the one obtained on the previous iteration. The new point $W(p_{\text{new}})$ is then used as one of the required three points and point 2 is discarded.

When the two-sided secant method is used, it is applied to each cell individually in what we call an internal iteration as opposed to the global iteration described previously which involves a sweep through the entire mesh on each iteration cycle. In the first internal iteration cycle, the Newton-Raphson method is used to obtain the second point in the W, p plane. (The first point is obtained by using p and p' either from the explicit phase or from the previous global iteration.) Those two points are used with a single-sided secant method in the second internal iteration to obtain the third point. In the third and subsequent internal iterations the two-sided secant method is used.

The internal iteration is used to achieve convergence for each cell individually. However, because the cells are not independent, this does not guarantee that global convergence will be achieved. Therefore, this process is repeated in a global iteration until overall convergence is obtained.

4.4.6 Artificial Viscosity. In some cases where real viscosity effects are not included, it is necessary to use an artificial viscosity to permit the calculation of large strain rate phenomena (particularly shock

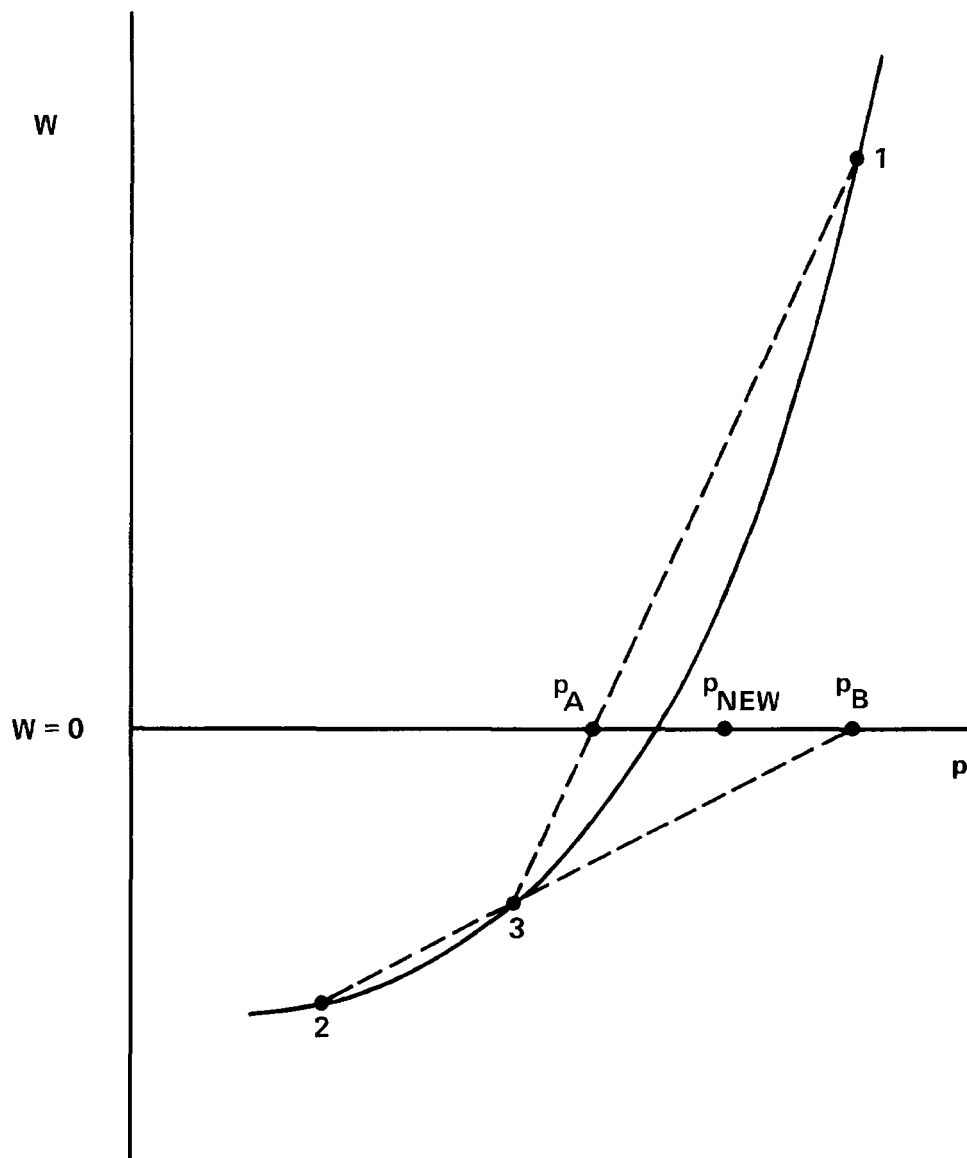


Figure 4.3. Graphical representation of the two-sided secant iteration method.

waves) in a finite-difference code. Although the versions described in this volume are intended for use on problems involving low speed, small strain rate flows, we have included the option of using artificial viscosity. In most cases of interest for these codes, it should not be needed. However, it is included so that it will be available for those few cases where it might be required.

The artificial viscosity formulation used in these codes is identical to that used in the explicit versions of STEALTH. It is described in detail in Section 4.3.1 of Volume 1. The reader is referred to that volume if details of the formulation are required.

4.4.7 Viscous Stresses. In Section 2.2.2, Eq.(2.13), we wrote the equation for the viscous stresses in tensor notation. In component form these principal stresses can be written

$$\begin{aligned} \left(s_{xx}\right)_{i-\frac{1}{2}}^{n+1} &= 2\zeta \left(\dot{\epsilon}_{xx}\right)_{i-\frac{1}{2}}^{n+1} + \lambda \left(\frac{\dot{V}}{V}\right)_{i-\frac{1}{2}}^{n+1}, \\ \left(s_{yy}\right)_{i-\frac{1}{2}}^{n+1} &= 2\zeta \left(\dot{\epsilon}_{yy}\right)_{i-\frac{1}{2}}^{n+1} + \lambda \left(\frac{\dot{V}}{V}\right)_{i-\frac{1}{2}}^{n+1}, \\ \left(s_{zz}\right)_{i-\frac{1}{2}}^{n+1} &= 2\zeta \left(\dot{\epsilon}_{zz}\right)_{i-\frac{1}{2}}^{n+1} + \lambda \left(\frac{\dot{V}}{V}\right)_{i-\frac{1}{2}}^{n+1}, \end{aligned} \quad (4.26)$$

where the ϵ_{xx} , etc., are the principal components of the strain rate tensor.

The equations for the principal strain rates depend on the symmetry. For all three one-dimensional symmetries the x-component is given by

$$\left(\dot{\epsilon}_{xx}\right)_{i-1/2}^{n+1} = \left(\frac{\partial \dot{x}}{\partial x}\right)_{i-1/2}^{n+1} = \frac{\dot{x}_i^{n+1} - \dot{x}_{i-1}^{n+1}}{x_i^{n+1} - x_{i-1}^{n+1}} . \quad (4.27)$$

The other two principal strain rates can be calculated from the following equation which expresses the volume strain rate in terms of the individual strain rates for one-dimensional symmetries:

$$(\dot{V}/V) = \dot{\epsilon}_{xx} + \dot{\epsilon}_{yy} + \dot{\epsilon}_{zz} = \frac{\partial \dot{x}}{\partial x} + f \frac{\dot{x}}{x} . \quad (4.28)$$

For planar symmetry the other two principal strain rates are

$$\left(\dot{\epsilon}_{yy}\right)_{i-1/2}^{n+1} = \left(\dot{\epsilon}_{zz}\right)_{i-1/2}^{n+1} = 0 ; \quad (4.29)$$

while for cylindrical symmetry we have

$$\left(\dot{\epsilon}_{yy}\right)_{i-1/2}^{n+1} = \left(\dot{V}/V\right)_{i-1/2}^{n+1} - \left(\dot{\epsilon}_{xx}\right)_{i-1/2}^{n+1} , \quad (4.30a)$$

$$\left(\dot{\epsilon}_{zz}\right)_{i-1/2}^{n+1} = 0 ; \quad (4.30b)$$

and for spherical symmetry

$$\left(\dot{\epsilon}_{yy}\right)_{i-1/2}^{n+1} = \left(\dot{\epsilon}_{zz}\right)_{i-1/2}^{n+1} = \frac{1}{2} \left[\left(\dot{V}/V\right)_{i-1/2}^{n+1} - \left(\dot{\epsilon}_{xx}\right)_{i-1/2}^{n+1} \right] . \quad (4.31)$$

4.4.8 Internal Energy Equation. In the explicit versions of STEALTH the internal energy equation is solved using a one-step iteration to improve the accuracy, i.e., to provide a degree of "implicitness" to the solution. (See Section 4.3.4 of Volume 1.) In the versions described here the one-step iteration is omitted because the stresses used in the internal energy equation are already centered at time $n+1$ as a result of the implicit solution of the momentum equation. During the solution of the momentum equation, however, the energies used in the pressure equation of state, $p(u,V)$, were centered at time n so that the coupling of the energy equation with the momentum equation is explicit. In general, for the types of flow situations for which these codes have been designed (i.e., low speed, small strain-rate flows), this should not introduce any significant error into the solution.

In some cases it is desirable to run the implicit, compressible flow versions in an explicit mode for some short time, perhaps during an initial transient period of a problem. In that case the iterative second phase of the solution is omitted, and we proceed directly from the explicit, Lagrange phase (Section 4.3) to the calculations of the artificial viscosity, the viscous stresses and the Lagrange internal energy equation. In this case the one-step iteration is used in the solution of the energy equation. See Section 4.3.4 of Volume 1 for details of that method of solution. Below we provide a description of the solution of the internal energy equation as it is used for implicit calculations.

The internal energy equation may be written as follows:

$$u_{i-\frac{1}{2}}^{n+1} = u_{i-\frac{1}{2}}^n - \left(p_{i-\frac{1}{2}}^{n+\frac{1}{2}} + q_{i-\frac{1}{2}}^{n+\frac{1}{2}} \right) \Delta V_{i-\frac{1}{2}}^{n+\frac{1}{2}} + \Delta Z_{i-\frac{1}{2}}^{n+\frac{1}{2}} + \Delta h_{i-\frac{1}{2}}^{n+\frac{1}{2}} + \Delta U_{i-\frac{1}{2}}^{n+\frac{1}{2}} . \quad (4.32)$$

In this equation $p^{n+\frac{1}{2}}$ and $q^{n+\frac{1}{2}}$ are averages of quantities at times n and $n+1$; ΔV is defined in Eq.(4.8); and ΔZ , Δh , and ΔU are changes in the

internal energy from viscosity, heat conduction, and heat sources or sinks, respectively. The viscous energy term can be written

$$\begin{aligned} \Delta Z_{i-\frac{1}{2}}^{n+\frac{1}{2}} = & V_{i-\frac{1}{2}}^{n+1} \Delta t^{n+\frac{1}{2}} \left[\left(s_{xx} \right)_{i-\frac{1}{2}}^{n+1} \left(\dot{\epsilon}_{xx} \right)_{i-\frac{1}{2}}^{n+1} \right. \\ & \left. + \left(s_{yy} \right)_{i-\frac{1}{2}}^{n+1} \left(\dot{\epsilon}_{yy} \right)_{i-\frac{1}{2}}^{n+1} + \left(s_{zz} \right)_{i-\frac{1}{2}}^{n+1} \left(\dot{\epsilon}_{zz} \right)_{i-\frac{1}{2}}^{n+1} \right]. \end{aligned} \quad (4.33)$$

The heat conduction term is computed by solving the heat conduction equation (diffusion equation). The method used here is identical to that used in other versions of the STEALTH codes and described in Section 4.3.4 of Volume 1. The reader is referred to that volume for details of the calculation. The source energy density term is determined from a time dependent function

$$\Delta U_{i-\frac{1}{2}}^{n+\frac{1}{2}} = \Delta U_{i-\frac{1}{2}} \left(t^{n+\frac{1}{2}}, \Delta t^{n+\frac{1}{2}} \right). \quad (4.34)$$

4.5 TIME STEP CALCULATION

In the explicit versions of STEALTH, a stable time step is calculated for each cycle based on stability criteria related to the sound speed, the artificial viscosity, and heat flow. This is described in Section 4.4 of Volume 1. In the implicit versions described here a stable time step is also calculated. Since the calculations of artificial viscosity and heat flow are treated identically in the different versions, the dependence of the stable time step on those quantities is also treated identically. However, for an implicit solution of the momentum equation, the stable time

step is not limited by the sound speed. If effects such as artificial viscosity, real viscosity or heat conduction are ignored, the linearized equations can be shown to be unconditionally stable. In practice the equations do not turn out to be stable for all time steps. Experience has shown, however, that the solution usually will be stable if the material is not permitted to move more than one zone width in a time step. Therefore, a reasonable stability criterion for the mechanical equations can be obtained by replacing the sound speed in the explicit stability criterion by the material velocity. The resultant criterion, is

$$\left(\Delta t_{i-\frac{1}{2}}^{n+1}\right)^2 = \frac{\left(\Delta x_{i-\frac{1}{2}}^{n+1}\right)^2}{\left(\dot{x}_{i-\frac{1}{2}}^{n+1}\right)^2 + (c_q)^2} , \quad (4.35)$$

where c_q is an equivalent speed calculated for the artificial viscosity effects. (See Eq.(4.54) of Volume 1.) The stable time step for the heat conduction equations is given in Section 4.4.3 of Volume 1. The overall stable time step for a zone is defined to be the minimum of the stable mechanical or thermal timestep.

When real viscosity effects are calculated they can have an effect on the stable time step since they are calculated explicitly. However, unless the viscosity coefficients are very large, the other time step criteria dominate. Therefore, we have omitted consideration of this effect in calculating the stable time step.

A stable time step for each zone is calculated as described above. The maximum time step for a cycle is then defined to be the minimum stable time step for all zones in the mesh multiplied by some safety factor (usually $\approx 1/4$). It should be pointed out that accuracy considerations often dictate the use of a smaller time step than would be required for stability. In that case a smaller constant time step can be used. This is explained more completely in Section 6.3.3.

SECTION 5

TWO-DIMENSIONAL FINITE-DIFFERENCE EQUATIONS

5.1 INTRODUCTION

The finite-difference equations representing the two-dimensional equations of motion for a fluid are solved using two staggered meshes -- a displacement mesh and a stress mesh. This is the same approach as is used in the other versions of STEALTH described in Volume 1. The displacement mesh is made up of grid points which define geometric quantities such as shapes, interfaces, boundaries, etc. The equation for conservation of momentum is solved in the displacement mesh to calculate the vector quantities, acceleration $(\ddot{x}, \ddot{y})$, velocity $(\dot{x}, \dot{y})$, and position (x, y) , which are said to be centered in space at the grid points. Actually, the first-order finite difference method used here assumes that these quantities are constant (average values) over some volume encompassing the grid point as shown (dashed) in Figure 5.1a. This diamond-shaped region is sometimes referred to as the momentum zone or momentum cell.

The stress mesh is made up of zones encompassing the volume between grid points. Scalar and tensor quantities such as pressure, internal energy, density, and viscous stresses are calculated in this mesh and are said to be centered at the zone centers as shown in Figure 5.1b. These quantities also are assumed to be constant over the zone volume.

5.2 CALCULATIONAL SEQUENCE

The two-dimensional equations of motion for a fluid are solved in two steps. These are shown schematically in Figure 5.2a and b. Figure 5.2a applies to the incompressible flow version while Figure 5.2b applies to the implicit, compressible flow version. In both cases the explicit, Lagrangian momentum equation is solved first using the stress (or pressure)

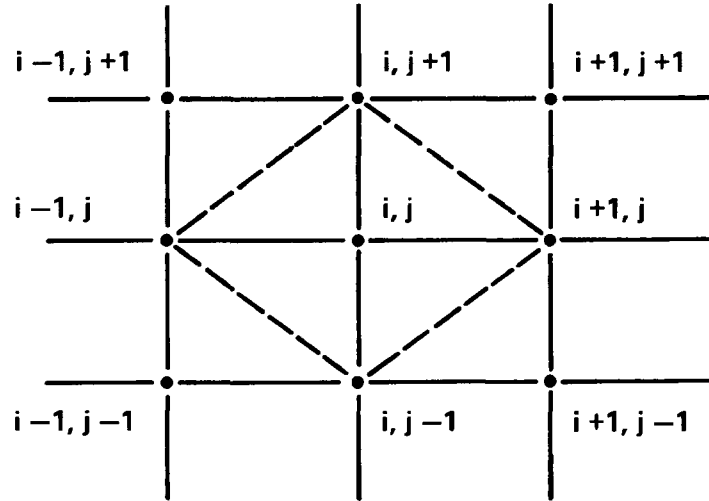


Figure 5.1a. Diagram of 2D displacement mesh showing momentum zone (dashed).

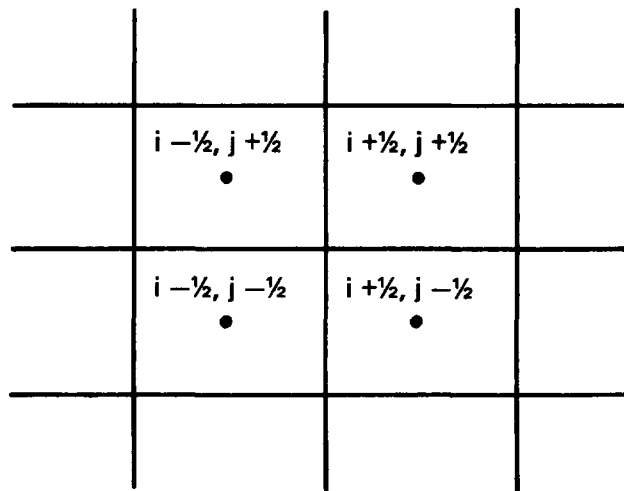


Figure 5.1b. Diagram of 2D stress mesh.

CALCULATIONAL SEQUENCE 2D INCOMPRESSIBLE FLOW VERSION

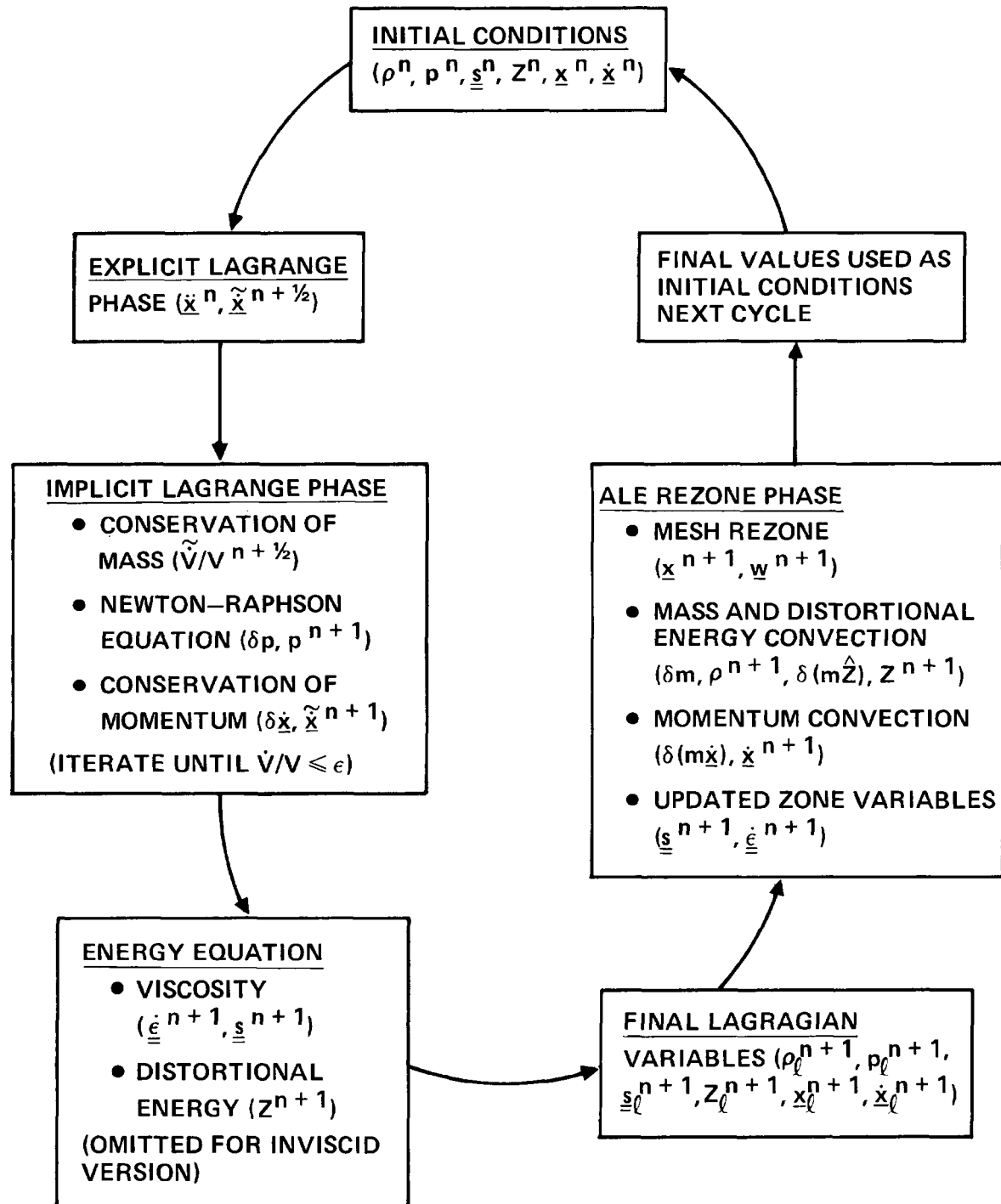


Figure 5.2a. Calculational sequence for 2D incompressible flow version of STEALTH.

CALCULATIONAL SEQUENCE **2D IMPLICIT, COMPRESSIBLE FLOW VERSION**

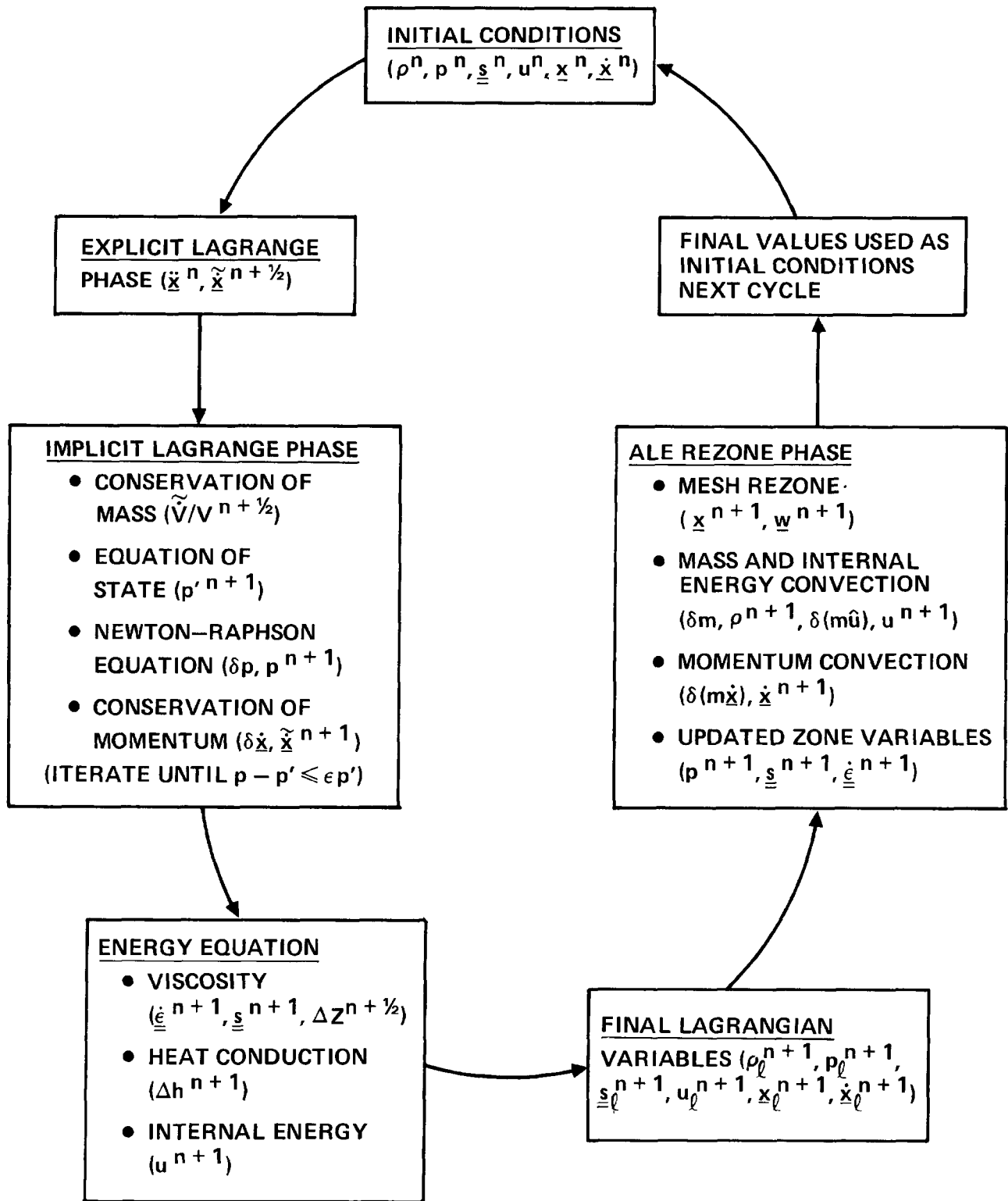


Figure 5.2b. Calculational sequence for 2D implicit, compressible flow version of STEALTH.

and density distributions existing at the beginning of the cycle. The resulting velocities are temporary (indicated by the tilde) and are arbitrarily given time centering $n+\frac{1}{2}$ to indicate that they represent intermediate values somewhere between the initial time n at the start of the cycle and the final time $n+1$.

Next an iteration is performed to solve simultaneously the implicit equations for each zone in the mesh. The principal difference between the two versions described here is in this implicit phase. In both versions the velocities resulting from the explicit Lagrangian phase are used as initial conditions for this iteration, and these velocities are used to calculate the volume strain rate (equal to the divergence of velocity). In the incompressible flow version we are attempting to find a solution such that this quantity is approximately zero. Therefore if this quantity is larger than some small number ϵ (specified by input), then the Newton-Raphson equation is used to calculate a pressure increment for each zone, and a modified form of the momentum equation is used to calculate the resulting change in velocity for the four grid points adjoining each zone. The pressure and velocity increments are added to the old values of pressure and velocity for each zone and this entire process is repeated until convergence is achieved, i.e., until $\dot{V}/V \leq \epsilon$ for all zones.

In the implicit, compressible flow version we are looking for a solution such that the pressure p used in the momentum equation and the new velocities obtained from that equation are centered at the same point in time. An equivalent condition is as follows. We can define another pressure variable p' which is obtained from the equation of state using an updated relative volume based on the new velocity field. Then an implicit solution is obtained when the two pressures, p and p' , are equal. Therefore, we define a variable $W = p - p'$ which we want to be zero and use a Newton-Raphson equation in conjunction with a modified form of the momentum equation, the same as was done for incompressible flow, to calculate new pressures and velocities.

When these iterations have converged, we have a new set of pressures, velocities and relative volumes at time $n+1$. At this point the solution of the Lagrangian equation of motion for an inviscid, incompressible fluid is complete. For the compressible flow and viscous, incompressible flow versions, however, we have the additional tasks of solving the Lagrange internal energy equation (including heat conduction for the compressible flow version) and of calculating the updated viscous stresses based on the new velocity field.*

The first two phases of a calculational cycle constitute a complete solution of the Lagrangian equations of motion. In the final phase, the convection terms required for the full set of equations for a general coordinate system are solved.

First the mesh positions are calculated according to some prescription. For a Lagrangian calculation, the grid points are left in the positions calculated at the end of the second phase and this final phase is omitted. For an Eulerian calculation, the grid points are returned to the positions that existed at the start of the cycle. For other mesh motions, the positions are calculated from some prescription. At the same time that the new positions are calculated, a corresponding mesh velocity is determined, and the relative velocity between the fluid and the mesh is calculated.

Next these relative velocities are used to calculate the mass, internal energy, and momentum fluxes. In the case of the mass and energy equations, the flow is across the surface shown in Figure 5.3a. These

*The internal energy equation is solved for the viscous, incompressible flow version to keep track of viscous energy dissipation for editing purposes only. This is not a necessary part of the calculation since the momentum and energy equations are decoupled in the incompressible flow approximation as long as the viscosity coefficients are energy independent.

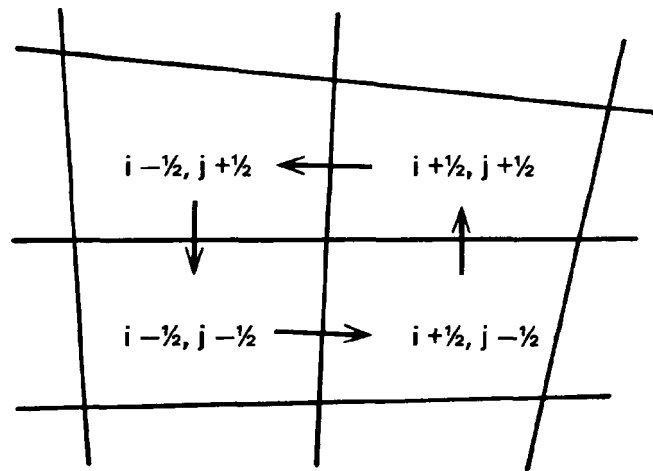


Figure 5.3a. Location of mass fluxes.

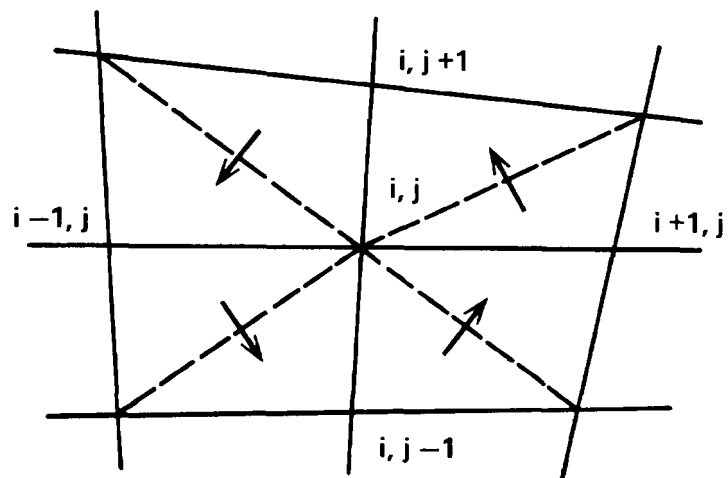


Figure 5.3b. Location of momentum fluxes.

fluxes result in new densities and internal energies in the four zones surrounding the grid point being rezoned. In the case of the momentum equation, the flow is across surfaces of momentum zones (defined in Section 5.1) as shown in Figure 5.3b, and the resulting momentum changes are to the grid points directly above, below, and to either side of the rezoned point. This appears to be a somewhat different procedure than that presented in Section 3.3.3; however, the results are the same. By following this procedure for each grid point, the flow across all surfaces of both stress zones and momentum zones is calculated so that the integration of the convection terms as described in Section 3.3.3 and shown schematically in Figure 3.1 is accomplished.

For the compressible flow and viscous, incompressible flow versions, once new densities, internal energies and velocities have been calculated several other quantities must be updated for use on the next cycle. New strain rates are calculated from the new velocity field; these are then used to calculate new viscous stresses. Also, for the compressible flow version, a new pressure is calculated based on the new values of density and internal energy.

At the end of this phase, the solution of the full set of equations has been accomplished for one time step. The results are then used as initial conditions for the next computational cycle.

In the following sections, the complete finite-difference equations corresponding to the above calculational sequence are provided.

5.3 EXPLICIT, LAGRANGIAN PHASE

5.3.1 Momentum Equations. The conservation of momentum equation for a general fluid was given for a Lagrangian coordinate system in Section 2.2.2, Eq.(2.13). The component forms of that equation can be written for

two independent space variables (for plane and cylindrical symmetry) as follows:

$$\ddot{x} = \frac{1}{\rho} \left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} \right) + f \frac{1}{\rho} \left(\frac{\sigma_{xx} - \sigma_{zz}}{x} \right) + (1-f)g_x \quad , \quad (5.1a)$$

$$\ddot{y} = \frac{1}{\rho} \left(\frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{xy}}{\partial x} \right) + f \frac{1}{\rho} \left(\frac{\sigma_{xy}}{x} \right) + g_y \quad , \quad (5.1b)$$

where g_x and g_y are gravity components and

$$f = \begin{cases} 0 & \text{for plane symmetry} \\ 1 & \text{for cylindrical symmetry.} \end{cases}$$

For inviscid, incompressible flow this reduces to

$$\ddot{x} = - \frac{1}{\rho} \frac{\partial p}{\partial x} + (1 - f)g_x \quad , \quad (5.1c)$$

$$\ddot{y} = - \frac{1}{\rho} \frac{\partial p}{\partial y} + g_y \quad . \quad (5.1d)$$

Following the method described in Section 5.2.2 of Volume 1, and using the space-centering conventions illustrated in Figures 5.1a and b, we can write the finite-difference form of Eqs.(5.1a) and (5.1b) as

$$\begin{aligned}
\ddot{x}_{i,j}^n = & \frac{1}{2\rho_{i,j}^n A_{i,j}^n} \left[\sigma_{xx_{i+\frac{1}{2},j+\frac{1}{2}}}^n \left(y_{i,j+1}^n - y_{i+1,j}^n \right) \right. \\
& + \sigma_{xx_{i-\frac{1}{2},j+\frac{1}{2}}}^n \left(y_{i-1,j}^n - y_{i,j+1}^n \right) \\
& + \sigma_{xx_{i-\frac{1}{2},j-\frac{1}{2}}}^n \left(y_{i,j-1}^n - y_{i-1,j}^n \right) \\
& + \sigma_{xx_{i+\frac{1}{2},j-\frac{1}{2}}}^n \left(y_{i+1,j}^n - y_{i,j-1}^n \right) \\
& - \sigma_{xy_{i+\frac{1}{2},j+\frac{1}{2}}}^n \left(x_{i,j+1}^n - x_{i+1,j}^n \right) \\
& - \sigma_{xy_{i-\frac{1}{2},j+\frac{1}{2}}}^n \left(x_{i-1,j}^n - x_{i,j+1}^n \right) \\
& - \sigma_{xy_{i-\frac{1}{2},j-\frac{1}{2}}}^n \left(x_{i,j-1}^n - x_{i-1,j}^n \right) \\
& \left. - \sigma_{xy_{i+\frac{1}{2},j-\frac{1}{2}}}^n \left(x_{i+1,j}^n - x_{i,j-1}^n \right) \right] \\
& + f\beta_{x_{i,j}}^n + (1-f)g_x, \tag{5.2a}
\end{aligned}$$

$$\begin{aligned}
\ddot{y}_{i,j}^n = \frac{1}{2\rho_{i,j}^n A_{i,j}^n} & \left[-\sigma_{yy_{i+\frac{1}{2},j+\frac{1}{2}}}^n \left(x_{i,j+1}^n - x_{i+1,j}^n \right) \right. \\
& - \sigma_{yy_{i-\frac{1}{2},j+\frac{1}{2}}}^n \left(x_{i-1,j}^n - x_{i,j+1}^n \right) \\
& - \sigma_{yy_{i-\frac{1}{2},j-\frac{1}{2}}}^n \left(x_{i,j-1}^n - x_{i-1,j}^n \right) \\
& - \sigma_{yy_{i+\frac{1}{2},j-\frac{1}{2}}}^n \left(x_{i+1,j}^n - x_{i,j-1}^n \right) \\
& + \sigma_{xy_{i+\frac{1}{2},j+\frac{1}{2}}}^n \left(y_{i,j+1}^n - y_{i+1,j}^n \right) \\
& + \sigma_{xy_{i-\frac{1}{2},j+\frac{1}{2}}}^n \left(y_{i-1,j}^n - y_{i,j+1}^n \right) \\
& + \sigma_{xy_{i-\frac{1}{2},j-\frac{1}{2}}}^n \left(y_{i,j-1}^n - y_{i-1,j}^n \right) \\
& + \sigma_{xy_{i+\frac{1}{2},j-\frac{1}{2}}}^n \left(y_{i+1,j}^n - y_{i,j-1}^n \right) \\
& \left. + f\beta_{y_{i,j}}^n + g_y \right], \tag{5.2b}
\end{aligned}$$

where $\frac{1}{\rho_{i,j}^n A_{i,j}^n}$, $\beta_{x_{i,j}}^n$ and $\beta_{y_{i,j}}^n$ are defined as follows,

$$\frac{1}{\rho_{i,j}^n A_{i,j}^n} = \frac{1}{4} \left[\frac{1}{\rho_{i+\frac{1}{2},j+\frac{1}{2}}^n A_{i+\frac{1}{2},j+\frac{1}{2}}^n} + \frac{1}{\rho_{i-\frac{1}{2},j+\frac{1}{2}}^n A_{i-\frac{1}{2},j+\frac{1}{2}}^n} \right. \\ \left. + \frac{1}{\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} + \frac{1}{\rho_{i+\frac{1}{2},j-\frac{1}{2}}^n A_{i+\frac{1}{2},j-\frac{1}{2}}^n} \right], \quad (5.3a)$$

$$\beta_{x,i,j}^n = \frac{2\pi}{4} \left[\left(\sigma_{xx} - \sigma_{zz} \right)_{i+\frac{1}{2},j+\frac{1}{2}}^n \frac{A_{i+\frac{1}{2},j+\frac{1}{2}}^n}{m_{i+\frac{1}{2},j+\frac{1}{2}}^n} \right. \\ + \left(\sigma_{xx} - \sigma_{zz} \right)_{i-\frac{1}{2},j+\frac{1}{2}}^n \frac{A_{i-\frac{1}{2},j+\frac{1}{2}}^n}{m_{i-\frac{1}{2},j+\frac{1}{2}}^n} \\ + \left(\sigma_{xx} - \sigma_{zz} \right)_{i-\frac{1}{2},j-\frac{1}{2}}^n \frac{A_{i-\frac{1}{2},j-\frac{1}{2}}^n}{m_{i-\frac{1}{2},j-\frac{1}{2}}^n} \\ \left. + \left(\sigma_{xx} - \sigma_{zz} \right)_{i+\frac{1}{2},j-\frac{1}{2}}^n \frac{A_{i+\frac{1}{2},j-\frac{1}{2}}^n}{m_{i+\frac{1}{2},j-\frac{1}{2}}^n} \right], \quad (5.3b)$$

$$\begin{aligned}
\beta_{y,i,j}^n = \frac{2\pi}{4} & \left[\sigma_{xy,i+\frac{1}{2},j+\frac{1}{2}}^n \left(\frac{A_{i+\frac{1}{2},j+\frac{1}{2}}^n}{m_{i+\frac{1}{2},j+\frac{1}{2}}^n} \right) \right. \\
& + \sigma_{xy,i-\frac{1}{2},j+\frac{1}{2}}^n \left(\frac{A_{i-\frac{1}{2},j+\frac{1}{2}}^n}{m_{i-\frac{1}{2},j+\frac{1}{2}}^n} \right) \\
& + \sigma_{xy,i-\frac{1}{2},j-\frac{1}{2}}^n \left(\frac{A_{i-\frac{1}{2},j-\frac{1}{2}}^n}{m_{i-\frac{1}{2},j-\frac{1}{2}}^n} \right) \\
& \left. + \sigma_{xy,i+\frac{1}{2},j-\frac{1}{2}}^n \left(\frac{A_{i+\frac{1}{2},j-\frac{1}{2}}^n}{m_{i+\frac{1}{2},j-\frac{1}{2}}^n} \right) \right] . \tag{5.3c}
\end{aligned}$$

In these equations, A is the quadrilateral zone area calculated as described in Section 5.2.2 of Volume 1 and m is the zone mass which is calculated at the beginning of the cycle from the true volume $\mathcal{V}$ of the zone according to the equation

$$m_{i-\frac{1}{2},j-\frac{1}{2}}^n = \rho_{i-\frac{1}{2},j-\frac{1}{2}}^n \mathcal{V}_{i-\frac{1}{2},j-\frac{1}{2}}^n , \tag{5.4}$$

where $\mathcal{V}$ is calculated as described in Section 5.2.4 of Volume 1.

Similarly, the finite difference forms of Eqs. (5.1c) and (5.1d) are

$$\begin{aligned}
 \ddot{x}_{i,j}^n = \frac{1}{2\rho_{i,j}^n A_{i,j}^n} & \left[-p_{i+\frac{1}{2},j+\frac{1}{2}}^n \left(y_{i,j+1}^n - y_{i+1,j}^n \right) \right. \\
 & - p_{i-\frac{1}{2},j+\frac{1}{2}}^n \left(y_{i-1,j}^n - y_{i,j+1}^n \right) \\
 & - p_{i-\frac{1}{2},j-\frac{1}{2}}^n \left(y_{i,j-1}^n - y_{i-1,j}^n \right) \\
 & \left. - p_{i+\frac{1}{2},j-\frac{1}{2}}^n \left(y_{i+1,j}^n - y_{i,j-1}^n \right) \right] \\
 & + (1 - f) g_x, \tag{5.5a}
 \end{aligned}$$

$$\begin{aligned}
 \ddot{y}_{i,j}^n = \frac{1}{2\rho_{i,j}^n A_{i,j}^n} & \left[p_{i+\frac{1}{2},j+\frac{1}{2}}^n \left(x_{i,j+1}^n - x_{i+1,j}^n \right) \right. \\
 & + p_{i-\frac{1}{2},j+\frac{1}{2}}^n \left(x_{i-1,j}^n - x_{i,j+1}^n \right) \\
 & + p_{i-\frac{1}{2},j-\frac{1}{2}}^n \left(x_{i,j-1}^n - x_{i-1,j}^n \right) \\
 & \left. + p_{i+\frac{1}{2},j-\frac{1}{2}}^n \left(x_{i+1,j}^n - x_{i,j-1}^n \right) \right] \\
 & + g_y. \tag{5.5b}
 \end{aligned}$$

Evaluation of Eqs.(5.2) and (5.5) provides grid point accelerations at time n . Velocities are then determined from an explicit, forward-differenced integration,

$$\begin{aligned}\tilde{x}_{i,j}^{n+1/2} &= \dot{x}_{i,j}^n + \ddot{x}_{i,j}^n \Delta t^{n+1/2} , \\ \tilde{y}_{i,j}^{n+1/2} &= \dot{y}_{i,j}^n + \ddot{y}_{i,j}^n \Delta t^{n+1/2} .\end{aligned}\tag{5.6}$$

As we said previously, the new velocities are arbitrarily centered at time $n+1/2$ to show that they are temporary values obtained prior to completing the implicit solution for the final velocities at time $n+1$.

The time step $\Delta t^{n+1/2}$ used in Eq.(5.6) is generally a constant* specified by input. Because all time integrations in this version of STEALTH take place over the interval $n \rightarrow n+1$, only this time step is used. This is in contrast to other versions of the codes which employ an explicit, centered time integration (see Section 3.2) and, therefore, must use two different time steps, Δt^n and $\Delta t^{n+1/2}$.

5.3.2 Momentum Boundary Conditions. Section 5.2.3 of Volume 1 provides a detailed discussion of momentum boundary conditions for the 2D STEALTH codes. That discussion is directly applicable to these versions of the code described here with a few obvious exceptions for the incompressible flow version (e.g., σ_{xx} , σ_{yy} , etc., are replaced by $-p$ for this version since the full stress tensor is not used). That discussion will not be repeated here, but rather the reader is referred to the discussion in Volume 1.

*An automatic time step calculation based on stability considerations has been incorporated into the codes. However, accuracy considerations generally dictate a smaller time step than would be required for stability. In that case a constant time step is used, although some programmed variation is allowed. See Sections 3.4 and 6.3.3 for more details.

The only difference in momentum boundary conditions between these versions and the other versions of STEALTH is in the addition of a continuative outflow boundary condition. This allows a fluid to flow out of the mesh through a non-Lagrangian boundary. For this phase of the calculation, however, this boundary condition is handled in the same way as a free boundary, so discussion of it will be delayed until a later section.

5.4 IMPLICIT, LAGRANGIAN PHASE

5.4.1 Mass Equation. The general continuity equation or conservation of mass equation for two-dimensional symmetries is

$$\frac{\dot{V}}{V} = \nabla \cdot \underline{\dot{x}} = \frac{\partial \dot{x}}{\partial x} + \frac{\partial \dot{y}}{\partial y} + \frac{\partial \dot{z}}{\partial z} . \quad (5.7)$$

In plane symmetry, x , y , and z have their usual meanings and $\frac{\partial \dot{z}}{\partial z} = 0$; in cylindrical symmetry, x is the radial coordinate, y is the axial coordinate, z is the tangential or angular coordinate, and $\frac{\partial \dot{z}}{\partial z} = \frac{\dot{x}}{x}$.

In writing the finite-difference representation for this equation, several options are open to us within the general STEALTH differencing format. First, the quantity $\dot{V}/V$ can be calculated directly from the change in true volume $\mathcal{V}$ calculated from coordinates. This is the method used in other 2D versions of STEALTH because it is generally the most accurate for the majority of situations for which these codes were designed. The second option is to treat the individual strain rates separately with the volume strain rate calculated as the sum of the individual strain rates. The last option is to evaluate $\nabla \cdot \underline{\dot{x}}$ directly using the surface integral approach. This is the option used here, primarily because it facilitates the evaluation of certain terms in the Newton-Raphson equation. This will be made clearer in the discussion of that equation in the next section.

The finite-difference equation for the volume strain rate is

$$\begin{aligned}
 (\tilde{V}/V)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} = & \frac{\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n}{4m_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ \left(r_{i,j}^n + r_{i-1,j}^n \right) \left[\left(\tilde{x}_{i,j}^{n+\frac{1}{2}} + \tilde{x}_{i-1,j}^{n+\frac{1}{2}} \right) \left(y_{i-1,j}^n - y_{i,j}^n \right) \right. \right. \\
 & \left. \left. - \left(\tilde{y}_{i,j}^{n+\frac{1}{2}} + \tilde{y}_{i-1,j}^{n+\frac{1}{2}} \right) \left(x_{i-1,j}^n - x_{i,j}^n \right) \right] \right. \\
 & + \left(r_{i-1,j}^n + r_{i-1,j-1}^n \right) \left[\left(\tilde{x}_{i-1,j}^{n+\frac{1}{2}} + \tilde{x}_{i-1,j-1}^{n+\frac{1}{2}} \right) \left(y_{i-1,j-1}^n - y_{i-1,j}^n \right) \right. \\
 & \left. \left. - \left(\tilde{y}_{i-1,j}^{n+\frac{1}{2}} + \tilde{y}_{i-1,j-1}^{n+\frac{1}{2}} \right) \left(x_{i-1,j-1}^n - x_{i-1,j}^n \right) \right] \right. \\
 & + \left(r_{i-1,j-1}^n + r_{i,j-1}^n \right) \left[\left(\tilde{x}_{i-1,j-1}^{n+\frac{1}{2}} + \tilde{x}_{i,j-1}^{n+\frac{1}{2}} \right) \left(y_{i,j-1}^n - y_{i-1,j-1}^n \right) \right. \\
 & \left. \left. - \left(\tilde{y}_{i-1,j-1}^{n+\frac{1}{2}} + \tilde{y}_{i,j-1}^{n+\frac{1}{2}} \right) \left(x_{i,j-1}^n - x_{i-1,j-1}^n \right) \right] \right. \\
 & + \left(r_{i,j-1}^n + r_{i,j}^n \right) \left[\left(\tilde{x}_{i,j-1}^{n+\frac{1}{2}} + \tilde{x}_{i,j}^{n+\frac{1}{2}} \right) \left(y_{i,j}^n - y_{i,j-1}^n \right) \right. \\
 & \left. \left. - \left(\tilde{y}_{i,j-1}^{n+\frac{1}{2}} + \tilde{y}_{i,j}^{n+\frac{1}{2}} \right) \left(x_{i,j}^n - y_{i,j-1}^n \right) \right] \right\} , \quad (5.8)
 \end{aligned}$$

where

$$r_{i,j}^n = \begin{Bmatrix} 1 \\ 2\pi x_{i,j}^n \end{Bmatrix} \quad \text{when} \quad f = \begin{Bmatrix} 0 \\ 1 \end{Bmatrix} .$$

In this equation, the positions, densities, and masses are centered at time n in contrast to the velocities which are centered at the advanced time. This is done to simplify the actual computerized solution of these equations. For low speed flow problems of the type for which this version of the code was intended, the error introduced by this approximation is

negligible because the positions and velocities change very little in one cycle.

The result of Eq.(5.8) can be integrated to determine the change in relative volume,

$$\Delta V_{i-\frac{1}{2}}^{n+\frac{1}{2}} = V_{i-\frac{1}{2}}^n \Delta t^{n+\frac{1}{2}} (\tilde{V}/V)_{i-\frac{1}{2}}^{n+\frac{1}{2}} . \quad (5.9)$$

This becomes approximately a backward differenced equation as $(\tilde{V}/V)^{n+\frac{1}{2}}$ approaches the final value of $(\dot{V}/V)^{n+1}$. Backward differencing is used here so that this calculation will be compatible with the eventual calculation of the updated positions from the velocities. This also uses backward differencing (described in Section 5.4.3). Next we calculate the change in compression,

$$\Delta C_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} = - \Delta V_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} \quad (5.10)$$

and the new compression

$$C_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} = C_{i-\frac{1}{2},j-\frac{1}{2}}^n + \Delta C_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} . \quad (5.11)$$

The new relative volume is

$$V_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} = 1 - C_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} , \quad (5.12)$$

and the density is

$$\rho_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} = \rho_{i-\frac{1}{2},j-\frac{1}{2}}^0 / V_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} . \quad (5.13)$$

This method of computing relative volume and density by using the calculation of compression as an intermediate step is done to minimize round-off error. This is discussed in Section 4.2.4 of Volume 1.

5.4.2 Newton-Raphson Equation. For the incompressible flow version the objective of the implicit phase of the calculation is to calculate a velocity field such that $\tilde{\dot{V}}/V \simeq 0$. This is done by means of a Newton-Raphson iteration. If the volume strain rate calculated as described in the previous section exceeds some specified small number ϵ , then a pressure increment, δp , is calculated from the Newton-Raphson equation. This is then used in the momentum equations to calculate a new velocity field. This process is repeated until

$$(\tilde{\dot{V}}/V)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} \leq \epsilon . \quad (5.14)$$

The Newton-Raphson equation for the pressure increment is

$$\delta p_{i-\frac{1}{2},j-\frac{1}{2}} = - \omega \left[(\tilde{\dot{V}}/V)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} \right] / \left[\frac{\partial (\tilde{\dot{V}}/V)_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} \right] , \quad (5.15)$$

where ω is the relaxation factor used to accelerate the convergence of the iteration. The acceptable range for ω is $1 \leq \omega < 2$; for $\omega \leq 1$, an unstable iteration results.

The derivative in the denominator of Eq.(5.15) can be evaluated as follows:

$$\frac{\partial (\tilde{\dot{V}}/V)_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} = \sum_{\ell=1}^4 \left[\frac{\partial (\tilde{\dot{V}}/V)_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial \tilde{x}_{\ell}} \frac{\partial \tilde{x}_{\ell}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} + \frac{\partial (\tilde{\dot{V}}/V)_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial \tilde{y}_{\ell}} \frac{\partial \tilde{y}_{\ell}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} \right] , \quad (5.16)$$

where ℓ indicates the four corners of the cell $(i-\frac{1}{2}, j-\frac{1}{2})$. The derivatives of the velocity strain rate in this expression are derived from Eq.(5.8). The method of writing $\dot{\tilde{V}}/V$ in terms of $\nabla \cdot \dot{\tilde{x}}$ as described in the previous section facilitates obtaining these terms. They are

$$\frac{\partial(\tilde{V}/V)_{i-\frac{1}{2}, j-\frac{1}{2}}}{\partial \tilde{x}_{i,j}} = \frac{\rho_{i-\frac{1}{2}, j-\frac{1}{2}}^n}{4m_{i-\frac{1}{2}, j-\frac{1}{2}}^n} \left\{ \left(r_{i,j}^n + r_{i-1,j}^n \right) \left(y_{i-1,j}^n - y_{i,j}^n \right) \right. \\ \left. + \left(r_{i,j-1}^n - r_{i,j}^n \right) \left(y_{i,j}^n - y_{i,j-1}^n \right) \right\},$$

$$\frac{\partial(\tilde{V}/V)_{i-\frac{1}{2}, j-\frac{1}{2}}}{\partial \tilde{x}_{i-1,j}} = \frac{\rho_{i-\frac{1}{2}, j-\frac{1}{2}}^n}{4m_{i-\frac{1}{2}, j-\frac{1}{2}}^n} \left\{ \left(r_{i-1,j}^n + r_{i-1,j-1}^n \right) \left(y_{i-1,j-1}^n - y_{i-1,j}^n \right) \right. \\ \left. + \left(r_{i,j}^n + r_{i-1,j}^n \right) \left(y_{i-1,j}^n - y_{i,j}^n \right) \right\},$$

$$\frac{\partial(\tilde{V}/V)_{i-\frac{1}{2}, j-\frac{1}{2}}}{\partial \tilde{x}_{i-1,j-1}} = \frac{\rho_{i-\frac{1}{2}, j-\frac{1}{2}}^n}{4m_{i-\frac{1}{2}, j-\frac{1}{2}}^n} \left\{ \left(r_{i-1,j-1}^n + r_{i,j-1}^n \right) \left(y_{i,j-1}^n - y_{i-1,j-1}^n \right) \right. \\ \left. + \left(r_{i-1,j}^n + r_{i-1,j-1}^n \right) \left(y_{i-1,j-1}^n - y_{i-1,j}^n \right) \right\},$$

$$\frac{\partial(\tilde{V}/V)_{i-\frac{1}{2}, j-\frac{1}{2}}}{\partial \tilde{x}_{i,j-1}} = \frac{\rho_{i-\frac{1}{2}, j-\frac{1}{2}}^n}{4m_{i-\frac{1}{2}, j-\frac{1}{2}}^n} \left\{ \left(r_{i,j-1}^n + r_{i,j}^n \right) \left(y_{i,j}^n - y_{i,j-1}^n \right) \right. \\ \left. + \left(r_{i-1,j-1}^n + r_{i,j-1}^n \right) \left(y_{i,j-1}^n - y_{i-1,j-1}^n \right) \right\},$$

$$\begin{aligned}
\frac{\partial (\tilde{V}/V)_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial \tilde{y}_{i,j}} &= \frac{\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n}{4m_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ \begin{pmatrix} r_{i,j}^n & + r_{i-1,j}^n \end{pmatrix} \begin{pmatrix} x_{i-1,j}^n & - x_{i,j}^n \end{pmatrix} \right. \\
&\quad \left. + \begin{pmatrix} r_{i,j-1}^n & + r_{i,j}^n \end{pmatrix} \begin{pmatrix} x_{i,j}^n & - x_{i,j-1}^n \end{pmatrix} \right\}, \\
\frac{\partial (\tilde{V}/V)_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial \tilde{y}_{i-1,j}} &= \frac{\rho_{i-p,j-\frac{1}{2}}^n}{4m_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ \begin{pmatrix} r_{i-1,j}^n & + r_{i-1,j-1}^n \end{pmatrix} \begin{pmatrix} x_{i-1,j-1}^n & - x_{i-1,j}^n \end{pmatrix} \right. \\
&\quad \left. + \begin{pmatrix} r_{i,j}^n & + r_{i-1,j}^n \end{pmatrix} \begin{pmatrix} x_{i-1,j}^n & - x_{i,j}^n \end{pmatrix} \right\}, \\
\frac{\partial (\tilde{V}/V)_{i-p,j-\frac{1}{2}}}{\partial \tilde{y}_{i-1,j-1}} &= \frac{\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n}{4m_{i-1,j-1}^n} \left\{ \begin{pmatrix} r_{i-1,j-1}^n & + r_{i,j-1}^n \end{pmatrix} \begin{pmatrix} x_{i,j-1}^n & - x_{i-1,j-1}^n \end{pmatrix} \right. \\
&\quad \left. + \begin{pmatrix} r_{i-1,j}^n & + r_{i-1,j-1}^n \end{pmatrix} \begin{pmatrix} x_{i-1,j-1}^n & - x_{i-1,j}^n \end{pmatrix} \right\}, \\
\frac{\partial (\tilde{V}/V)_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial \tilde{y}_{i,j-1}} &= \frac{\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n}{4m_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ \begin{pmatrix} r_{i,j-1}^n & + r_{i,j}^n \end{pmatrix} \begin{pmatrix} x_{i,j}^n & - x_{i,j-1}^n \end{pmatrix} \right. \\
&\quad \left. + \begin{pmatrix} r_{i-1,j-1}^n & + r_{i,j-1}^n \end{pmatrix} \begin{pmatrix} x_{i,j-1}^n & - x_{i-1,j-1}^n \end{pmatrix} \right\}.
\end{aligned}$$

(5.17)

The derivatives of the velocities in terms of the pressure are derived from the momentum equations (5.5). These terms are

$$\begin{aligned}
\frac{\partial \tilde{x}_{i,j}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} &= - \frac{\Delta t^{n+\frac{1}{2}}}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left(y_{i,j-1}^n - y_{i-1,j}^n \right) , \\
\frac{\partial \tilde{x}_{i-1,j}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} &= - \frac{\Delta t^{n+\frac{1}{2}}}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left(y_{i,j}^n - y_{i-1,j-1}^n \right) , \\
\frac{\partial \tilde{x}_{i-1,j-1}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} &= - \frac{\Delta t^{n+\frac{1}{2}}}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left(y_{i-1,j}^n - y_{i,j-1}^n \right) , \\
\frac{\partial \tilde{x}_{i,j-1}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} &= - \frac{\Delta t^{n+\frac{1}{2}}}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left(y_{i-1,j-1}^n - y_{i,j}^n \right) , \\
\frac{\partial \tilde{y}_{i,j}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} &= \frac{\Delta t^{n+\frac{1}{2}}}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left(x_{i,j-1}^n - x_{i-1,j}^n \right) , \\
\frac{\partial \tilde{y}_{i-1,j}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} &= \frac{\Delta t^{n+\frac{1}{2}}}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left(x_{i,j}^n - x_{i-1,j-1}^n \right) , \\
\frac{\partial \tilde{y}_{i-1,j-1}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} &= \frac{\Delta t^{n+\frac{1}{2}}}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left(x_{i-1,j}^n - x_{i,j-1}^n \right) , \\
\frac{\partial \tilde{y}_{i,j-1}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} &= \frac{\Delta t^{n+\frac{1}{2}}}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left(x_{i-1,j-1}^n - x_{i,j}^n \right) .
\end{aligned}$$

(5.18)

For the implicit, compressible flow versions, the objective is to calculate a velocity field such that the pressure p (used in the momentum equation) is equal to the equation of state pressure p' , calculated using $\dot{V}/V$ derived from the velocity field. Therefore we define the variable

$$W_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} = p_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} - (p')_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} , \quad (5.19)$$

where $p_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1}$ is the pressure used in the momentum equation and $(p')_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1}$ is the equation of state pressure

$$(p')_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} = p'(\tilde{V}_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1}, u_{i-\frac{1}{2},j-\frac{1}{2}}^n) . \quad (5.20)$$

If W exceeds some small number, then, as in the case of the incompressible flow version, a pressure increment calculated from the Newton-Raphson equation is used in a form of the momentum equation to calculate a new velocity field.

The Newton-Raphson equation for the implicit, compressible flow version is

$$\delta p_{i-\frac{1}{2},j-\frac{1}{2}} = - \omega W_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} / \left(\frac{\partial W_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} \right) . \quad (5.21)$$

In this case, although the normal range for ω is $1 \leq \omega \leq 2$, in some cases it may turn out that $\omega < 1$ gives acceptable results. This is discussed further in Section 6.3.4.

The derivative in the denominator of Eq.(5.21) can be evaluated as follows:

$$\frac{\partial W_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} = 1 - \frac{\partial p'_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} = 1 - \frac{\partial p'_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial (\tilde{V}/V)_{i-\frac{1}{2},j-\frac{1}{2}}} \frac{\partial (\tilde{V}/V)_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial p_{i-\frac{1}{2},j-\frac{1}{2}}} \quad (5.22)$$

In this equation, the derivative of $\tilde{V}/V$ with respect to p is evaluated from Eq.(5.16) while the derivative of p' with respect to $\tilde{V}/V$ is calculated from the equation of state, Eq.(5.20).

Once the pressure increment has been calculated, using either Eq.(5.15) or Eq.(5.21), the pressure is updated,

$$p_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1}(\text{new}) = p_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1}(\text{old}) + \delta p_{i-\frac{1}{2},j-\frac{1}{2}} \quad (5.23)$$

In the first iteration cycle, the old pressure in Eq.(5.23) is the pressure that existed at the start of the time step, i.e.,

$$p_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1}(\text{old}) = p_{i-\frac{1}{2},j-\frac{1}{2}}^n$$

Thereafter, $p_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1}$ is updated by $\delta p_{i-\frac{1}{2},j-\frac{1}{2}}$ on each iteration cycle until convergence is achieved.

5.4.3 Momentum Equation. Once a pressure increment for a zone has been calculated from the Newton-Raphson equation, it is then used in a modified form of the momentum equation, Eq.(5.2) to calculate new velocities. In Eqs.(5.2) and (5.5) the acceleration of a grid point produced by the pressures in the surrounding zones is calculated. In this phase, however, we calculate the change in velocity of the four grid points at each corner of a zone produced by the pressure increment in that zone. This procedure is used primarily for computational convenience. The net

effect is the same as is achieved in Eqs.(5.2), and (5.5) since by sweeping through the mesh we pick up the contributions to the grid point velocity change from the pressure increments in the four adjacent zones.

The velocity changes are calculated from the modified momentum equation as follows:

$$\begin{aligned}
\delta \tilde{x}_{i,j} &= \frac{1}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ -\delta p_{i-\frac{1}{2},j-\frac{1}{2}} (y_{i,j-1}^n - y_{i-1,j}^n) \right\}, \\
\delta \tilde{x}_{i-1,j} &= \frac{1}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ -\delta p_{i-\frac{1}{2},j-\frac{1}{2}} (y_{i,j}^n - y_{i-1,j-1}^n) \right\}, \\
\delta \tilde{x}_{i-1,j-1} &= \frac{1}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ -\delta p_{i-\frac{1}{2},j-\frac{1}{2}} (y_{i-1,j}^n - y_{i,j-1}^n) \right\}, \\
\delta \tilde{x}_{i,j-1} &= \frac{1}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ -\delta p_{i-\frac{1}{2},j-\frac{1}{2}} (y_{i-1,j-1}^n - y_{i,j}^n) \right\}, \\
\delta \tilde{y}_{i,j} &= \frac{1}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ \delta p_{i-\frac{1}{2},j-\frac{1}{2}} (x_{i,j-1}^n - x_{i-1,j}^n) \right\}, \\
\delta \tilde{y}_{i-1,j} &= \frac{1}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ \delta p_{i-\frac{1}{2},j-\frac{1}{2}} (x_{i,j}^n - x_{i-1,j-1}^n) \right\}, \\
\delta \tilde{y}_{i-1,j-1} &= \frac{1}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ \delta p_{i-\frac{1}{2},j-\frac{1}{2}} (x_{i-1,j}^n - x_{i,j-1}^n) \right\}, \\
\delta \tilde{y}_{i,j-1} &= \frac{1}{2\rho_{i-\frac{1}{2},j-\frac{1}{2}}^n A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left\{ \delta p_{i-\frac{1}{2},j-\frac{1}{2}} (x_{i-1,j-1}^n - x_{i,j}^n) \right\}. \quad (5.24)
\end{aligned}$$

As we did in the case of the mass equation, Eq.(5.8), the positions and densities in Eq.(5.24) are centered at time n (as is the area which is calculated from the positions). This is done for computational convenience and introduces a negligible error because the positions and densities change very little in one cycle.

Once the velocity increments are calculated, a new set of velocities can then be calculated as follows:

$$\begin{aligned}
\tilde{x}_{i,j}^{n+\frac{1}{2}}(\text{new}) &= \tilde{x}_{i,j}^{n+\frac{1}{2}}(\text{old}) + \delta\tilde{x}_{i,j} \quad , \\
\tilde{x}_{i-1,j}^{n+\frac{1}{2}}(\text{new}) &= \tilde{x}_{i-1,j}^{n+\frac{1}{2}}(\text{old}) + \delta\tilde{x}_{i-1,j} \quad , \\
\tilde{x}_{i-1,j-1}^{n+\frac{1}{2}}(\text{new}) &= \tilde{x}_{i-1,j-1}^{n+\frac{1}{2}}(\text{old}) + \delta\tilde{x}_{i-1,j-1} \quad , \\
\tilde{x}_{i,j-1}^{n+\frac{1}{2}}(\text{new}) &= \tilde{x}_{i,j-1}^{n+\frac{1}{2}}(\text{old}) + \delta\tilde{x}_{i,j-1} \quad , \\
\tilde{y}_{i,j}^{n+\frac{1}{2}}(\text{new}) &= \tilde{y}_{i,j}^{n+\frac{1}{2}}(\text{old}) + \delta\tilde{y}_{i,j} \quad , \\
\tilde{y}_{i-1,j}^{n+\frac{1}{2}}(\text{new}) &= \tilde{y}_{i-1,j}^{n+\frac{1}{2}}(\text{old}) + \delta\tilde{y}_{i-1,j} \quad , \\
\tilde{y}_{i-1,j-1}^{n+\frac{1}{2}}(\text{new}) &= \tilde{y}_{i-1,j-1}^{n+\frac{1}{2}}(\text{old}) + \delta\tilde{y}_{i-1,j-1} \quad , \\
\tilde{y}_{i,j-1}^{n+\frac{1}{2}}(\text{new}) &= \tilde{y}_{i,j-1}^{n+\frac{1}{2}}(\text{old}) + \delta\tilde{y}_{i,j-1} \quad .
\end{aligned} \tag{5.25}$$

5.4.4 Convergence. The iterative process described above is repeated until either the volume strain rate or the pressure difference approaches zero, i.e., until

$$(\tilde{V}/V)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} \leq \epsilon$$

or

$$w_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} \leq \epsilon \quad p_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} \quad , \quad (5.14)$$

where ϵ is a small number (input constant); the actual value used for ϵ is problem-dependent. When convergence is reached, the velocities and pressures have achieved their $n+1$ values so that we can write

$$\dot{x}_{i,j}^{n+1} = \tilde{x}_{i,j}^{n+\frac{1}{2}} \quad ,$$

$$\dot{y}_{i,j}^{n+1} = \tilde{y}_{i,j}^{n+\frac{1}{2}} \quad .$$

The new positions are then calculated from a backward-differenced integration,

$$x_{i,j}^{n+1} = x_{i,j}^n + \dot{x}_{i,j}^{n+1} \Delta t^{n+\frac{1}{2}} \quad ,$$

$$y_{i,j}^{n+1} = y_{i,j}^n + \dot{y}_{i,j}^{n+1} \Delta t^{n+\frac{1}{2}} \quad . \quad (5.26)$$

A centered integration could have been used here, but experience has shown that it does not result in a substantial increase in accuracy and that it can have an adverse effect on stability.

At this point a new set of pressures, velocities, positions and densities at time $n+1$ have been obtained. For the inviscid, incompressible

flow version a Lagrangian cycle has been completed. Either the updated variables can be used as initial conditions for the next time step (if a purely Lagrangian calculation is desired) or the rezone/convection phase can be calculated as described in Section 5.5. For the viscous, incompressible flow version and the compressible flow version, however, we still need to calculate the remaining variables that are centered in the stress mesh. This includes calculation of the individual strain rates and the viscous stresses in both versions and the artificial viscosity as well as the solution of the Lagrangian internal energy equation (including heat conduction) in the compressible flow version. This is described below in Sections 5.4.6 - 5.4.8. However, first we discuss a modification to the implicit iteration for highly nonlinear problems.

5.4.5 Two-Sided Secant Iteration. In some cases in which the fluid exhibits highly nonlinear behavior (e.g., near the saturated liquid phase line in a steam-water phase transition) the Newton-Raphson iteration method may converge slowly or may even diverge. In these situations a two-sided secant method provides more rapid convergence.

This method is shown graphically in Figure 4.3. In this figure the pressure difference $W = p - p'$ is plotted on the ordinate with the pressure p on the abscissa. The solid curve represents the function $W(p)$ for which we are trying to find the point $W = 0$. Three points in the W, p plane are required; points 1 and 2 must bound the solution $W = 0$, and point 3 must lie between them. Secants are constructed through points 1 and 3 and points 2 and 3 which intersect the $W = 0$ axis at p_A and p_B , respectively. The new pressure p_{new} is then calculated to be the average of these two pressures, and the pressure increment δp is calculated from the difference between this pressure and the one obtained on the previous iteration. The new point $W(p_{\text{new}})$ is then used as one of the required three points and point 2 is discarded.

When the two-sided secant method is used, it is applied to each cell individually in what we call an internal iteration as opposed to the global iteration described previously which involves a sweep through the entire mesh on each iteration cycle. In the first internal iteration cycle, the Newton-Raphson method is used to obtain the second point in the W, p plane. (The first point is obtained by using p and p' either from the explicit phase or from the previous global iteration.) Those two points are used with a single-sided secant method in the second internal iteration to obtain the third point. In the third and subsequent internal iterations the two-sided secant method is used.

The internal iteration is used to achieve convergence for each cell individually. However, because the cells are not independent, this does not guarantee that global convergence will be achieved. Therefore, this process is repeated in a global iteration until overall convergence is obtained.

5.4.6 Artificial Viscosity. In some cases where real viscosity effects are not included it is necessary to use an artificial viscosity to permit the calculation of large strain rate phenomena (particularly shock waves) in a finite-difference code. Although the versions described in this volume are intended for use on problems involving low-speed, small strain-rate flows, we have included the option of using artificial viscosity. In most cases of interest for these codes, it should not be needed. However, it is included so that it will be available for those few cases where it might be required.

The artificial viscosity formulation used in these codes is identical to that used in the explicit versions of STEALTH. It is described in detail in Section 5.3.1 of Volume 1. The reader is referred to that volume if details of the formulation are required.

5.4.7 Viscous Stresses. In Section 2.2.2, Eq.(2.13), we wrote the equation for the viscous stresses in tensor notation. In component form the principal stresses can be written

$$\begin{aligned}
 (s_{xx})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} &= 2\zeta(\dot{\epsilon}_{xx})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} + \lambda(\dot{V}/V)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} \\
 (s_{yy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} &= 2\zeta(\dot{\epsilon}_{yy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} + \lambda(\dot{V}/V)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} \\
 (s_{zz})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} &= 2\zeta(\dot{\epsilon}_{zz})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} + \lambda(\dot{V}/V)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} \\
 (s_{xy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} &= \zeta(\dot{\epsilon}_{xy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1}
 \end{aligned} \tag{5.27}$$

where the $\dot{\epsilon}_{xx}$, etc., are the components of the strain rate tensor. The equations for the x- and y-components of the strain rate tensor are

$$\begin{aligned}
 (\dot{\epsilon}_{xx})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} &= \left(\frac{\partial x}{\partial x} \right)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} \\
 &= \frac{1}{2A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left[\left(\dot{x}_{i,j-1}^{n+\frac{1}{2}} - \dot{x}_{i-1,j}^{n+\frac{1}{2}} \right) \left(y_{i,j}^{n+\frac{1}{2}} - y_{i-1,j-1}^{n+\frac{1}{2}} \right) \right. \\
 &\quad \left. - \left(\dot{x}_{i,j}^{n+\frac{1}{2}} - \dot{x}_{i-1,j-1}^{n+\frac{1}{2}} \right) \left(y_{i,j-1}^{n+\frac{1}{2}} - y_{i-1,j}^{n+\frac{1}{2}} \right) \right], \tag{5.28a}
 \end{aligned}$$

$$\begin{aligned}
 (\dot{\epsilon}_{yy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} &= \left(\frac{\partial y}{\partial y} \right)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} \\
 &= -\frac{1}{2A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left[\left(\dot{y}_{i,j-1}^{n+\frac{1}{2}} - \dot{y}_{i-1,j}^{n+\frac{1}{2}} \right) \left(x_{i,j}^{n+\frac{1}{2}} - x_{i-1,j-1}^{n+\frac{1}{2}} \right) \right. \\
 &\quad \left. - \left(\dot{y}_{i,j}^{n+\frac{1}{2}} - \dot{y}_{i-1,j-1}^{n+\frac{1}{2}} \right) \left(x_{i,j-1}^{n+\frac{1}{2}} - x_{i-1,j}^{n+\frac{1}{2}} \right) \right], \tag{5.28b}
 \end{aligned}$$

and the shear strain rate is given by

$$\begin{aligned}
 (\dot{\epsilon}_{xy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} &= \left(\frac{\partial \dot{y}}{\partial x} + \frac{\partial \dot{x}}{\partial y} \right)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} \\
 &= \frac{1}{2A_{i-\frac{1}{2},j-\frac{1}{2}}^n} \left[\left(\dot{y}_{i,j-1}^{n+\frac{1}{2}} - \dot{y}_{i-1,j}^{n+\frac{1}{2}} \right) \left(y_{i,j}^{n+\frac{1}{2}} - y_{i-1,j-1}^{n+\frac{1}{2}} \right) \right. \\
 &\quad - \left(\dot{y}_{i,j}^{n+\frac{1}{2}} - \dot{y}_{i-1,j-1}^{n+\frac{1}{2}} \right) \left(y_{i,j-1}^{n+\frac{1}{2}} - y_{i-1,j}^{n+\frac{1}{2}} \right) \\
 &\quad - \left(\dot{x}_{i,j-1}^{n+\frac{1}{2}} - \dot{x}_{i-1,j}^{n+\frac{1}{2}} \right) \left(x_{i,j}^{n+\frac{1}{2}} - x_{i-1,j-1}^{n+\frac{1}{2}} \right) \\
 &\quad \left. + \left(\dot{x}_{i,j}^{n+\frac{1}{2}} - \dot{x}_{i-1,j-1}^{n+\frac{1}{2}} \right) \left(x_{i,j-1}^{n+\frac{1}{2}} - x_{i-1,j}^{n+\frac{1}{2}} \right) \right] .
 \end{aligned} \tag{5.28c}$$

The remaining strain rate component depends on symmetry. In planar symmetry it is zero,

$$(\dot{\epsilon}_{zz})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} = \left(\frac{\partial \dot{z}}{\partial z} \right)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} = 0 , \tag{5.28d}$$

where z is the coordinate perpendicular to the x,y plane. For axial symmetry the tangential strain rate is given by

$$(\dot{\epsilon}_{zz})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} = \left(\frac{\partial \dot{z}}{\partial z} \right)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} = \left(\frac{\dot{V}}{V} \right)_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} - (\dot{\epsilon}_{xx})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} - (\dot{\epsilon}_{yy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} , \tag{5.28e}$$

where, in this case, x is the radial coordinate, y is the axial coordinate, and z is the tangential or angular coordinate.

5.4.8 Internal Energy Equation. In the explicit versions of STEALTH the internal energy equation is solved using a one-step iteration to improve the accuracy, i.e., to provide a degree of "implicitness" to the solution. (See Section 5.3.4 of Volume 1.) In the versions described here the one-step iteration is omitted because the stresses used in the internal energy equation are already centered at time $n+1$ as a result of the implicit solution of the momentum equation. During the solution of the momentum equation, however, the energies used in the pressure equation of state, $p(u,V)$, were centered at time n so that the coupling of the energy equation with the momentum equation is explicit. In general, for the types of flow situations for which these codes have been designed (i.e., low speed, small strain-rate flows), this should not introduce any significant error into the solution.

In some cases it is desirable to run the implicit, compressible flow versions in an explicit mode for some short time, perhaps during an initial transient period of a problem. In that case the iterative second phase of the solution is omitted, and we proceed directly from the explicit, Lagrange phase (Section 5.3) to the calculations of the artificial viscosity, the viscous stresses and the Lagrange internal energy equation. In this case the one-step iteration is used in the solution of the energy equation. See Section 5.3.4 of Volume 1 for details of that method of solution. Below we provide a description of the solution of the internal energy equation as it is used for implicit calculations.

The internal energy equation may be written as follows.

$$\begin{aligned}
 u_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} = & u_{i-\frac{1}{2},j-\frac{1}{2}}^n - \left(p_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} + q_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} \right) \Delta V_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} \\
 & + \Delta Z_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} + \Delta h_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} + \Delta U_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} . \quad (5.29)
 \end{aligned}$$

In this equation $p^{n+\frac{1}{2}}$ and $q^{n+\frac{1}{2}}$ are averages of quantities at times n and $n+1$; ΔV is defined in Eq.(4.8); and ΔZ , Δh , and ΔU represent changes in the internal energy from viscosity, heat conduction and heat sources or sinks, respectively. The viscous energy term can be written

$$\begin{aligned}
 \Delta Z_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} = & V_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} \Delta t^{n+\frac{1}{2}} \left[(s_{xx})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} (\dot{\epsilon}_{xx})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} \right. \\
 & + (s_{yy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} (\dot{\epsilon}_{yy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} \\
 & + (s_{zz})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} (\dot{\epsilon}_{zz})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} \\
 & \left. + (s_{xy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} (\dot{\epsilon}_{xy})_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} \right] . \quad (5.30)
 \end{aligned}$$

The heat conduction term is computed by solving the heat conduction equation (diffusion equation). The method used here is identical to that used in other versions of the STEALTH codes and described in Section 5.3.4 of Volume 1. The reader is referred to that volume for details of the calculation. The source energy density term is determined from a time dependent function

$$\Delta S_{i-\frac{1}{2},j-\frac{1}{2}}^{n+\frac{1}{2}} = \Delta S_{i-\frac{1}{2},j-\frac{1}{2}}(t^{n+\frac{1}{2}}, \Delta t^{n+\frac{1}{2}}) . \quad (5.31)$$

5.5 TIME STEP CALCULATION

In the explicit versions of STEALTH, a stable time step is calculated for each cycle based on stability criteria related to the sound speed, the artificial viscosity, and heat flow. This is described in Section 5.4 of Volume 1. In the implicit versions described here a stable time step is also calculated. Since the calculations of artificial viscosity and heat flow are treated identically in the different versions, the dependence of the stable time step on those quantities is also treated identically. However, for an implicit solution of the momentum equation, the stable time step is not limited by the sound speed. If effects such as artificial viscosity, real viscosity or heat conduction are ignored, the linearized equations can be shown to be unconditionally stable. In practice the equations do not turn out to be stable for all time steps. Experience has shown, however, that the solution usually will be stable if the material is not permitted to move more than one zone width in a time step. Therefore, a reasonable stability criterion for the mechanical equations can be obtained by replacing the sound speed in the explicit stability criterion by the material velocity. The resultant criterion, is

$$(\Delta t_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1})^2 = \frac{(\Delta l_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1})^2}{(\dot{x}_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1})^2 + (\dot{y}_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1})^2 + (c_q^2)_{i-\frac{1}{2},j-\frac{1}{2}}}, \quad (5.32)$$

where c_q is an equivalent speed calculated for the artificial viscosity effects (see Eq.(5.54) of Volume 1), Δl is the distance across a zone in the direction of the zone centered velocity vector, and the zone centered velocity components are given by the average of the velocity components at the four corners of the zone. The stable time step for the heat conduction equations is given in Section 5.4.3 of Volume 1. The overall stable time step for a zone is defined to be the minimum of the stable mechanical or thermal time step.

When real viscosity effects are calculated they can have an effect on the stable time step since they are calculated explicitly. However, unless the viscosity coefficients are very large, the other time step criteria dominate. Therefore, we have omitted consideration of this effect in calculating the stable time step.

A stable time step for each zone is calculated as described above. The maximum time step for a cycle is then defined to be the minimum stable time step for all zones in the mesh multiplied by some safety factor (usually $\sim 1/4$). It should be pointed out that accuracy considerations often dictate the use of a smaller time step than would be required for stability. In that case a smaller constant time step can be used. This is explained more completely in Section 6.3.3.

At this point, a new set of variables at time $n+1$ has been obtained. These can either be used as initial conditions for the next time step (if a purely Lagrangian calculation is desired) or the rezone/convection phase can be calculated.

5.6 CONVECTION PHASE

In the previous phases we solved the equations of motion for a fluid for a Lagrangian coordinate system. In this phase we calculate the convection terms that arise in the equations when they are written for a general coordinate system, i.e., one moving at some arbitrary velocity, $\underline{w}$, relative to the fluid. Thus, we are attempting to solve the following equations:

$$\frac{\partial \rho}{\partial t} = \frac{D}{Dt} \rho - (\nabla \cdot \underline{w}) \rho \quad , \quad (3.10)$$

$$\frac{\partial}{\partial t}(\rho \underline{v}) = \frac{D}{Dt}(\rho \underline{v}) - (\nabla \cdot \underline{w})(\rho \underline{v}) \quad , \quad (3.11)$$

and

$$\frac{\partial}{\partial t}(\rho \hat{u}) = \frac{D}{Dt}(\rho \hat{u}) - (\nabla \cdot \underline{w})(\rho \hat{u}) \quad , \quad (3.12)$$

where the terms $\frac{D}{Dt}(\)$ indicate the previously obtained solution for a Lagrangian coordinate system. For the inviscid, incompressible flow version, Eq.(3.12) is omitted since we do not calculate internal energy in that version.

5.6.1 Mesh Velocity. The first step in solving these equations is to compute the velocity of the grid relative to some fixed reference system and the velocity of the fluid relative to that grid. This is written

$$\begin{aligned} \left(w_x \right)_{i,j}^{n+1} &= \dot{x}_{i,j}^{n+1} - \left(\dot{x}_g \right)_{i,j}^{n+1}, \\ \left(w_y \right)_{i,j}^{n+1} &= \dot{y}_{i,j}^{n+1} - \left(\dot{y}_g \right)_{i,j}^{n+1}, \end{aligned} \quad (5.33)$$

where w_x and w_y are the x and y components of the relative fluid velocity and $\dot{x}_g$ and $\dot{y}_g$ are the x and y components of the grid velocity. For a Lagrangian mesh, $\dot{x}_g = \dot{x}$, and $\dot{y}_g = \dot{y}$, so that $w_x = w_y = 0$. For an Eulerian mesh, $\dot{x}_g = \dot{y}_g = 0$, so that $w_x = \dot{x}$ and $w_y = \dot{y}$. Besides these two extremes, the mesh can be moved in any specified manner. Several options are programmed into the code and others can be added easily.

After calculating the grid velocity, we can also calculate new grid point positions,

$$\begin{aligned}
x_{i,j}^{n+1} &= \left(x_L\right)_{i,j}^{n+1} - \left(\dot{x}_g\right)_{i,j}^{n+1} \Delta t^{n+\frac{1}{2}} , \\
y_{i,j}^{n+1} &= \left(y_L\right)_{i,j}^{n+1} - \left(\dot{y}_g\right)_{i,j}^{n+1} \Delta t^{n+\frac{1}{2}} ,
\end{aligned}
\tag{5.34}$$

where x_L and y_L are the updated positions that were calculated at the end of the implicit, Lagrangian phase of the calculation.

At this point, we are ready to evaluate the terms $(\nabla \cdot \underline{w})\rho$, $(\nabla \cdot \underline{w})(\rho \underline{v})$ and $(\nabla \cdot \underline{w})(\rho \hat{u})$ in Eqs.(3.10-3.12).

5.6.2 Mass and Energy Convection. The mass and energy convection equations, Eqs.(3.10) and (3.12), are solved by the surface integral approach as described in Section 3.3.3. This is done by integrating those equations over the zone volume shown in Figure 3.1a and converting the divergence terms into surface integrals by means of Gauss' theorem. The equations then become

$$\frac{\partial m_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial t} = \frac{D}{Dt} m_{i-\frac{1}{2},j-\frac{1}{2}} - \int_S \rho_S (\underline{w} \cdot \underline{n}) dS
\tag{5.35}$$

and

$$\frac{\partial (m \hat{u})_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial t} = \frac{D}{Dt} (m \hat{u})_{i-\frac{1}{2},j-\frac{1}{2}} - \int_S \rho_S \hat{u}_S (\underline{w} \cdot \underline{n}) dS ,
\tag{5.36}$$

where ρ_S and $\hat{u}_S$ are the values of density and internal energy at the surface of the integration volume, i.e., at the boundaries of zone $(i-\frac{1}{2},j-\frac{1}{2})$. Since the mass is constant in a Lagrangian calculation, Eq.(5.35) can be written

$$\frac{\partial m_{i-\frac{1}{2},j-\frac{1}{2}}}{\partial t} = - \int_S \rho_S (\underline{w} \cdot \underline{n}) dS .
\tag{5.37}$$

Note that for the energy convection equation, Eq.(5.36), we are using the internal energy per unit mass ($\hat{u}$) rather than the internal energy per unit initial volume (u) that was used in the previous phases. The conversion is

$$\hat{u}_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} = u_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} / \rho_{i-\frac{1}{2},j-\frac{1}{2}}^0$$

where ρ^0 is the reference density.

The finite-difference forms of these equations could be written in a straightforward way by performing the integrations over the surface of each zone as shown in Figure 3.1a. However, for computational convenience and increased flexibility, a somewhat different but equivalent approach is used. The mass and energy flow resulting from the motion of each grid point relative to the fluid is calculated separately. This is shown schematically in Figure 5.4. The point in the center connected by dashed lines represents the position at the end of the Lagrangian phases. The new (rezoned) position is calculated for that point (connected with solid lines) as is the relative velocity, $\underline{w}_{i,j}^{n+1}$. Then the mass and energy flow produced by that relative velocity is calculated for the four surfaces as shown. This is repeated for each grid point in the mesh so that for each surface, the flow produced by the relative velocity of each adjacent grid point is evaluated and the total flow across each such surface surrounding a zone is also computed. This effectively results in the evaluation of Eqs.(5.36) and (5.37) for each zone.

The main difference between this approach and a more straightforward evaluation of these equations is that in this approach the motion of each grid point relative to the fluid is considered separately. This is done partially for computational convenience, but also because it provides more flexibility in the type of rezone schemes that can be implemented easily and executed efficiently. For example, it facilitates moving single points

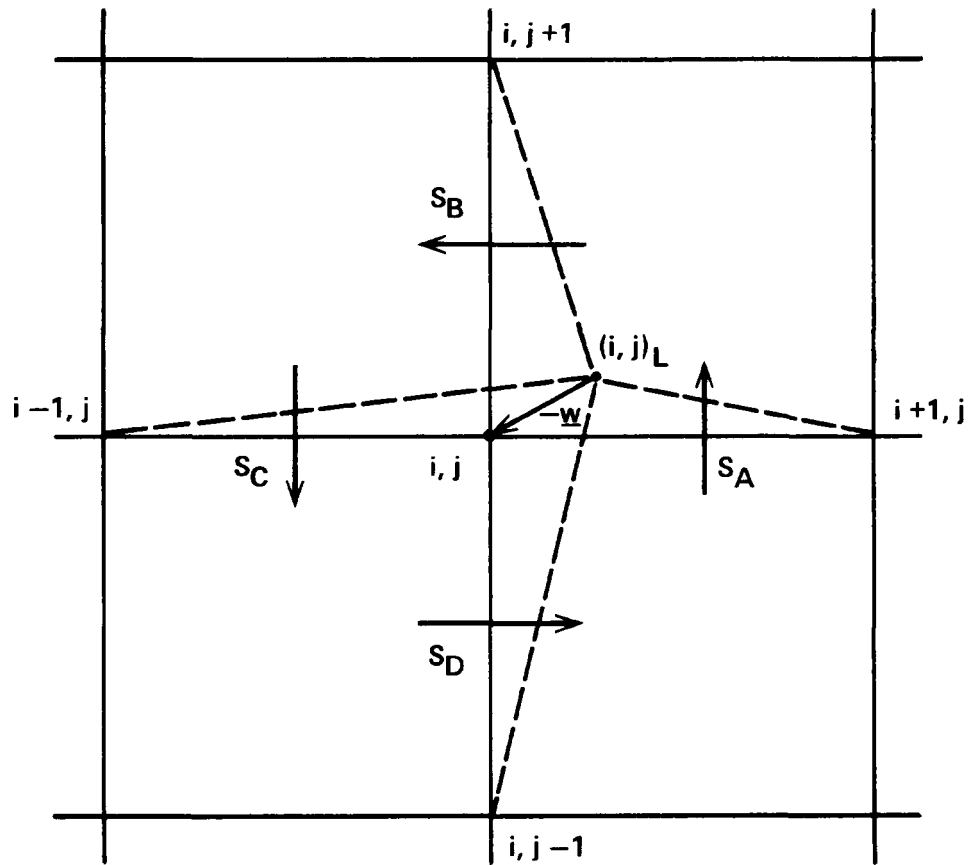


Figure 5.4. Schematic of the procedure for calculating mass convection.

or a few selected points in the grid while allowing the majority to remain as Lagrangian points.

Using this method, the equations equivalent to Eq.(5.37) are

$$\begin{aligned}
\delta m_{i+\frac{1}{2}, j+\frac{1}{2}} &= \left\{ -\rho_A \int_{S_A} (\underline{w} \cdot \underline{n}_A) dS_A - \rho_B \int_{S_B} (\underline{w} \cdot \underline{n}_B) dS_B \right\} \Delta t^{n+\frac{1}{2}}, \\
\delta m_{i-\frac{1}{2}, j+\frac{1}{2}} &= \left\{ -\rho_B \int_{S_B} (\underline{w} \cdot \underline{n}_B) dS_B - \rho_C \int_{S_C} (\underline{w} \cdot \underline{n}_C) dS_C \right\} \Delta t^{n+\frac{1}{2}}, \\
\delta m_{i-\frac{1}{2}, j-\frac{1}{2}} &= \left\{ -\rho_C \int_{S_C} (\underline{w} \cdot \underline{n}_C) dS_C - \rho_D \int_{S_D} (\underline{w} \cdot \underline{n}_D) dS_D \right\} \Delta t^{n+\frac{1}{2}}, \\
\delta m_{i+\frac{1}{2}, j-\frac{1}{2}} &= \left\{ -\rho_D \int_{S_D} (\underline{w} \cdot \underline{n}_D) dS_D - \rho_A \int_{S_A} (\underline{w} \cdot \underline{n}_A) dS_A \right\} \Delta t^{n+\frac{1}{2}}, \quad (5.38)
\end{aligned}$$

and the equations equivalent to Eq.(5.36) are

$$\begin{aligned}
\delta(\hat{m}\hat{u})_{i+\frac{1}{2},j+\frac{1}{2}} &= \left\{ -\rho_A \hat{u}_A \int_{S_A} (\underline{w} \cdot \underline{n}_A) dS_A - \rho_B \hat{u}_B \int_{S_B} (\underline{w} \cdot \underline{n}_B) dS_B \right\} \Delta t^{n+\frac{1}{2}} , \\
\delta(\hat{m}\hat{u})_{i-\frac{1}{2},j+\frac{1}{2}} &= \left\{ -\rho_B \hat{u}_B \int_{S_B} (\underline{w} \cdot \underline{n}_B) dS_B - \rho_C \hat{u}_C \int_{S_C} (\underline{w} \cdot \underline{n}_C) dS_C \right\} \Delta t^{n+\frac{1}{2}} , \\
\delta(\hat{m}\hat{u})_{i-\frac{1}{2},j-\frac{1}{2}} &= \left\{ -\rho_C \hat{u}_C \int_{S_C} (\underline{w} \cdot \underline{n}_C) dS_C - \rho_D \hat{u}_D \int_{S_D} (\underline{w} \cdot \underline{n}_D) dS_D \right\} \Delta t^{n+\frac{1}{2}} , \\
\delta(\hat{m}\hat{u})_{i+\frac{1}{2},j-\frac{1}{2}} &= \left\{ -\rho_D \hat{u}_D \int_{S_D} (\underline{w} \cdot \underline{n}_D) dS_D - \rho_A \hat{u}_A \int_{S_A} (\underline{w} \cdot \underline{n}_A) dS_A \right\} \Delta t^{n+\frac{1}{2}} , \quad (5.39)
\end{aligned}$$

where the surfaces are as shown in Figure 5.4, and the densities and energies are interpolated values at the respective surfaces. In finite-difference form, these equations are written as follows. First, we evaluate the integrals,

$$F_A = \int_{S_A} (\underline{w} \cdot \underline{n}_A) dS_A, \text{ etc.}$$

These are

$$\begin{aligned}
F_A &= r_A \left\{ \frac{1}{2} (w_x)_{i,j}^{n+1} \left[(y_L)_{i,j}^{n+1} - y_{i+1,j}^{n+1} \right] - \frac{1}{2} (w_y)_{i,j}^{n+1} \left[(x_L)_{i,j}^{n+1} - x_{i+1,j}^{n+1} \right] \right\} , \\
F_B &= r_B \left\{ \frac{1}{2} (w_x)_{i,j}^{n+1} \left[(y_L)_{i,j}^{n+1} - y_{i,j+1}^{n+1} \right] - \frac{1}{2} (w_y)_{i,j}^{n+1} \left[(x_L)_{i,j}^{n+1} - x_{i,j+1}^{n+1} \right] \right\} , \\
F_C &= r_C \left\{ \frac{1}{2} (w_x)_{i,j}^{n+1} \left[(y_L)_{i,j}^{n+1} - y_{i-1,j}^{n+1} \right] - \frac{1}{2} (w_y)_{i,j}^{n+1} \left[(x_L)_{i,j}^{n+1} - x_{i-1,j}^{n+1} \right] \right\} , \\
F_D &= r_D \left\{ \frac{1}{2} (w_x)_{i,j}^{n+1} \left[(y_L)_{i,j}^{n+1} - y_{i,j-1}^{n+1} \right] - \frac{1}{2} (w_y)_{i,j}^{n+1} \left[(x_L)_{i,j}^{n+1} - x_{i,j-1}^{n+1} \right] \right\} ,
\end{aligned} \tag{5.40}$$

where

$$\begin{aligned}
r_A &= \frac{2\pi}{3} \left[2(x_L)_{i,j}^{n+1} + x_{i+1,j}^{n+1} \right] , \\
r_B &= \frac{2\pi}{3} \left[2(x_L)_{i,j}^{n+1} + x_{i,j+1}^{n+1} \right] , \\
r_C &= \frac{2\pi}{3} \left[2(x_L)_{i,j}^{n+1} + x_{i-1,j}^{n+1} \right] , \\
r_D &= \frac{2\pi}{3} \left[2(x_L)_{i,j}^{n+1} + x_{i,j-1}^{n+1} \right]
\end{aligned}$$

when $f = 1$ (cylindrical symmetry), and

$$r_A = r_B = r_C = r_D = 1$$

when $f = 0$ (planar symmetry). Then the mass flow across each surface is

$$\begin{aligned}
(\mathcal{F}_m)_A &= \frac{1}{2} \left\{ (1+\theta_A) \rho_{i+\frac{1}{2}, j-\frac{1}{2}}^{n+1} + (1-\theta_A) \rho_{i+\frac{1}{2}, j+\frac{1}{2}}^{n+1} \right\} F_A \Delta t^{n+\frac{1}{2}} , \\
(\mathcal{F}_m)_B &= \frac{1}{2} \left\{ (1+\theta_B) \rho_{i+\frac{1}{2}, j+\frac{1}{2}}^{n+1} + (1-\theta_B) \rho_{i-\frac{1}{2}, j+\frac{1}{2}}^{n+1} \right\} F_B \Delta t^{n+\frac{1}{2}} , \\
(\mathcal{F}_m)_C &= \frac{1}{2} \left\{ (1+\theta_C) \rho_{i-\frac{1}{2}, j+\frac{1}{2}}^{n+1} + (1-\theta_C) \rho_{i-\frac{1}{2}, j-\frac{1}{2}}^{n+1} \right\} F_C \Delta t^{n+\frac{1}{2}} , \\
(\mathcal{F}_m)_D &= \frac{1}{2} \left\{ (1+\theta_D) \rho_{i-\frac{1}{2}, j-\frac{1}{2}}^{n+1} + (1-\theta_D) \rho_{i+\frac{1}{2}, j-\frac{1}{2}}^{n+1} \right\} F_D \Delta t^{n+\frac{1}{2}} , \tag{5.41}
\end{aligned}$$

and the energy flow is

$$\begin{aligned}
(\mathcal{F}_u)_A &= \frac{1}{2} \left\{ (1+\theta_A) (\rho \hat{u})_{i+\frac{1}{2}, j-\frac{1}{2}}^{n+1} + (1-\theta_A) (\rho \hat{u})_{i+\frac{1}{2}, j+\frac{1}{2}}^{n+1} \right\} F_A \Delta t^{n+\frac{1}{2}} , \\
(\mathcal{F}_u)_B &= \frac{1}{2} \left\{ (1+\theta_B) (\rho \hat{u})_{i+\frac{1}{2}, j+\frac{1}{2}}^{n+1} + (1-\theta_B) (\rho \hat{u})_{i-\frac{1}{2}, j+\frac{1}{2}}^{n+1} \right\} F_B \Delta t^{n+\frac{1}{2}} , \\
(\mathcal{F}_u)_C &= \frac{1}{2} \left\{ (1+\theta_C) (\rho \hat{u})_{i-\frac{1}{2}, j+\frac{1}{2}}^{n+1} + (1-\theta_C) (\rho \hat{u})_{i-\frac{1}{2}, j-\frac{1}{2}}^{n+1} \right\} F_C \Delta t^{n+\frac{1}{2}} , \\
(\mathcal{F}_u)_D &= \frac{1}{2} \left\{ (1+\theta_D) (\rho \hat{u})_{i-\frac{1}{2}, j-\frac{1}{2}}^{n+1} + (1-\theta_D) (\rho \hat{u})_{i+\frac{1}{2}, j-\frac{1}{2}}^{n+1} \right\} F_D \Delta t^{n+\frac{1}{2}} . \tag{5.42}
\end{aligned}$$

The sign convention in Eqs.(5.40-5.42) gives positive fluxes in the counter-clockwise direction around point (i,j) as shown.

The θ 's in Eqs.(5.41) and (5.42) determine the space-centering of the densities. They are given by

$$\theta_A = \begin{cases} + \theta_z & \text{if } F_A > 0 \\ - \theta_z & \text{if } F_A < 0 \end{cases} \tag{5.43}$$

with corresponding expressions for the other three θ 's. The value of θ_Z (an input constant) then determines the centering:

$$\begin{aligned}\theta_Z &= 0 && \text{centered,} \\ \theta_Z &= 1 && \text{donor cell,} \\ 0 < \theta_Z < 1 && \text{interpolated donor cell.}\end{aligned}$$

The mass change of each cell is

$$\begin{aligned}\delta m_{i+\frac{1}{2}, j+\frac{1}{2}} &= (\mathcal{F}_m)_A - (\mathcal{F}_m)_B, \\ \delta m_{i-\frac{1}{2}, j+\frac{1}{2}} &= (\mathcal{F}_m)_B - (\mathcal{F}_m)_C, \\ \delta m_{i-\frac{1}{2}, j-\frac{1}{2}} &= (\mathcal{F}_m)_C - (\mathcal{F}_m)_D, \\ \delta m_{i+\frac{1}{2}, j-\frac{1}{2}} &= (\mathcal{F}_m)_D - (\mathcal{F}_m)_A,\end{aligned}\tag{5.44}$$

and the energy changes are

$$\begin{aligned}\delta(\hat{m}u)_{i+\frac{1}{2}, j+\frac{1}{2}} &= (\mathcal{F}_u)_A - (\mathcal{F}_u)_B, \\ \delta(\hat{m}u)_{i-\frac{1}{2}, j+\frac{1}{2}} &= (\mathcal{F}_u)_B - (\mathcal{F}_u)_C, \\ \delta(\hat{m}u)_{i-\frac{1}{2}, j-\frac{1}{2}} &= (\mathcal{F}_u)_C - (\mathcal{F}_u)_D, \\ \delta(\hat{m}u)_{i+\frac{1}{2}, j-\frac{1}{2}} &= (\mathcal{F}_u)_D - (\mathcal{F}_u)_A.\end{aligned}\tag{5.45}$$

Finally, the total mass change in a zone is calculated from the m 's obtained by applying this procedure for each corner of the cell, i.e.,

$$m_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} = m_{i-\frac{1}{2},j-\frac{1}{2}}^n + \sum_{\ell=1}^4 \left(\delta m_{i-\frac{1}{2},j-\frac{1}{2}} \right)_{\ell} , \quad (5.46)$$

and similarly for the internal energy

$$u_{i-\frac{1}{2},j-\frac{1}{2}}^{n+1} = u_{i-\frac{1}{2},j-\frac{1}{2}}^n + \rho_{i-\frac{1}{2},j-\frac{1}{2}}^0 \sum_{\ell=1}^4 \left[\delta (m\hat{u})_{i-\frac{1}{2},j-\frac{1}{2}} \right]_{\ell} \quad (5.47)$$

Here we have converted back to energy per unit initial volume which is used throughout the rest of the code.

5.6.3 Momentum Convection. The momentum convection equation, Eq.(3.11), is also solved using a surface integral approach, but in this case, the integration is performed over the diamond-shaped volume (momentum zone) shown in Figure 3.1b. After using Gauss' theorem to convert the divergence term to a surface integral, Eq.(3.11) becomes

$$\frac{\partial (m\mathbf{v})_{i,j}}{\partial t} = \frac{D}{Dt}(m\mathbf{v})_{i,j} - \int_S (\rho \mathbf{v})_S (\mathbf{w} \cdot \mathbf{n}) dS \quad (5.48)$$

where $(\rho \mathbf{v})_S$ is the value at the surface of the integration volume.

Rather than integrating in one step over the entire surface of the momentum zone as shown in Figure 3.1b, Eq.(5.48) is calculated using an indirect approach similar to that used for the mass convection equation. The momentum flow resulting from the motion of each grid point relative to the fluid is calculated separately as shown in Figure 5.5. As before, the point in the center connected by dashed lines represents the position at the end of the implicit, Lagrangian phase. Using the new (rezoned) position (connected with solid lines) and the relative velocity, the momentum flow is calculated for the four surfaces shown. Thus, momentum convection takes place between points $(i+1,j)$ and $(i,j+1)$, between $(i,j+1)$ and $(i-1,j)$, etc; but the momentum of point (i,j) is unchanged. When this

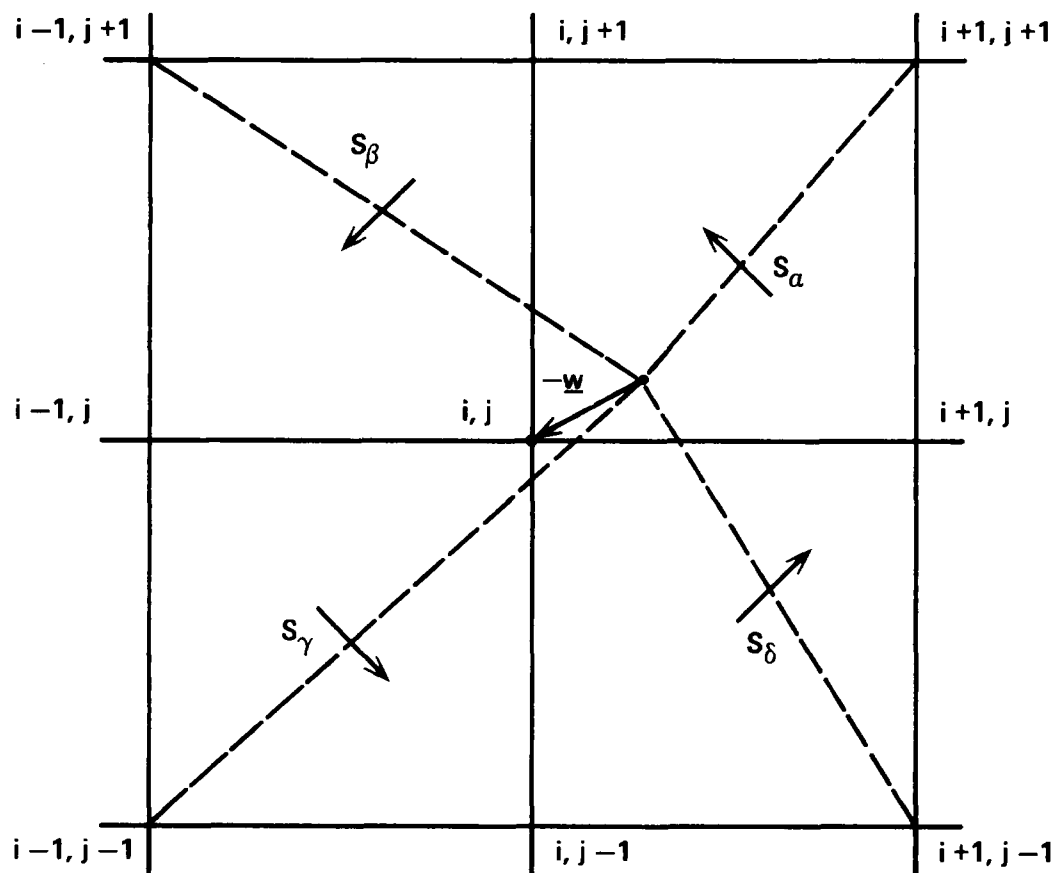


Figure 5.5. Schematic of the procedure for calculating momentum convection.

is repeated for each grid point, the flow across each momentum zone surface produced by the relative velocity of each adjacent grid point is evaluated, so that the total flow across each such surface surrounding each momentum zone is calculated. This effectively results in the evaluation of Eq.(5.48) for each momentum zone.

The momentum convection equations derived from Eq.(5.31) using this approach are

$$\begin{aligned}
 \delta(\underline{mv})_{i+1,j} &= \left\{ -\rho_{\alpha} \underline{v}_{\alpha} \int_{S_{\alpha}} (\underline{w} \cdot \underline{n}_{\alpha}) dS_{\alpha} - \rho_{\delta} \underline{v}_{\delta} \int_{S_{\delta}} (\underline{w} \cdot \underline{n}_{\delta}) dS_{\delta} \right\} \Delta t^{n+\frac{1}{2}} , \\
 \delta(\underline{mv})_{i,j+1} &= \left\{ -\rho_{\beta} \underline{v}_{\beta} \int_{S_{\beta}} (\underline{w} \cdot \underline{n}_{\beta}) dS_{\beta} - \rho_{\alpha} \underline{v}_{\alpha} \int_{S_{\alpha}} (\underline{w} \cdot \underline{n}_{\alpha}) dS_{\alpha} \right\} \Delta t^{n+\frac{1}{2}} , \\
 \delta(\underline{mv})_{i-1,j} &= \left\{ -\rho_{\gamma} \underline{v}_{\gamma} \int_{S_{\gamma}} (\underline{w} \cdot \underline{n}_{\gamma}) dS_{\gamma} - \rho_{\beta} \underline{v}_{\beta} \int_{S_{\beta}} (\underline{w} \cdot \underline{n}_{\beta}) dS_{\beta} \right\} \Delta t^{n+\frac{1}{2}} , \\
 \delta(\underline{mv})_{i,j-1} &= \left\{ -\rho_{\delta} \underline{v}_{\delta} \int_{S_{\delta}} (\underline{w} \cdot \underline{n}_{\delta}) dS_{\delta} - \rho_{\gamma} \underline{v}_{\gamma} \int_{S_{\gamma}} (\underline{w} \cdot \underline{n}_{\gamma}) dS_{\gamma} \right\} \Delta t^{n+\frac{1}{2}} ,
 \end{aligned}
 \tag{5.49}$$

where the surfaces S_{α} , S_{β} , etc., are shown in Figures 5.5 and the $(\rho_{\alpha} \underline{v}_{\alpha})$, $(\rho_{\beta} \underline{v}_{\beta})$, etc., are interpolated values at the respective surfaces. In finite-difference form these equations are expressed as follows. The integrals

$$F_{\alpha} = \int_{S_{\alpha}} (\underline{w} \cdot \underline{n}_{\alpha}) dS_{\alpha} , \text{ etc.},$$

are expressed as

$$\begin{aligned}
F_{\alpha} &= r_{\alpha} \left\{ \frac{1}{2} (w_x)^{n+1}_{i,j} \left[(y_L)^{n+1}_{i,j} - y^{n+1}_{i+1,j+1} \right] - \frac{1}{2} (w_y)^{n+1}_{i,j} \left[(x_L)^{n+1}_{i,j} - x^{n+1}_{i+1,j+1} \right] \right\}, \\
F_{\beta} &= r_{\beta} \left\{ \frac{1}{2} (w_x)^{n+1}_{i,j} \left[(y_L)^{n+1}_{i,j} - y^{n+1}_{i-1,j+1} \right] - \frac{1}{2} (w_y)^{n+1}_{i,j} \left[(x_L)^{n+1}_{i,j} - x^{n+1}_{i-1,j+1} \right] \right\}, \\
F_{\gamma} &= r_{\gamma} \left\{ \frac{1}{2} (w_x)^{n+1}_{i,j} \left[(y_L)^{n+1}_{i,j} - y^{n+1}_{i-1,j-1} \right] - \frac{1}{2} (w_y)^{n+1}_{i,j} \left[(x_L)^{n+1}_{i,j} - x^{n+1}_{i-1,j-1} \right] \right\}, \\
F_{\delta} &= r_{\delta} \left\{ \frac{1}{2} (w_x)^{n+1}_{i,j} \left[(y_L)^{n+1}_{i,j} - y^{n+1}_{i+1,j-1} \right] - \frac{1}{2} (w_y)^{n+1}_{i,j} \left[(x_L)^{n+1}_{i,j} - x^{n+1}_{i+1,j-1} \right] \right\},
\end{aligned}$$

where

(5.50)

$$\begin{aligned}
r_{\alpha} &= \frac{2\pi}{3} \left[2 (x_L)^{n+1}_{i,j} + x^{n+1}_{i+1,j+1} \right], \\
r_{\beta} &= \frac{2\pi}{3} \left[2 (x_L)^{n+1}_{i,j} + x^{n+1}_{i-1,j+1} \right], \\
r_{\gamma} &= \frac{2\pi}{3} \left[2 (x_L)^{n+1}_{i,j} + x^{n+1}_{i-1,j-1} \right], \\
r_{\delta} &= \frac{2\pi}{3} \left[2 (x_L)^{n+1}_{i,j} + x^{n+1}_{i+1,j-1} \right],
\end{aligned}$$

when $f = 1$ (cylindrical symmetry), and

$$r_{\alpha} = r_{\beta} = r_{\gamma} = r_{\delta} = 1$$

when $f = 0$ (planar symmetry). The flow across each surface then is

$$\begin{aligned}
(\mathcal{F}_{\dot{\mathbf{x}}})_{\alpha} &= \frac{1}{2} \Delta t^{n+\frac{1}{2}} (\rho_L)_{i+\frac{1}{2}, j+\frac{1}{2}}^{n+1} \left\{ (1+\theta_{\alpha}) \dot{\mathbf{x}}_{i+1, j}^{n+1} + (1-\theta_{\alpha}) \dot{\mathbf{x}}_{i, j+1}^{n+1} \right\} F_{\alpha} \quad , \\
(\mathcal{F}_{\dot{\mathbf{y}}})_{\alpha} &= \frac{1}{2} \Delta t^{n+\frac{1}{2}} (\rho_L)_{i+\frac{1}{2}, j+\frac{1}{2}}^{n+1} \left\{ (1+\theta_{\alpha}) \dot{\mathbf{y}}_{i+1, j}^{n+1} + (1-\theta_{\alpha}) \dot{\mathbf{y}}_{i, j+1}^{n+1} \right\} F_{\alpha} \quad , \\
(\mathcal{F}_{\dot{\mathbf{x}}})_{\beta} &= \frac{1}{2} \Delta t^{n+\frac{1}{2}} (\rho_L)_{i-\frac{1}{2}, j+\frac{1}{2}}^{n+1} \left\{ (1+\theta_{\beta}) \dot{\mathbf{x}}_{i, j+1}^{n+1} + (1-\theta_{\beta}) \dot{\mathbf{x}}_{i-1, j}^{n+1} \right\} F_{\beta} \quad , \\
(\mathcal{F}_{\dot{\mathbf{y}}})_{\beta} &= \frac{1}{2} \Delta t^{n+\frac{1}{2}} (\rho_L)_{i-\frac{1}{2}, j+\frac{1}{2}}^{n+1} \left\{ (1+\theta_{\beta}) \dot{\mathbf{y}}_{i, j+1}^{n+1} + (1-\theta_{\beta}) \dot{\mathbf{y}}_{i-1, j}^{n+1} \right\} F_{\beta} \quad , \\
(\mathcal{F}_{\dot{\mathbf{x}}})_{\gamma} &= \frac{1}{2} \Delta t^{n+\frac{1}{2}} (\rho_L)_{i-\frac{1}{2}, j-\frac{1}{2}}^{n+1} \left\{ (1+\theta_{\gamma}) \dot{\mathbf{x}}_{i-1, j}^{n+1} + (1-\theta_{\gamma}) \dot{\mathbf{x}}_{i, j-1}^{n+1} \right\} F_{\gamma} \quad , \\
(\mathcal{F}_{\dot{\mathbf{y}}})_{\gamma} &= \frac{1}{2} \Delta t^{n+\frac{1}{2}} (\rho_L)_{i-\frac{1}{2}, j-\frac{1}{2}}^{n+1} \left\{ (1+\theta_{\gamma}) \dot{\mathbf{y}}_{i-1, j}^{n+1} + (1-\theta_{\gamma}) \dot{\mathbf{y}}_{i, j-1}^{n+1} \right\} F_{\gamma} \quad , \\
(\mathcal{F}_{\dot{\mathbf{x}}})_{\delta} &= \frac{1}{2} \Delta t^{n+\frac{1}{2}} (\rho_L)_{i+\frac{1}{2}, j-\frac{1}{2}}^{n+1} \left\{ (1+\theta_{\delta}) \dot{\mathbf{x}}_{i, j-1}^{n+1} + (1-\theta_{\delta}) \dot{\mathbf{x}}_{i+1, j}^{n+1} \right\} F_{\delta} \quad , \\
(\mathcal{F}_{\dot{\mathbf{y}}})_{\delta} &= \frac{1}{2} \Delta t^{n+\frac{1}{2}} (\rho_L)_{i+\frac{1}{2}, j-\frac{1}{2}}^{n+1} \left\{ (1+\theta_{\delta}) \dot{\mathbf{y}}_{i, j-1}^{n+1} + (1-\theta_{\delta}) \dot{\mathbf{y}}_{i+1, j}^{n+1} \right\} F_{\delta} \quad .
\end{aligned}$$

(5.51)

The sign convention for these fluxes is the same as for the mass fluxes, i.e., they are positive in the counterclockwise direction around the point (i,j). The space centering of the momenta are determined by the θ 's which are determined from an input constant θ_G in the same way as was done for the mass flows.

The momentum changes are now calculated as follows:

$$\begin{aligned}
\delta(\dot{mx})_{i+1,j} &= (\mathcal{F}_{\dot{x}})_{\delta} - (\mathcal{F}_{\dot{x}})_{\alpha} , \\
\delta(\dot{my})_{i+1,j} &= (\mathcal{F}_{\dot{y}})_{\delta} - (\mathcal{F}_{\dot{y}})_{\alpha} , \\
\delta(\dot{mx})_{i,j+1} &= (\mathcal{F}_{\dot{x}})_{\alpha} - (\mathcal{F}_{\dot{x}})_{\beta} , \\
\delta(\dot{my})_{i,j+1} &= (\mathcal{F}_{\dot{y}})_{\alpha} - (\mathcal{F}_{\dot{y}})_{\beta} , \\
\delta(\dot{mx})_{i-1,j} &= (\mathcal{F}_{\dot{x}})_{\beta} - (\mathcal{F}_{\dot{x}})_{\gamma} , \\
\delta(\dot{my})_{i-1,j} &= (\mathcal{F}_{\dot{y}})_{\beta} - (\mathcal{F}_{\dot{y}})_{\gamma} , \\
\delta(\dot{mx})_{i,j-1} &= (\mathcal{F}_{\dot{x}})_{\gamma} - (\mathcal{F}_{\dot{x}})_{\delta} , \\
\delta(\dot{my})_{i,j-1} &= (\mathcal{F}_{\dot{y}})_{\gamma} - (\mathcal{F}_{\dot{y}})_{\delta} .
\end{aligned} \tag{5.52}$$

Then, using the $\delta(\dot{mx})$'s and $\delta(\dot{my})$'s calculated by this procedure for each corner of a momentum zone, we calculate the new momenta and new velocities from

$$m_{i,j}^{n+1} \dot{x}_{i,j}^{n+1} = m_{i,j}^n x_{i,j}^n + \sum_{\ell=1}^4 \left[\delta(m\dot{x})_{i,j} \right]_{\ell} ,$$

$$m_{i,j}^{n+1} \dot{y}_{i,j}^{n+1} = m_{i,j}^n y_{i,j}^n + \sum_{\ell=1}^4 \left[\delta(m\dot{y})_{i,j} \right]_{\ell} , \quad (5.53)$$

where the $m_{i,j}$ are calculated as the average of the four adjacent zone masses, i.e.,

$$m_{i,j} = \frac{1}{4} \left(m_{i+\frac{1}{2},j+\frac{1}{2}} + m_{i-\frac{1}{2},j+\frac{1}{2}} + m_{i-\frac{1}{2},j-\frac{1}{2}} + m_{i+\frac{1}{2},j-\frac{1}{2}} \right) . \quad (5.54)$$

5.6.4 Momentum Boundary Conditions. We stated in Section 5.3.2 that the only difference in momentum boundary conditions between the version of STEALTH described in this volume and the other versions is the addition of a continuative outflow option. With this boundary condition, fluid is permitted to flow out of the mesh through some non-Lagrangian boundary.

The correct application of such a boundary condition requires knowledge of the solution outside of the computational domain. In general, this is not known, so any outflow boundary condition that we apply will introduce some error and will perturb the solution to some extent. Therefore, we need to find a scheme that will minimize such perturbation.

One method that has been successful is to set the velocity at the boundary grid points equal to the velocity of the grid points just inside the boundary. Thus, for the $i = 1$ boundary, we have

$$\dot{x}_{i,j}^{n+1} = \dot{x}_{i+1,j}^{n+1} ,$$

$$\dot{y}_{i,j}^{n+1} = \dot{y}_{i+1,j}^{n+1} ,$$

and similarly for the other boundaries. These velocities are set at the end of the convection phase. In the Lagrangian phases, the continuative

outflow boundaries are treated as free. Although this method is not exact, experience has shown that it is adequate for most situations.

5.6.5 Stress Calculations. After the convection equations have been solved, we have new (rezoned) values of positions, velocities, densities and internal energies. For the incompressible flow version, this completes the calculational cycle. New pressures are not calculated in the convective phase. Instead, the pressures carried over to the next cycle are actually centered in the Lagrangian mesh rather than in the new rezoned mesh. This introduces a small error, but, since these pressures are only used in the explicit Lagrangian phase of the next cycle to compute trial velocities for the first iteration in the implicit phase, this error does not affect the calculation in any significant way.

For the implicit, compressible flow version, however, it is necessary to recalculate at least the viscous stress (both real and artificial components) based on the new velocity field. This is necessary because all viscous stress effects are treated explicitly. In addition we also have chosen to recalculate the pressure based on the new values of density and internal energy in order to increase the overall accuracy of the calculation. The equations used to calculate these quantities are the same as those used to calculate them originally at the end of the implicit, Lagrangian phase. These were discussed earlier in Section 5.

5.7 DAMPING OF SHORT WAVELENGTH INSTABILITIES

The 2D STEALTH codes, in common with most other 2D Lagrangian codes, are subject to what is usually called the "alternating errors" or "hourglass" instability. This instability results from the fact that the finite-difference equation for the volume strain rate, Eq.(5.8), is insensitive to modes of deformation of a zone in which the velocities are equal along zone diagonals. Therefore, errors or perturbations which produce these modes of deformation are free to grow without resistance. The

typical pattern of this instability is shown in Figure 5.6; its wavelength is equal to twice the zone width.

Several different methods have been developed to damp out this instability. In the other versions of the STEALTH codes, an anisotropic artificial viscosity is used. In the YAQUI code (Reference 6), developed at the Los Alamos Scientific Laboratory, an artificial damping force related to the difference between the grid point velocity and the surrounding velocity field is added into the equations. This type of damping mechanism is often termed a node coupler.

Although these methods are intended to damp out only the short wavelength errors, they also have some effect on the longer wavelength motions which are part of the solution. Therefore, care must be taken to minimize this effect.

In this version of STEALTH, we have chosen to include a node coupling type of damping mechanism which appears to have less effect on the actual solution than the two methods discussed above. This method, which is described below, is based on one employed in the GALE code (Reference 10).

Consider the error pattern shown in Figure 5.6. A pair of discrepancy parameters that are very sensitive to these errors can be defined as follows:

$$\begin{aligned} (\psi_x)_{i-\frac{1}{2},j-\frac{1}{2}} &= (\dot{x}_{i,j} + \dot{x}_{i-1,j-1}) - (\dot{x}_{i-1,j} + \dot{x}_{i,j-1}) , \\ (\psi_y)_{i-\frac{1}{2},j-\frac{1}{2}} &= (\dot{y}_{i,j} + \dot{y}_{i-1,j-1}) - (\dot{y}_{i-1,j} + \dot{y}_{i,j-1}) . \end{aligned} \quad (5.55)$$

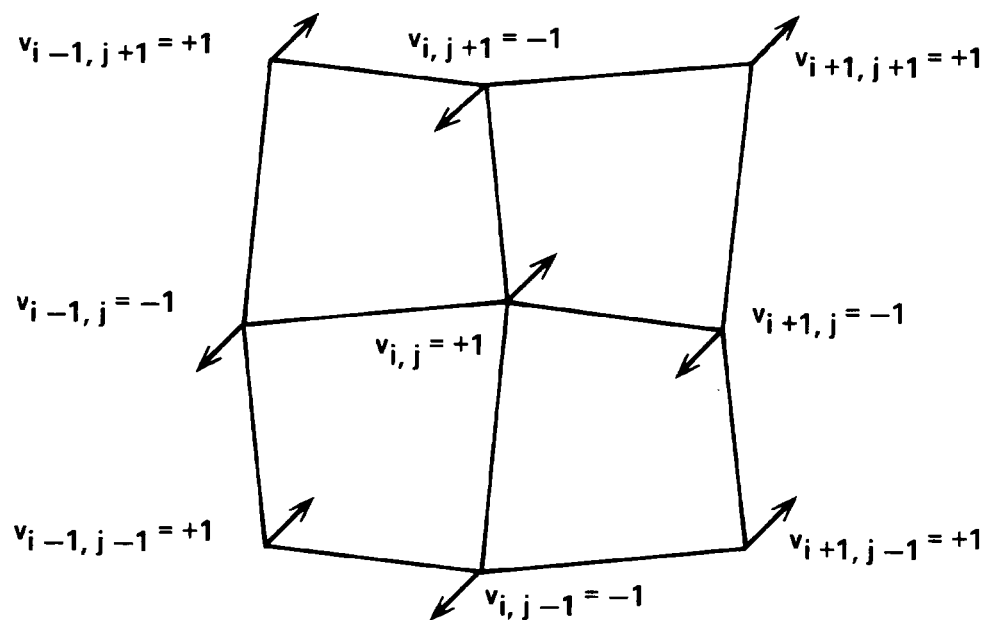


Figure 5.6. Schematic of alternating error pattern leading to the hourglass instability.

We would like to make corrections to the velocities that reduce these discrepancies; this suggests the first set of conditions to be satisfied by these corrections:

$$\begin{aligned}
 (\delta \dot{x}_{i,j} + \delta \dot{x}_{i-1,j-1}) - (\delta \dot{x}_{i-1,j} + \delta \dot{x}_{i,j-1}) &= -\kappa(\psi_x)_{i-\frac{1}{2},j-\frac{1}{2}} , \\
 (\delta \dot{y}_{i,j} + \delta \dot{y}_{i-1,j-1}) - (\delta \dot{y}_{i-1,j} + \delta \dot{y}_{i,j-1}) &= -\kappa(\psi_y)_{i-\frac{1}{2},j-\frac{1}{2}} , \quad (5.56)
 \end{aligned}$$

where κ is an input constant. We also want the volume changes to leave the volume strain rate unchanged. Looking at Eq.(5.8), we see that this condition can be satisfied by requiring that

$$\begin{aligned}
 \delta \dot{x}_{i,j} &= \delta \dot{x}_{i-1,j-1} , & \delta \dot{x}_{i-1,j} &= \delta \dot{x}_{i,j-1} , \\
 \delta \dot{y}_{i,j} &= \delta \dot{y}_{i-1,j-1} , & \delta \dot{y}_{i-1,j} &= \delta \dot{y}_{i,j-1} . \quad (5.57)
 \end{aligned}$$

Finally, we also want the velocity changes to conserve momentum. This means that

$$\begin{aligned}
 m_{i,j} \delta \dot{x}_{i,j} + m_{i-1,j} \delta \dot{x}_{i-1,j} + m_{i-1,j-1} \delta \dot{x}_{i-1,j-1} + m_{i,j-1} \delta \dot{x}_{i,j-1} &= 0 , \\
 m_{i,j} \delta \dot{y}_{i,j} + m_{i-1,j} \delta \dot{y}_{i-1,j} + m_{i-1,j-1} \delta \dot{y}_{i-1,j-1} + m_{i,j-1} \delta \dot{y}_{i,j-1} &= 0 .
 \end{aligned} \quad (5.58)$$

Solving Eqs.(5.56) and (5.58) simultaneously gives

$$\begin{aligned}
\dot{\delta x}_{i,j} &= \dot{\delta x}_{i-1,j-1} = -\frac{\kappa}{2} \left(\frac{m_{i-1,j} + m_{i,j-1}}{M} \right) (\psi_x)_{i-\frac{1}{2},j-\frac{1}{2}}, \\
\dot{\delta x}_{i-1,j} &= \dot{\delta x}_{i,j-1} = \frac{\kappa}{2} \left(\frac{m_{i,j} + m_{i-1,j-1}}{M} \right) (\psi_x)_{i-\frac{1}{2},j-\frac{1}{2}}, \\
\dot{\delta y}_{i,j} &= \dot{\delta y}_{i-1,j-1} = -\frac{\kappa}{2} \left(\frac{m_{i-1,j} + m_{i,j-1}}{M} \right) (\psi_y)_{i-\frac{1}{2},j-\frac{1}{2}}, \\
\dot{\delta y}_{i-1,j} &= \dot{\delta y}_{i,j-1} = \frac{\kappa}{2} \left(\frac{m_{i,j} + m_{i-1,j-1}}{M} \right) (\psi_y)_{i-\frac{1}{2},j-\frac{1}{2}}, \quad (5.59)
\end{aligned}$$

where

$$M = m_{i,j} + m_{i-1,j} + m_{i-1,j-1} + m_{i,j-1}.$$

These changes are then added to the respective velocities, and the procedure is repeated for each zone in the mesh. This effectively provides coupling of the velocity at each grid point with the velocities of the surrounding eight grid points.

The parameter κ determines the strength of the coupling and, therefore, governs the degree to which the instabilities are damped. According to Reference 10, the limits on κ for stability are $0 \leq \kappa \leq \frac{1}{2}$. For $\kappa = \frac{1}{4}$, the error pattern shown in Figure 5.6 is completely damped out in one cycle. For most cases, κ in the range $0.025 \leq \kappa \leq 0.25$ works well and has a minimal effect on the solution.

In the STEALTH calculational sequence, this node coupler is applied to the final velocities that result from the convection phase. For computational convenience this is done at the beginning of the next cycle just before the explicit, Lagrangian phase; this is equivalent to applying it at the end of the previous cycle.

SECTION 6
INPUT INSTRUCTIONS FOR THE
IMPLICIT FLUID MECHANICS VERSIONS
OF THE STEALTH COMPUTER PROGRAMS

6.1 INTRODUCTION

General input instructions for the STEALTH computer programs are found in Sections 6 and 7 of Volume 1. Since the intent is to standardize the input for all versions of STEALTH, those instructions are generally applicable to the versions described in this volume. However, some significant changes have been made for these versions. Some new input records have been added, some new variables have been added to existing records, and in a few cases, existing variables have taken on different meanings. Therefore, to avoid ambiguity, the material found in Sections 6 and 7 of Volume 1 has been repeated here and modified to reflect these changes so that Sections 6 and 7 of this volume contain complete user instructions for the implicit fluid mechanics versions of the STEALTH computer programs.

6.1.1 Record Format. Input data for the STEALTH computer programs are provided as seven distinct blocks of input in addition to a title record. The title record must precede the seven input blocks and first input block must always be the PRB input block. The remaining six input blocks may be in any order. The last record of the input data must always be an END record; this END record is in addition to the END record of the last input block.

The first input block is always the problem specification input block, denoted by the control characters PRB. The remaining six input blocks are as follows:

Control CharactersType of Input

MAT	material specification input
GPT	grid-point specification input
ZON	zone initialization input
BDY	boundary specifications input
TIM	time specification input
EDT	edit specifications input

When prescribing input data for a particular input block, the first input record of the block is always the block specification (input control) record; the last input record of the block is always the end-of-data record, END. An additional END record must be placed at the end of the input deck following the END record of the last input block. Figure 6.1 shows the general structure of a STEALTH input deck.

All input records between an input control record and the next end-of-data record encountered must be appropriate input data for that block. The non-optional input block (PRB) contains input records which are specified by alphabetic specification characters, e.g., SOR, SYM, etc. The six optional input blocks (MAT, GPT, ZON, BDY, TIM, EDT) use three-character numeric specification, e.g., 153, 721, etc. The first numeric character identifies the input block as follows:

MAT = 1__
GPT = 2__
ZON = 3__
BDY = 4__
TIM = 5__
EDT = 6__

The second numeric character identifies an input decade or sub-block, while the third numeric character helps make the specification unique.

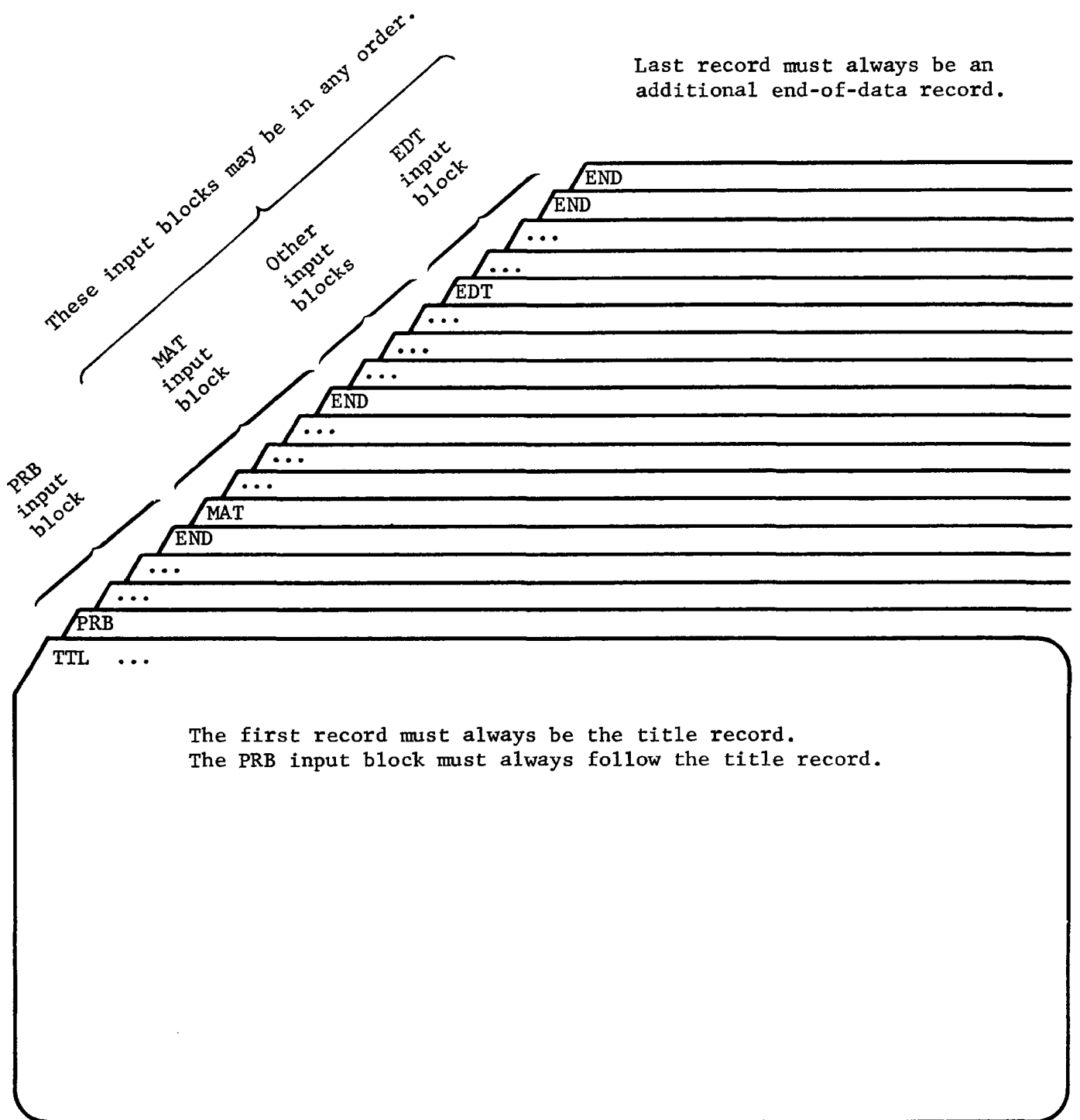


Figure 6.1. General structure of a STEALTH input deck.

The input format for all input data records (except the title input record) is the same. For a card or keyboard input record, the first three columns are used for the control specification characters (format code A3); the next seven columns are used for miscellaneous information at the user's discretion (format code 7A1); and the last 70 columns are used for specific numerical input data (format code 7E10.0). All numerical data is input in floating point notation under the E-format; thus, the input for the integers as well as for real numbers should be in E- or F-formats. Figure 6.2 is a schematic of the input format.

The input format for the title record is similar to the standard input record for numerical data described above. The difference is that the last 70 columns are used for alphanumeric title data (format code 70A1).

6.1.2 Manual Format. The input manual (Section 7) has been divided into sections corresponding to the input blocks. The section numbers and input blocks have the following correspondence:

<u>Section number</u>	<u>Input block</u>
7.0	PRB
7.1	MAT
7.2	GPT
7.3	ZON
7.4	BDY
7.5	TIM
7.6	EDT
7.7	END

Each section contains an overview of the input in the section, a summary of the input records and input variables, and detailed descriptions of the input variables by record type.

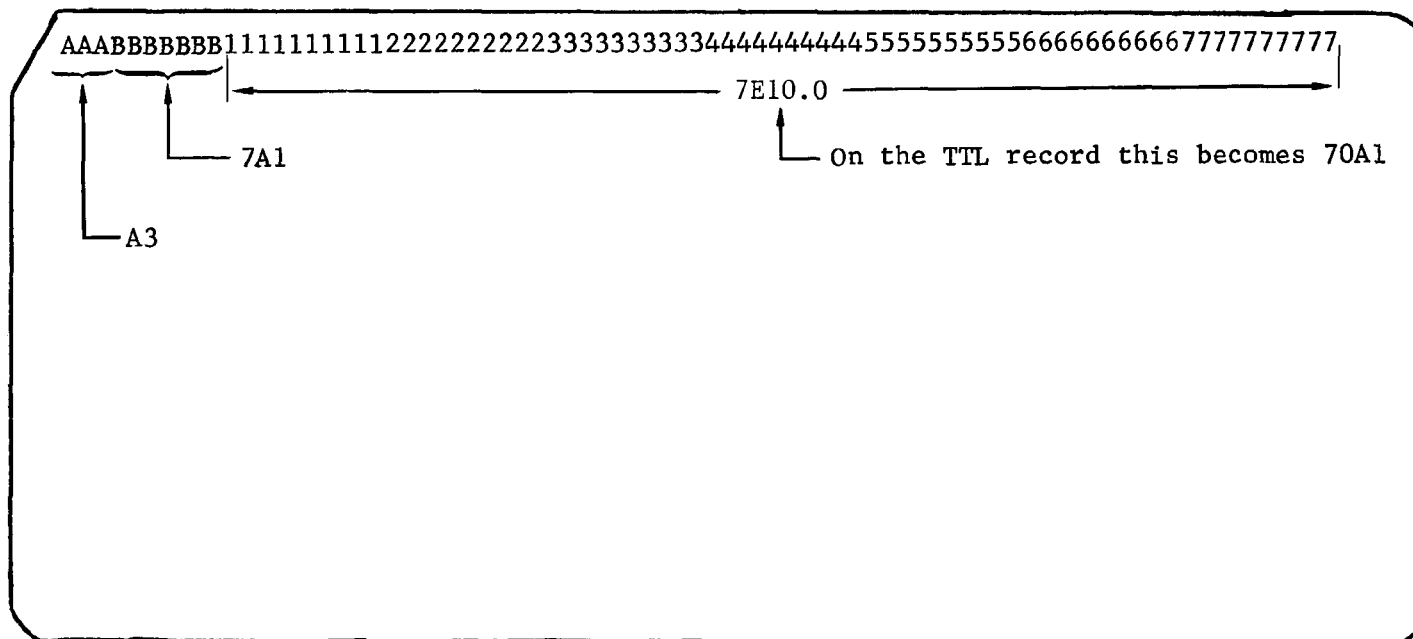


Figure 6.2. Input record format.

The format of the detailed input record documentation is shown in Figure 6.3. Most of the terminology used to describe a particular variable should be fairly clear. However, a convention is used to describe output error messages which requires some additional information. When an error message prints the value of a variable, the following notations are used:

floating point variable	eeeeeeeeeeee
fixed point variable	iiiiii
Hollerith variable	aaaaaa

where "e" represents an E format, "i" represents an I format, and "a" represents an A format. The number of e's, i's or a's indicates the field width. Thus, in the examples above, the notation corresponds to the formats E12, I5, and A6, respectively.

The discussion of the input variables relies heavily on the Appendices which are ordered alphabetically according to the appendix name.

6.2 INDEX SPACE

Providing the input data for a STEALTH run is primarily a process of inserting problem-related information into computer memory in such a way that it is consistent with STEALTH's memory addressing conventions. The STEALTH addressing system is such that contiguous mesh points in the physical space are contiguous in the memory address or "index" space. For one-dimensional problems, the index space is an ordered string of points, while for a two-dimensional problem, the index space is a rectangular array of points. The contiguous storage approach eliminates any need for additional connectivity information.

The one-dimensional index convention in STEALTH counts mesh points from left to right (i increases from left to right). The real space coordinate (x) also increases from left to right; thus, two consecutive

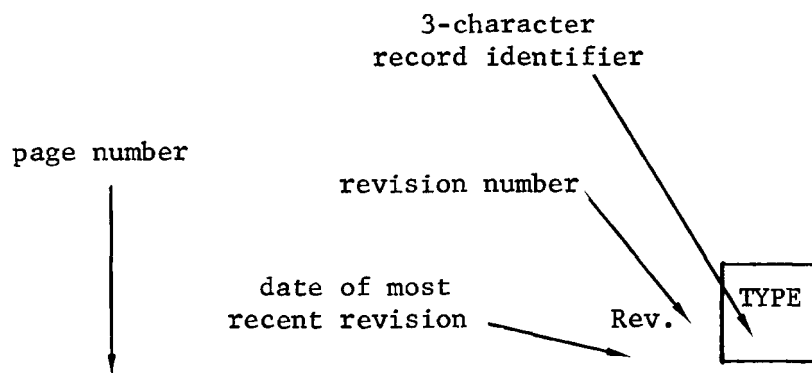
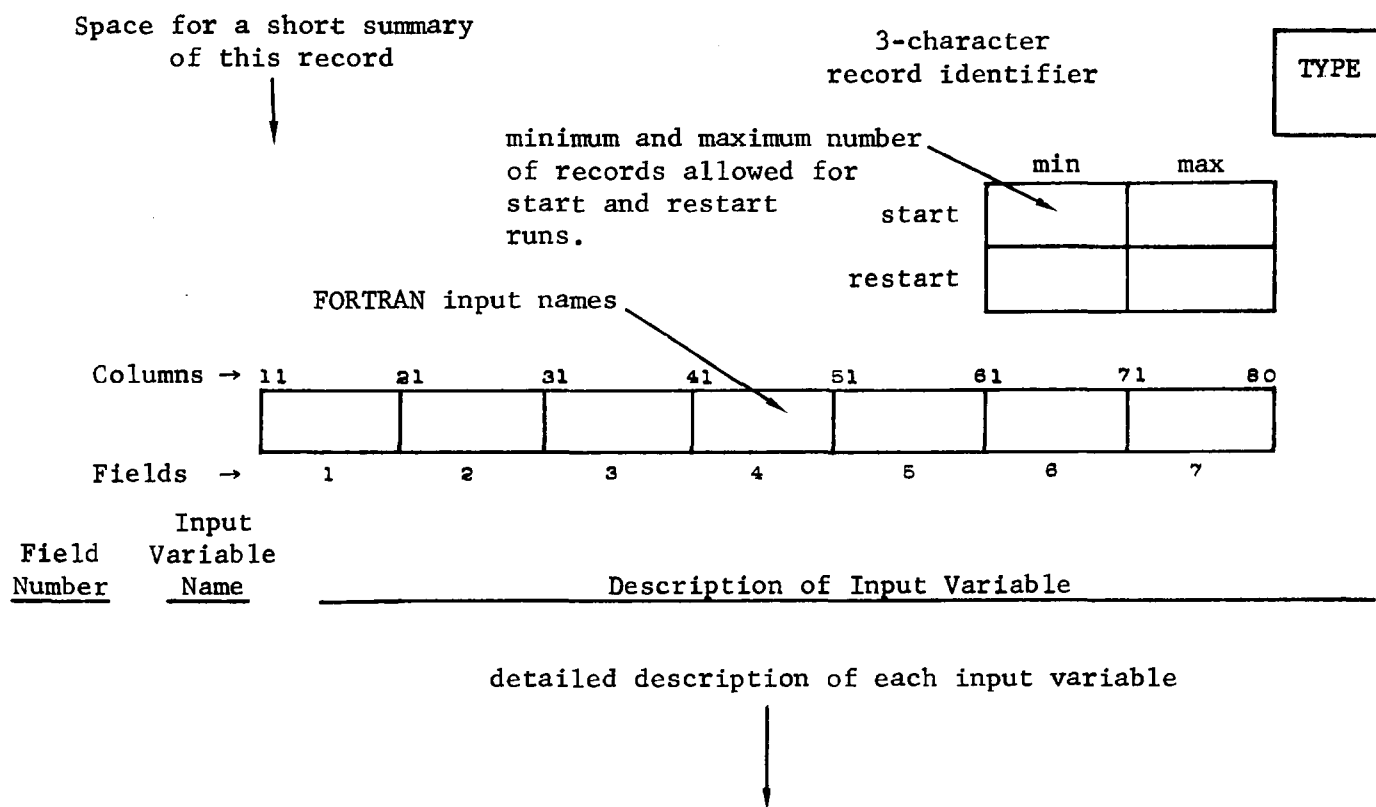


Figure 6.3. Input record documentation format.

points form a positive volume. (See Figure 6.4.) This convention does not restrict physical one-dimensional geometries in any way.

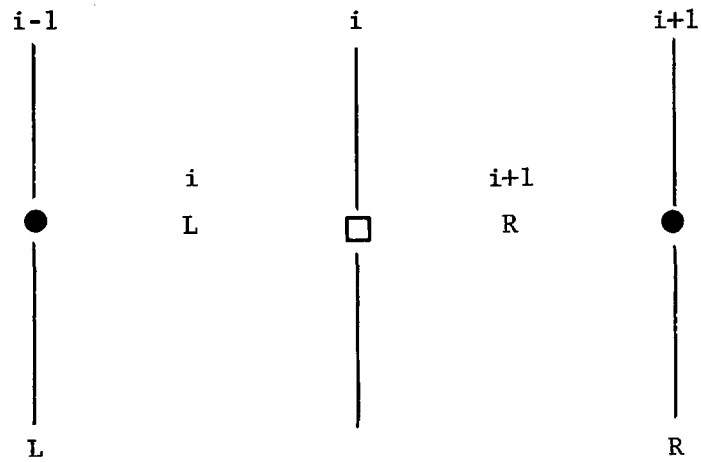
In a two-dimensional mesh, there are two indexes (i,j) . One index increases from left to right, while the other increases from bottom to top. The left-to-right index is denoted by increasing i , while the bottom-to-top index is denoted by increasing j . (See Figure 6.5.) Real space coordinates can increase or decrease in any direction relative to the index space as long as the index space (i,j) and real space (x,y) coordinate systems are both right-handed, and as long as four contiguous mesh points always form a positive volume in the real space. Just as in the one-dimensional case, these conventions do not limit the real space geometries in any significant way.*

In both cases, the indexing system for mesh points can also be used as an indexing system for zones. The following conventions apply:

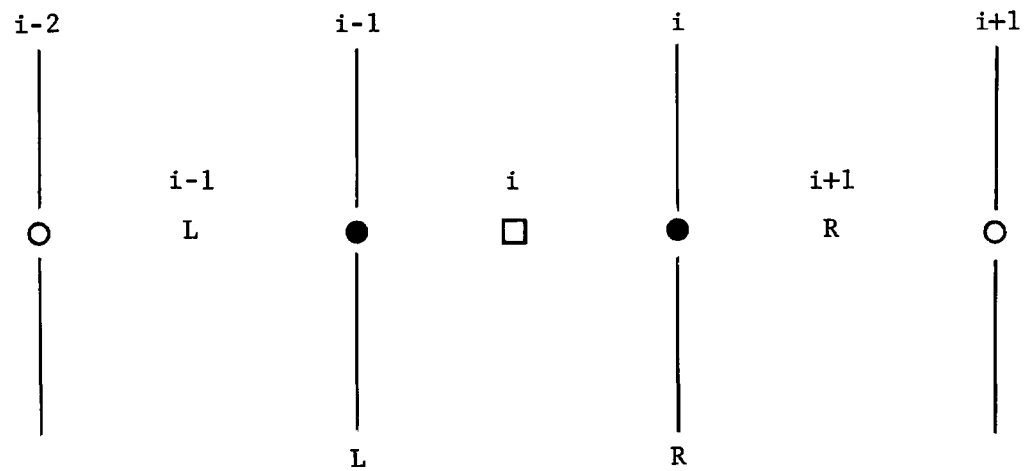
- In one dimension, the zone index value is defined to be the grid point index value of the grid point on its right. (See Figure 6.4.) Since two contiguous grid points define a zone, this is a unique specification. A consequence of this address notation is that the left boundary grid point of a grid never has a zone associated with its index value.
- In two dimensions, the zone index value is defined to be the grid point index value of the grid point at the upper right hand corner of the zone. (See Figure 6.5.) This is also a unique specification since four contiguous grid points define a zone. A consequence of the two-dimensional address notation is that left-side and bottom-side grid points never have zones associated with those index values.

*The use of certain ALE rezone options may require that x increase in the direction of increasing i and y increase in the direction of increasing j . This restriction is noted in the discussion of the ALE input record (PRB phase) which specifies this option.

GRID POINT CALCULATION CONVENTIONS (Interior Grid Point i)



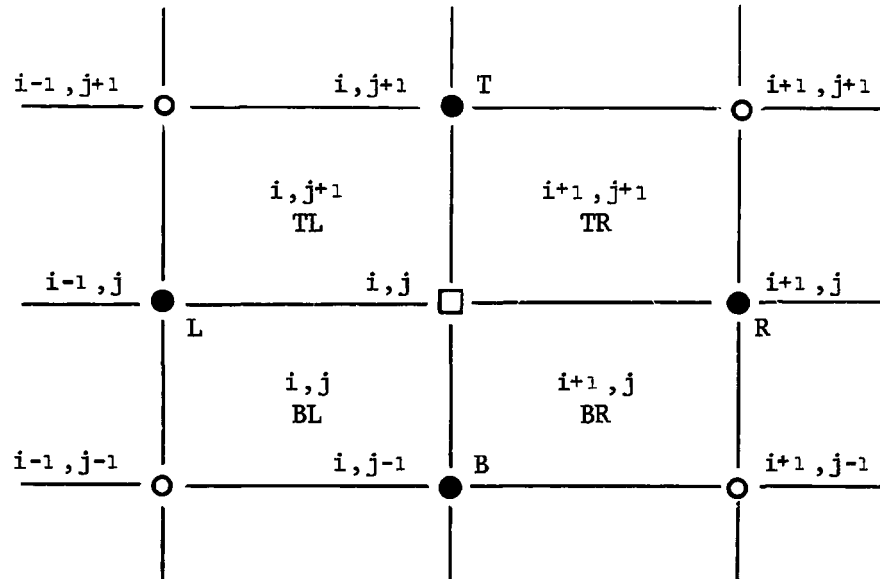
ZONE CALCULATION CONVENTIONS (Zone i)



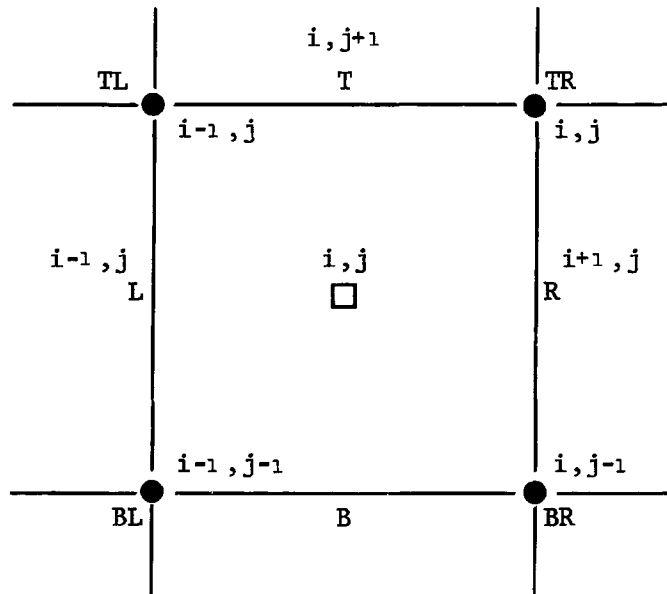
$L = \text{left}; R = \text{right}.$

Figure 6.4. One-dimensional index conventions.

GRID POINT CALCULATION CONVENTIONS (Interior Grid Point i,j)



ZONE CALCULATION CONVENTIONS (Zone i,j)



L = left, R = right, B = bottom, T = top, TL = top left, TR = top right, BL = bottom left, BR = bottom right.

Figure 6.5. Two-dimensional index conventions.

6.3 OPERATIONAL CONSIDERATIONS

In applying these computer codes to physics and engineering problems, a number of factors must be considered in order to avoid the many pitfalls that might be encountered. In the following sections, we discuss some of these factors and provide guidance to help avoid the pitfalls. Unfortunately, it is impossible to cover all areas where trouble might occur since each calculation is unique and has its own set of difficulties. Here we only attempt to give general guidelines for the use of these codes on the assumption that the intelligent user will be able to find his own way around such trouble spots as he becomes more experienced.

6.3.1 Code Selection. One of the first factors to consider is which, if either, of the two general types of codes (incompressible flow or implicit, compressible flow) described here is applicable to a particular physical problem. Both types of codes are designed for problems involving slow flow or situations where small strain rates are involved. However, in some cases, particularly for liquids, an incompressible flow approximation can be made. In other cases, for example where pressure wave effects are involved, the implicit, compressible version should be used.

6.3.1.1 Incompressible Flow Versions. This approximation is most often applied to liquids but may also be applied in some instances to the low speed flow of gases. As a general rule of thumb, the incompressible flow approximation is valid if the flow velocity is much less than the local sound speed,

$$v \ll c \quad . \quad (6.1)$$

Another way of looking at this is to consider whether pressure wave effects are important. The incompressible flow approximation assumes that pressure wave effects are absent or take place on a time scale that is short compared to the dominant motions in the problem and can, therefore, be ignored.

Another factor to consider is whether heat conduction effects may be important to the flow. In some cases, the flow may be approximately incompressible but may be driven by buoyancy effects that are strongly affected by heat conduction. It is possible to develop an incompressible flow model that includes thermal expansion effects driven by heat conduction, but that approach was not taken here. Rather, problems of that type should be treated with the implicit, compressible flow version of STEALTH which includes heat conduction.

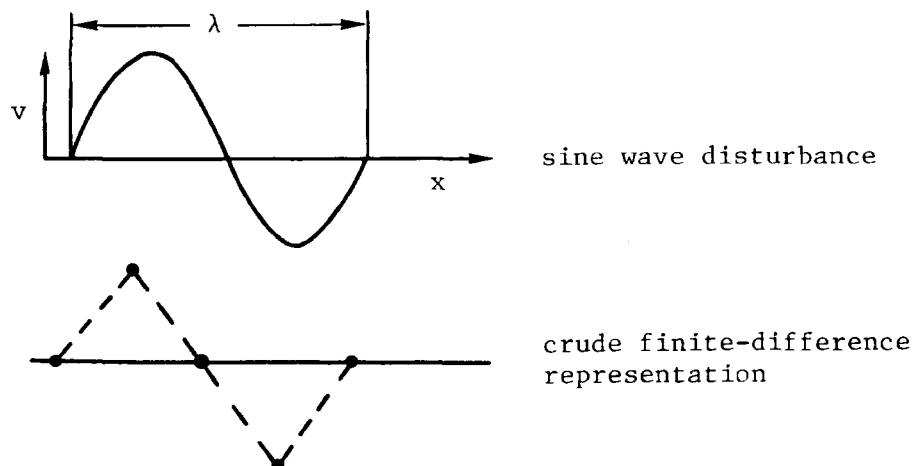
6.3.1.2 Implicit, Compressible Flow Versions. These versions of the STEALTH codes will most often be applied to the low speed flow of gases, but they are applicable to any fluid dynamics problem involving low speed flow or small strain rates where compressibility effects and/or heat conduction effects are important. This may include problems involving pressure wave effects where the dominant wavelengths are long, but it does not include problems involving shock waves. Although the implicit, compressible flow codes can be used to calculate shock wave propagation, the time step must be restricted to a small value (on the order of the stable explicit time step) to provide adequate time resolution. In this case, the additional computations done each cycle to obtain the implicit solution usually make these versions less cost effective than the explicit versions. Therefore the following rule-of-thumb should be used in deciding whether or not the implicit, compressible flow version is applicable. If the time step required to provide the desired time resolution (see Section 6.3.3) is approximately equal to or smaller than the stable explicit time step, then an explicit method will probably be more cost effective (although the implicit versions may in some cases provide a more accurate solution).

In some cases the implicit versions may be applicable to the later stages of a calculation after the high strain-rate phenomena have dissipated or have propagated out of the computational domain and only long wavelength motions remain. In those cases an explicit version could be

used initially, and the calculations could be switched to one of the implicit versions at a later time. As an alternative the implicit code could be run in an explicit mode for the early stages (with a small loss in efficiency compared to a purely explicit version) and then could be switched automatically to the implicit mode at some later time (specified by input). This second method is easier operationally but may be slightly more expensive if the explicit phase is a major part of the calculation.

6.3.2 Zoning Considerations. Determination of the zoning or mesh configuration to be used in a problem involves a tradeoff between accuracy and economy. In the extreme, the solution of the finite-difference equations should approach the solution of the corresponding differential equations as the mesh spacing approaches zero; however, at the same time, the computer requirements (storage space and computing time) approach infinity. The objective is to find a compromise such that acceptable accuracy is obtained with reasonable requirements for computer resources. What is reasonable will depend on the individual user's situation, i.e., computer cost versus budget, available storage, etc. Keeping in mind that each problem is unique, we have attempted to provide some general zoning guidelines.

The first zoning principal to be considered is that the zoning must be sufficiently fine (closely spaced) to resolve the expected gradients in pressure and velocity. As an example, consider a disturbance in the form of a sine wave. In a simple 1D picture, a minimum of three grid points are required to resolve a half wavelength crudely.



Even five grid points per half wavelength provides only fairly crude resolution. Generally, on the order of at least ten grid points are required over a half wavelength interval to provide reasonable resolution.

In some cases, it is fairly straightforward to determine beforehand what the wavelengths of the dominant motions are likely to be. As an example, for a surface wave driven either by a time-dependent boundary condition or by an initial free surface configuration, the dominant wavelength is determined by either the initial conditions or boundary conditions. As another example, for the interaction of a fluid with an obstacle, it is certain that gradients will exist at least on the scale of the obstacle and perhaps on a smaller scale, depending on other conditions.

Unfortunately, in many cases it may not be easy or even possible to determine the dominant wavelengths from the initial and/or boundary conditions. In these cases, judgment based on experience must be used. Sometimes it is necessary to rerun the initial stages of a calculation several times before the desired resolution is achieved. One further consideration may help in these cases, however. It is often helpful to view zoning considerations from the perspective of what the objectives of the calculation are. In some situations finely resolved details are required (e.g., to determine peak transient loads on an obstacle interacting with a fluid), while in other situations they are not (e.g., when only the integrated load or impulse is required). In the latter case, it may be possible to sacrifice some resolution because of cost considerations and still achieve the overall objectives of the calculation.

In many calculations it is not necessary to provide the same resolution in all regions of the computational domain. This is particularly important in 2D calculations where computer storage and cost considerations are more of a factor. With the flexibility provided by the STEALTH mesh generator, it is possible and often desirable to concentrate zoning resolution in the areas where it is required (i.e., near obstacles,

free surfaces, interfaces, etc.) and to reduce the resolution in other areas. Some caution should be exercised, however. In attempting to provide resolution where required while minimizing the total number of zones, zones with large aspect ratios may result. If these are in non-critical areas, they may not affect the solution. But large aspect ratios ($>5:1$) should be avoided, if possible, in important regions, since they can result in a loss of accuracy or may produce numerical noise in the solution. Even aspect ratios on the order of $5:1$ should be used with care, i.e., only when the motion is nearly one-dimensional. As a general rule, the aspect ratio of zones in critical regions of the calculation should be kept as close to $1:1$ as possible.

6.3.3 Time Step Considerations. The factors affecting the determination of the time step are accuracy and numerical stability. Accuracy considerations are similar to those discussed for zoning. Although for the implicit codes discussed here stability considerations generally allow the use of larger time steps than can be used with explicit methods, time resolution of the solution may be affected if the time steps are too large. It should be obvious that to resolve a disturbance, the time step must be shorter than the risetime of the disturbance. In the case of the sine wave disturbance discussed before, the risetime can be considered to be approximately one-fourth of the period τ . Thus, the time step Δt must be at least as small as $\tau/4$. In fact, for good resolution, the time step should be about one-fifth of this value or $t \sim \tau/20$. This provides equivalent resolution to the zoning criterion discussed in Section 6.3.2 (i.e., $\Delta x \sim \lambda/20$).

In Section 3, we discussed the fact that although the finite-difference methods used for these versions of the codes allow substantially larger time steps than equivalent explicit techniques, the codes are not unconditionally stable. Fortunately, accuracy considerations often dictate a time step that is smaller than would be required by stability, but in some instances that is not the case. Therefore stability

criteria must be considered in all cases in establishing the time step to make sure that it is well within the stable regime.

Instabilities arise primarily from two situations. In a Lagrangian calculation, when the strain rates become too large, zone boundaries can cross, causing the zone to turn inside out. In Eulerian calculations (or with any non-Lagrangian coordinate system), instabilities can occur when fluid velocities become large enough to require convection of the fluid more than one cell width per cycle. In most cases both of these instabilities can be avoided by requiring that

$$\Delta t < \Delta \ell / |\underline{v}| , \quad (6.2)$$

where $|\underline{v}|$ is the magnitude of the velocity and $\Delta \ell$ is the width of a zone in the direction of the velocity vector. In some cases in which the ALE method is used, the grid may be moving in the opposite direction from the fluid so that the relative velocity, $\underline{w}$, is larger than the fluid velocity. In those cases, the criterion should be rewritten

$$\Delta t < \Delta \ell / |\underline{w}| . \quad (6.3)$$

An automatic time step calculation based on Eqs.(6.2) and (6.3) has been incorporated into these versions of the codes. Therefore the time step will automatically be limited to some maximum value determined from one of those criteria. However, to be sure that the initial computational cycle is stable, Eq.(6.2) or (6.3) must be used to determine the initial time step.

Because Eqs.(6.2) and (6.3) do not hold rigorously in all cases (particularly for problems involving a high degree of nonlinearity), a safety factor which is specified by input is applied to the automatically calculated time step. In most cases this should be set in the range

$1/4 - 1/2$ (default value is $1/4$). However, for highly nonlinear problems a smaller value may be required, especially if the Newton-Raphson iteration method is used rather than the two-sided secant method. This same safety factor should be applied in determining the initial time step.

In an earlier section, we discussed the alternating node or hourglass instability that we attempt to damp out with an artificial node coupling force. The use of this node coupler also puts some stability restrictions on the time step, but experience has shown that for values of the node coupling coefficient in the range dictated by energy conservation requirements (i.e., $\kappa < 0.25$), no stability problems seem to arise. Therefore, node coupler stability restrictions are generally not a consideration in determining the initial time step.

The above discussion pertains to stability of the mechanical equations governing the fluid flow. Since the solution of the heat conduction equations is explicit, the time step may also be limited by the stability criterion for that part of the solution. This is discussed in Sections 4.4.3 and 5.4.3 of Volume 1. The automatic time step calculation uses the minimum of the stable mechanical and thermal time steps. This same procedure should be followed in determining the initial time step, but in general the mechanical time step will dominate.

6.3.4 Iteration Parameter Considerations. Two parameters for the implicit iteration must be set by input:^{*} 1) the relaxation factor ω and 2) the convergence criterion ϵ . The value for the relaxation factor is selected to maximize the rate of convergence of the iteration and thereby minimize computing costs. The convergence criterion, on the other hand, is determined by a trade-off between accuracy and cost considerations.

^{*}This does not include the maximum number of iterations.

The relaxation factor should usually be in the range of $1 \leq \omega < 2$. For $\omega \geq 2$, an unstable iteration results. For $\omega = 1$, the iteration is usually stable (assuming that the first guess is not too far off); however, in some cases the iteration may be somewhat slow to converge. Convergence may be accelerated by using values for ϵ between 1 and 2, but experience has shown that the chances for an unstable iteration also increase. The larger ω becomes, the closer the initial guess (from the explicit momentum equation in Phase 1) must be to the final solution to avoid an unstable iteration. A value of 1.5 usually gives good results. However, some experimentation may show that either a larger or smaller value is better for a particular problem.

Selecting a value of ω in the range $0 < \omega < 1$ usually decreases the rate of convergence. However, in some unusual instances it may have the opposite effect. In the case of highly nonlinear material properties, for instance, it may prevent an unstable iteration that could occur with the use of a larger relaxation factor, particularly when the Newton-Raphson method is used. Again, some experimentation may be necessary. The selection of the convergence criterion involves a trade-off between accuracy and cost. It is important that it be given careful consideration since an unnecessarily small value wastes computer time while a value that is too large affects the accuracy of the solution and, in extreme cases, could lead to an unstable solution.

The convergence criterion for the incompressible flow versions determines the maximum value of the volumetric strain rate allowed for the iteration to converge. Therefore the value to be selected for ϵ will vary from problem to problem, depending on the typical strain rates or velocity gradients in the problem. Experience has shown that good accuracy can be achieved by determining ϵ from

$$\epsilon \sim 10^{-3} \overline{\frac{\partial v}{\partial x}}, \quad (6.4)$$

where $\overline{\frac{\partial v}{\partial x}}$ is a typical velocity gradient in the problem. In some cases, when increased efficiency is desired at the sacrifice of some degree of accuracy, this can be reduced by an order of magnitude, i.e.,

$$\epsilon \sim 10^{-2} \overline{\frac{\partial v}{\partial x}} .$$

This latter value is often used for test problems where a high degree of accuracy is not required. It might also be used in preliminary runs to check out a calculation with the value obtained from Eq. (6.4) used for the final run.

The determination of the typical velocity gradient $\overline{\frac{\partial v}{\partial x}}$ may be difficult. Judgment based on experience is usually required. As is the case in setting some of the other parameters, it may be necessary to rerun the initial stages of a problem a few times in order to determine the optimum value for ϵ . For examples of some of the thinking that goes into determining ϵ (i.e., estimating $\overline{\frac{\partial v}{\partial x}}$) as well as some of the other input parameters discussed here, see the discussion of the test problems in Section 8.

Since the convergence criterion multiplies the pressure in the test for convergence in the implicit, compressible flow codes, the test is effectively normalized so that ϵ is not problem dependent. For these versions ϵ should be set in the range 10^{-2} to 10^{-4} depending on the accuracy desired. In general a value of 10^{-3} should be used.

SECTION 7

INPUT RECORDS

The title record specifies the 70-character title under which the problem (to be specified on subsequent records) will be printed and/or plotted. The title record must be the first input record in every run, start or restart.

Any number of free (optional) comment cards with columns 1-10 left blank may precede the title record (TTL card). These cards may contain from 1 to 70 alphanumeric characters in columns 11 - 80. These characters are neither saved nor printed. The purpose of this capability is to allow a user to summarize specific features of the data deck.

Problem Title

Page 1 of 1

TYPE
TTL

The TTL input record specifies the problem title.
The TTL input record is required as the first
input record in every run, start or restart.

	min	max
start	1	1
restart	1	1

Columns →	11	21	31	41	51	61	71	80
Fields →	1	2	3	4	5	6	7	

<u>Field Number</u>	<u>Input Variable Name</u>

Description of Input Variable

1

Problem title. Fields 1-7 may contain from 1-70 alphanumeric characters which will be stored as a problem title to be printed at the top of every page of printed output and on every plot.

TYPE
TTL

7.0 PROBLEM SPECIFICATION PHASE (PRB)

The problem specification phase (PRB) must be the first input block following the TTL record. The purpose of the PRB input block is to specify global properties of the problem. The minimum input records required for a start run are the PRB, GRD, and END records. These input records imply the default values shown below.

<u>Record Identifier</u>	<u>Variable Name</u>	<u>Default Value</u>	<u>Default Meaning</u>
PRO	NSPRO*	1.0	one-dimensional
SOR	NSSOR	1.0	start run
SOR	TIMSOR	0.0	start time
DTS	NSDTS	1.0	stress wave dynamic
SYM	NSSYM*	1.0	plane strain 1D or 2D symmetry
TOL	RELTOL	10^{-14}	60-bit word tolerance
TOL	SMLNUM	2.0×10^{-293}	60-bit word tolerance
TOL	BIGNUM	0.5×10^{293}	60-bit word tolerance
MIN	SSSMIN	10^{-4}	cm-g- μ s cut-off
MIN	XVLMIN	10^{-8}	cm-g- μ s cut-off
MIN	YVLMIN	10^{-8}	cm-g- μ s cut-off
MIN	ZVLMIN	10^{-8}	cm-g- μ s cut-off
MIN	DSTMIN	10^{-2}	cut-off for a zone size of 10^{-1}
MIN	PRHMIN	10^{-6}	minimum pressure for iteration
GRV	GRVX	0.0	no gravity
GRV	GRVY	0.0	no gravity
GRV	GRVZ	0.0	no gravity
GRV	NSGRV	1.0	no gravity overburden
ITR	MAXITR	200	maximum number of iterations

*Variables which may not be redefined at restart time.

ITR	EPSLN	10 ⁻³	iteration convergence criterion
ITR	RLXPRM	1.0	over-relaxation factor
ITR	NSITP	1.0	Newton-Raphson iteration
ITR	EXPBGN	0.0	fully explicit calculation starts at t=0
ITR	EXPEND	0.0	fully explicit calculation ends at t=0
ALE	NSALE	1.0	Langrangian
ALE	FLXCZ	0.0	interpolated mass convection
ALE	FLXCG	0.0	interpolated momentum convection
ALE	DPGFAC	1.0	undamped rezoning
CPL	CPLPRM	0.0	no node coupling

In a restart run, the minimum set of input records includes the SOR record in addition to PRB and END.

A summary of PRB phase input records and input variables appears in Table 7.0.

TABLE 7.0

SUMMARY OF PRB PHASE INPUT RECORDS AND INPUT VARIABLES

FIELDS 1-7

TYPE	1	2	3	4	5	6	7
PRB	NSINP	NSTRC	NSDBG	NSPLT	NSPRT		
PRO	NSPRO						
SOR	NSSOR	TIMSOR					
DTS	NSDTS						
SYM	NSSYM						
TOL	RELTOL	SMLNUM	BIGNUM				
MIN	SSSMIN	SVLMIN	YVLMIN	ZVLMIN	DSTMIN	PRHMIN	
GRV	GRVX	GRVY	GRVZ	NSGRV			
GRD	LG	MSHTYP	NUMILN	NUMJLN			
ITR	MAXITR	EPSLN	RLXPRM	NSITP	EXPBGN	EXPEND	
ALE	NSALE	FLXCZ	FLXCG	DPGFAC			
CPL	CPLPRM						
END							

The function of the PRB control record is to activate the PRB input phase. The PRB control record must follow the TTL input record and is required for all runs, start and restart. It is required whether or not PRB input records are used.

	min	max
start	1	1
restart	1	1

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSINP	Input mode switch. The value of NSINP specifies the mode of input to be used in this input phase. The value of NSINP must be integral and less than or equal to 3. The following definitions apply:

< 1.0	card input (default)
= 2.0	library input
= 3.0	keyboard input

If the field containing NSINP is left blank, then the mode of input is assumed to be card input. If the value of NSINP is greater than 3.0, the message,

INPUT MODE SWITCH
IMPROPERLY DEFINED

is written on the print and the message files, and the program terminates immediately in subroutine PRBGEN.

2	NSTRC	Trace mode switch. The value of NSTRC specifies whether or not the trace option is active. The value of NSTRC must be integral and less than or equal to 2. The following definitions apply:

< 1.0	trace is not active, off (default)
= 2.0	trace is active, on

If the field containing NSTRC is left blank, then the mode is assumed to be not active (off). If the value of NSTRC is greater than 2.0, the message,

TRACE MODE SWITCH
IMPROPERLY DEFINED

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files, and the program terminates immediately in subroutine PRBGEN. The trace logic, if active (on), will cause the name of the subroutine or logical phase just entered to be printed on both the print and message files. These actions are taken in subroutines SBRENT and PHSENT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
3	NSDBG	Debug mode switch. The value of NSDBG specifies whether or not the debug option is active. The value of NSDBG must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 debug is not active, off (default) $= 2.0$ debug is active, on If the field containing NSDBG is left blank, then the debug mode is assumed to be not active (off). If the value of NSDBG is greater than 2.0, the message, DEBUG MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine PRBGEN. The debug logic, if active (on), will cause the common blocks associated with this input phase to be dumped at the end of each subroutine in the phase and at the end of the logical phase. These actions are taken in subroutines SBREXT and PHSEXT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
4	NSPLT	Plot mode switch. The value of NSPLT specifies whether or not plots will be produced by this generator phase. The value of NSPLT must be integral and less than or equal to 2.0. The following definitions apply: ≤ 1.0 no plots produced, option off (default) $= 2.0$ plots produced, option on

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		If the field containing NSPLT is left blank, then no plots will be produced (off). If the value of NSPLT is greater than 2.0, the message, PLOT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine PRBGEN.
5	NSPRT	Print mode switch. The value of NSPRT controls the printing in this generator phase. The value of NSPRT must be integral and less than or equal to 2.0. The following definitions apply: = 1.0 only input records and error messages are printed, option off = 2.0 full printing done, option on (default) If the field containing NSPRT is left blank, full printing is done (option on). If the value of NSPRT is greater than 2.0, the message, PRINT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine PRBGEN.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The PRO input record specifies the processor to be used for the problem. The PRO input record is optional at start time and is not allowed at restart time. When used, one and only one record is required; when not used, default values are assumed.

	min	max
start	0	1
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	NSPRO	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable												
1	NSPRO	Processor indicator switch. The value of NSPRO indicates the type of processor to be used for this problem. The value of NSPRO must be integral and less than or equal to 13. The following definitions apply: <table><tr><td>< 1.0</td><td>one-dimensional, STEALTH 1D (default)</td></tr><tr><td>= 2.0</td><td>two-dimensional, STEALTH 2D</td></tr><tr><td>= 3.0</td><td>three-dimensional, STEALTH 3D (not available)</td></tr><tr><td>= 11.0</td><td>one-dimensional archive data processor, ADAPRO 1D</td></tr><tr><td>= 12.0</td><td>two-dimensional archive data processor, ADAPRO 2D</td></tr><tr><td>= 13.0</td><td>three-dimensional archive data processor, ADAPRO 3D (not available)</td></tr></table>	< 1.0	one-dimensional, STEALTH 1D (default)	= 2.0	two-dimensional, STEALTH 2D	= 3.0	three-dimensional, STEALTH 3D (not available)	= 11.0	one-dimensional archive data processor, ADAPRO 1D	= 12.0	two-dimensional archive data processor, ADAPRO 2D	= 13.0	three-dimensional archive data processor, ADAPRO 3D (not available)
< 1.0	one-dimensional, STEALTH 1D (default)													
= 2.0	two-dimensional, STEALTH 2D													
= 3.0	three-dimensional, STEALTH 3D (not available)													
= 11.0	one-dimensional archive data processor, ADAPRO 1D													
= 12.0	two-dimensional archive data processor, ADAPRO 2D													
= 13.0	three-dimensional archive data processor, ADAPRO 3D (not available)													

If the field containing NSPRO is left blank, then NSPRO is assumed to be equal to 1.0, i.e., one-dimensional processor. If the value of NSPRO is between 3.0 and 11.0 or is greater than 13.0, the message

PROCESSOR INDICATOR SWITCH
IMPROPERLY DEFINED

is written on the print and the message files, and the program terminates immediately in subroutine PRBINP.

2-7 -- Fields 2-7 must be left blank or FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The SOR input record specifies the start or restart mode and time for the problem. It is optional for start runs but is required for restart runs. When used, one and only one record is required; when not used, default values are assumed.

	min	max
start	0	1
restart	1	1

Columns →	11	21	31	41	51	61	71	80
	NSSOR	TIMSOR	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSSOR	Start or restart indicator switch. The value of NSSOR indicates if the run is a start or restart run. The value of NSSOR must be integral and less than or equal to 3. The following definitions apply: ≤ 1.0 start (default) $= 2.0$ standard restart $= 3.0$ special restart If the field containing NSSOR is left blank, then NSSOR is assumed to be equal to 1.0, i.e., a start run. If the value of NSSOR is greater than 3.0, the message, START OR RESTART INDICATOR SWITCH IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine PRBINP.
2	TIMSOR	Start or restart time. The value of TIMSOR must be positive. When NSSOR = 1.0, TIMSOR is equal to start time; when NSSOR = 2.0 or 3.0, TIMSOR is equal to restart time. Default is 0.0.
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The DTS input record specifies the time step stability criterion to be used for this problem. It is optional for both start and restart runs. When used, one and only one record is required; when not used, default values are assumed.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	NSDTS	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSDTS	Dynamic-thermal-static indicator switch. The value of NSDTS indicates the type of time step control to be used. The value of NSDTS must be integral and less than or equal to 3. The following definitions apply:

- ≤ 1.0 stress wave dynamic only (default)
- = 2.0 dynamic relaxation*
- = 3.0 thermal transient only*
- = 4.0 complete mechanical and thermal response

If the field containing NSDTS is left blank, then NSDTS is assumed to be equal to 1.0, i.e., stress wave dynamic. If the value of NSDTS is greater than 4.0, the message,

DYNAMIC-THERMAL-STATIC
INDICATOR SWITCH
IMPROPERLY DEFINED

is written on the print and the message files and the program terminates immediately in subroutine PRBINP.

2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Not available in implicit versions.

Symmetry Specification

Page 1 of 1

TYPE
SYM

The SYM input record specifies the symmetry for the problem. It is optional for start runs, but is not allowed for restart runs. When used, one and only one record is required; when not used, default values are assumed.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	NSSYM	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSSYM	Symmetry indicator switch. The value of NSSYM indicates the symmetry option to be used for this run. The value of NSSYM must be integral and less than or equal to 6. The following definitions apply:

≤ 1.0	plane 1-D or translational 2-D* (default)
= 2.0	cylindrical 1-D or axial 2-D*
= 3.0	spherical 1-D
= 4.0	plane flow in a variable-area cylindrical duct 1-D**
= 5.0	cylindrically divergent flow between plates 1-D**
= 6.0	special, user-supplied

If the field containing NSSYM is left blank, then NSSYM is assumed to be equal to 1.0, i.e., plane symmetry in one dimension or translational symmetry in two dimensions. If the value of NSSYM is greater than 6.0, the message,

SYMMETRY INDICATOR SWITCH
IMPROPERLY DEFINED

is written on the print and the message files and the program terminates immediately in subroutine PRBINP.

2-7 -- Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* In 2-D axial symmetry, the x-direction is the radial direction and the y-direction is the axial direction.

** Not available in the implicit versions.

Tolerances

Page 1 of 1

TYPE

TOL

The TOL input record specifies calculational tolerances for this problem. It is optional for both start and restart runs. When used, one and only one record is required; when not used, default values are assumed.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	RELTOL	SMLNUM	BIGNUM	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	RELTOL	Relative tolerance. The value of RELTOL must be positive. The purpose of RELTOL is to provide a "nearness" criterion when comparing two real numbers, neither of which is zero. If the TOL input record is omitted or if RELTOL is less than or equal to 10^{-14} , then the default value is assumed. The default value is machine-dependent. For a 60-bit word, 10^{-14} is used.
2	SMLNUM	Small number. The value of SMLNUM must be positive. The purpose of SMLNUM is to provide a "nearness" criterion when comparing the absolute value of a number to zero. If the TOL input record is omitted or if SMLNUM is less than or equal to zero, then the default value is assumed. The default value is machine-dependent. For a 60-bit word, 2.0×10^{-293} is used.
3	BIGNUM	Big Number. The value of BIGNUM must be positive. The purpose of BIGNUM is to provide a "nearness" criterion when comparing the absolute value of a number to the largest number handled by a particular computer (machine infinity). If the TOL input record is omitted or if BIGNUM is less than or equal to SMLNUM, then the default value is assumed. The default value is machine-dependent. For a 60-bit word, 0.5×10^{293} is used.
4-7	--	Fields 4-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The MIN input record specifies minimum values of velocity. It is optional for both start and restart runs. When used, one and only one record is required; when not used, default values are assumed.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	SSSMIN	XVLMIN	YVLMIN	ZVLMIN	DSTMIN	PRHMIN	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	SSSMIN	Sound-speed squared minimum value. The value of SSSMIN is the minimum allowable value of sound-speed squared. During a calculation, if the absolute value of sound-speed squared goes below this value, it is set equal to SSSMIN. The value of SSSMIN must be a positive number. The default value is 10^{-4} , which is a reasonable number for cm-gm- μ sec problem units. SSMIN is not used for the incompressible flow versions. Leave blank unless running in the explicit mode.
2	XVLMIN	x-component of material velocity minimum value. The value of XVLMIN is the minimum allowable absolute value of x-component material velocity before values of material velocity in the x-direction are set to zero. That is, the absolute value of an x-component material velocity below XVLMIN is set to zero, exactly. The value of XVLMIN must be a positive number. The default value is 10^{-8} , which is a reasonable number for cm-g- μ sec problem units.
3	YVLMIN	y-component of material velocity minimum value. The value of YVLMIN is the minimum allowable absolute value of y-component material velocity before values of material velocity in the y-direction are set to zero. That is, the absolute value of a y-component material velocity below YVLMIN is set to zero, exactly. The value of YVLMIN must be a positive number. The default value is 10^{-8} , which is a reasonable number for cm-g- μ sec problem units. (Only required for two-dimensional problems.)
4	ZVLMIN	z-component of material velocity minimum value. The value of ZVLMIN is the minimum allowable absolute value of z-component material velocity before values of material velocity in the z-direction are set to zero. That is, the absolute value of a z-component material velocity below ZVLMIN is set to zero, exactly. The value of ZVLMIN must be a positive number. The default value is 10^{-8} , which is a reasonable number for cm-g- μ sec problem units. (Only required for three-dimensional problems.)

TYPE MIN

Columns →	11	21	31	41	51	61	71	80
	SSSMIN	XVLMIN	YVLMIN	ZVLMIN	DSTMIN	PRHMIN	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
5	DSTMIN	Minimum distance. The value of DSTMIN should be set equal to 10% of the distance across a typical boundary zone in problem units.* This number is used to determine when a grid point and a constraint (i.e., wall segment) are in contact. The default value is 10^{-2} .
6	PRHMIN	Minimum pressure for iteration convergence test. If the zone pressure is below PRHMIN, the test for convergence in the implicit, compressible flow versions is skipped, and the iteration is assumed to have converged for that zone. The value of PRHMIN must be a positive number. The default value is 10^{-6} . Leave blank for the incompressible flow versions.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the generator phase group. (See Appendix "Messages".)

* 10% of the distance across a typical boundary zone should be used in fluid flow problems where it is desirable to avoid separation between the fluid and the constraining wall. If it is desirable to allow separation, a value of 1% should be used; however, this could retard convergence of the iteration in the implicit versions and in some cases could lead to an unstable iteration.

TYPE MIN

Acceleration of Gravity

Page 1 of 1

TYPE

GRV

The GRV input record specifies values of gravity acceleration components for an entire problem. If the GRV input record is omitted, the default values are used. The GRV record may be used at restart time to change the values of gravity acceleration components.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	GRVX	GRVY	GRVZ	NSGRV	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	GRVX	Acceleration of gravity in the x-direction. A positive value of GRVX results in an acceleration in the positive x-direction, while a negative value of GRVX results in an acceleration in the negative x-direction. The default value of GRVX is 0.0.
2	GRVY	Acceleration of gravity in the y-direction. A positive value of GRVY results in an acceleration in the positive y-direction, while a negative value of GRVY results in an acceleration in the negative y-direction. The default value of GRVY is 0.0. GRVY must be left blank for one-dimensional problems.
3	GRVZ	Acceleration of gravity in the z-direction. Not used for the incompressible flow versions. Leave blank.
4	NSGRV	Gravity overburden switch.* The value of NSGRV must be integer and less than or equal to two. The following definitions apply: ≤ 1.0 $= 2.0$ no overburden pressure gradient will be calculated the overburden pressure gradient balancing the gravitational force will be calculated automatically [assumes $P = 0$ at $y_{\max}^x(j_{\max})$ and gravity is in the negative y-direction].

*This parameter applies only to the 2D incompressible flow version, For the 1D incompressible flow version, initial pressures must be input directly. For the 1D and 2D compressible flow versions, initial pressures are determined by initial values of relative volume and internal energy specified in the ZON input phase.

The GRD input record defines a complete grid. At least one grid must be specified.* The GRD input record may not be used at restart time.

	min	max
start	1	MAXGRD
restart	1	0

Columns →	11	21	31	41	51	61	71	80
	LG	MSHTYP	NUMILN	NUMJLN	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	LG	Grid number.* The value of LG must be a unique number for each grid. The value of LG must be integral and greater than or equal to 1 and less than or equal to MAXGRD. (See Appendix "Maximums".) If LG is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
2	MSHTYP	Mesh type. The value of MSHTYP indicates the type of grid defined by this input record. The value of MSHTYP must be integral and less than or equal to 3. The following definitions apply: ≤ 1.0 Lagrange or ALE (default) $= 2.0$ Euler (not available) $= 3.0$ other (not available) If the field containing MSHTYP is left blank or has a value different from 1.0, then the value of MSHTYP is set equal to 1.0.
3	NUMILN	Number of I lines. The value of NUMILN must be integral and greater than or equal to 2 and less than or equal to MAXGPT. (See Appendix "Maximums".) If NUMILN is out of this range, a RGEERR message is written on the print and the message files, and the program terminates immediately in subroutine PRBINP. (See Appendix "Messages".)
4	NUMJLN	Number of J lines. The value of NUMJLN must be integral and greater than or equal to 2 and less than or equal to MAXBUF. (See Appendix "Maximums".) If NUMJLN is out of this range, a RGEERR message is written on the print and the message files, and the program terminates immediately in subroutine PRBINP. (See Appendix "Messages".) NUMJLN must be left blank for one-dimensional grids.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Implicit Iteration

Page 1 of 2

TYPE

ITR

The ITR input record defines parameters used in the ZON phase iteration. It is used only in the implicit versions.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MAXITR	EPSLN	RLXPRM	NSITP	EXPBGN	EXPEND	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MAXITR	Maximum number of ZON phase iterations. The calculation will terminate with an error message when this limit is exceeded. The value of MAXITR must be integer. The default value is 200.
2	EPSLN	Iteration convergence criterion. Convergence of the ZON phase iteration occurs when the convergence variable* is less than or equal to EPSLN. This value is problem-dependent (see the discussion in Section 6). The default value is 10^{-3} .
3	RLXPRM	Relaxation factor. The value of RLXPRM must be less than 2.0. Values greater than 1.0 can increase the rate of convergence in many cases, but as the value approaches 2.0, the chance for an unstable iteration increases. Values less than 1.0 may improve the rate of convergence in some unusual cases, but usually result in a slower rate of convergence. In general, a value of 1.5 seems to work well. The default value is 1.0.
4	NSITP	Iteration type switch. The value of NSITP indicates the type of iteration to be used to solve the implicit equations of motion for this run. The value of NSITP must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 Newton-Raphson method (default) $= 2.0$ two-sided secant method (for use primarily with highly non-linear material properties)
5	EXPBGN	Explicit integration start time. The value of EXPBGN indicates the problem time at which the time integration of the equation of motion will switch from the normal (for this version of the

*The convergence variable is the volume strain rate for the incompressible flow version; for the implicit, compressible flow version it is the ratio of a pressure difference to the zone pressure. See Sections 4 and 5 for details.

TYPE

ITR

Columns →	11	21	31	41	51	61	71	80
	MAXITR	EPSLN	RLXPRM	NSITP	EXPBGN	EXPEND	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		code) implicit method to an explicit method. The value of EXPBGN must be greater than or equal to zero and less than or equal to EXPEND. The default value is zero.
6	EXPEND	Explicit integration end time. The value of EXPEND indicates the problem time at which the time integration of the equations of motion will switch back from an explicit method to the normal implicit method. The value of EXPEND must be greater than or equal to EXPBGN. The default value is zero, which indicates that no explicit integration will be done for this run.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The ALE input record defines parameters used in the ALE rezone phase. It is used only in the implicit versions.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	NSALE	FLXCZ	FLXCG	DPGFAC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSALE	Mesh rezone model switch. The value of NSALE must be integer and less than or equal to nine. The following definitions apply: ≤ 1.0 Lagrangian (default) $= 2.0$ Eulerian $= 3.0^*$ Lagrangian free surface at the top (JMAX/YMAX) boundary; points within the mesh are rezoned to maintain a regular mesh. This is designed for surface wave problems. $= 4.0$ New position of each grid point is the mean of the positions of the eight surrounding points. $= 5.0$ New position of each grid point is the location that makes the four surrounding zones conform as closely as possible to parallelograms. $= 6.0$ New x-position of each grid point is the mean of the x-positions of the eight surrounding points; the new y-position is the Lagrangian y-position. $= 7.0$ New y-position of each grid point is the mean of the y-positions of the eight surrounding points; the new x-position is the Lagrangian x-position. $= 8.0$ New position of each grid point is the mean position of the intersections of four lines normal to the sides of the four-zone quadrilateral surrounding each point and through the mid-point of each side. This produces a mesh that roughly approximates one with orthogonal I- and J-lines (sometimes call an equipotential mesh). $= 9.0$ Available for special mesh rezoners.

*Use of this option requires that x increases in the direction of increasing i and y increases in the direction of increasing j.

TYPE ALE

Columns →	11	21	31	41	51	61	71	80
	NSALE	FLXCZ	FLXCG	DPGFAC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		For NSALE = 4 - 9, the amount each point is rezoned is controlled by the damping factor DMPFAC as described below. Rezoning of boundary points is controlled by the parameter NBRBSG on record type 412 in the boundary phase input block.
2	FLXCZ	Flux centering constant for zone-centered variables. The value of FLXCZ must be greater than or equal to zero and less than or equal to 1.0. Centering of zone variables for the flux calculations depends on this value as follows: $\begin{array}{ll} \text{FLXCZ} = 0.0 & \text{centered (default)} \\ \text{FLXCZ} = 1.0 & \text{donor cell} \\ 0.0 < \text{FLXCZ} < 1.0 & \text{interpolated donor cell} \end{array}$
3	FLXCG	Flux centering constant for grid point variables. Specification and default value are the same as for FLXCZ.
4	DMPFAC	Damping factor. DMPFAC controls the distance each point is moved from its Lagrangian position to the position specified by the rezone model according to the following prescription: $\underline{x}_{\text{new}} = f \cdot \underline{x}_{\text{mdl}} + (1.0 - f) \cdot \underline{x}_{\text{Lag}},$ where f is the damping factor. Notice that when f = 0.0 no rezoning occurs and when f = 1.0 each point is moved all the way to the position calculated by the model. The value of DMPFAC is limited to the range 0.0 - 1.0. The default value is 1.0.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE ALE

The CPL input record defines the parameters used in the node coupling routines.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	CPLPRM	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	CPLPRM	Node coupling parameter. The value of CPLPRM determines the strength of the artificial node coupling force used to damp the alternating node instability. Normally the value of CPLPRM should be in the range 0.0 - 0.25. Values greater than 0.25 could lead to energy conservation problems, so care should be exercised when using values in this range. For CPLPRM = 0.0, the node coupling calculation is omitted. The default value is 0.0.
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
END

The END input record signifies the end of a block of data for the PRB input phase. It is required whether or not PRB input records are used and must follow the PRB control record if there is no PRB input data.

	min	max
start	1	1
restart	1	1

Columns →	11	21	31	41	51	61	71	80
	--	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1-7	--	Fields 1-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
END

7.1 MATERIAL SPECIFICATION PHASE (MAT)

The material specification phase (MAT) input block may be located in any position in the input deck after the PRB input block and before the final END record. The purpose of the MAT input block is to specify the material models for the problem. One set of MAT records is required at start time for each material in the problem. At restart time, MAT records need be included only if a material parameter is to be changed. In this case all of the parameters on the record where the change is made must be input again. New materials may not be specified at restart time unless dummy materials were specified at start time; that is, certain parts of the mesh were given dummy material property numbers in the start run.

A material model is defined by a unique material property number, MPN. (MPN is the index of the material arrays in the /MATARY/ labeled COMMON blocks.) MPN is always specified in the first field of a record.

The MAT phase input records are divided into the following groups:

<u>Record Identifier</u>	<u>Group description</u>
11__	model-type specification
12__	equation-of-state parameters
13__	strength/viscosity parameters
14__	energy release parameters
15__	heat flow parameters
17__	artificial viscosity parameters

All variables on all records in the MAT phase except reference density, RDN, on record type 121 have default values. Thus, it is possible to specify a material by specifying only one input record, the 121 input

record with a reference density greater than the tolerance SMLNUM. The resulting material will have no properties other than inertia.

For the incompressible flow versions only a few of the MAT phase records are required. Since reference density is the only MAT phase variable used by the inviscid, incompressible flow versions, only record type 121 should be included. For the viscous, incompressible flow versions the only additional variables required are the viscosity parameters. Therefore only record types 112, 121, 134, and 135 should be included.

A summary of MAT phase input records and input variables appears in Table 7.1.

TABLE 7.1

SUMMARY OF MAT PHASE INPUT RECORDS AND INPUT VARIABLES

FIELDS 1-7

TYPE	1	2	3	4	5	6	7
MAT	NSINP	NSTRC	NSDBG	NSPLT	NSPRT		
111	MPN	MEOS					
112	MPN	MYLD	MSHR	MSPL			
113	MPN	MERL					
114	MPN	MCON	MSHC				
115	MPN	MAVS					
121	MPN	RDN					
122	MPN	EOS0	EOS1	EOS2	EOS3	EOS4	
123	MPN	EOS5	EOS6	EOS7	EOS8	EOS9	
134	MPN	SHR0	SHR1	SHR2	SHR3	SHR4	
135	MPN	SHR5	SHR6	SHR7	SHR8	SHR9	
142	MPN	ERL0	ERL1	ERL2	ERL3	ERL4	
152	MPN	CON0	CON1	CON2	CON3	CON4	
154	MPN	SHC0	SHC1	SHC2	SHC3	SHC4	
171	MPN	CQV	CLV	CVT			
END							

The function of the MAT control record is to activate the MAT input phase. The MAT control record must follow an END input record and is required for all start runs. It may be used at restart time to change data.

	min	max
start	1	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSINP	Input mode switch. The value of NSINP specifies the mode of input to be used in this input phase. The value of NSINP must be integral and less than or equal to 3. The following definitions apply:

≤ 1.0 card input (default)
 $= 2.0$ library input
 $= 3.0$ keyboard input

If the field containing NSINP is left blank, then the mode of input is assumed to be card input. If the value of NSINP is greater than 3.0, the message,

INPUT MODE SWITCH
 IMPROPERLY DEFINED

is written on the print and the message files, and the program terminates immediately in subroutine GENGEN.

2	NSTRC	Trace mode switch. The value of NSTRC specifies whether or not the trace option is active. The value of NSTRC must be integral and less than or equal to 2. The following definitions apply:

≤ 1.0 trace is not active, off (default)
 $= 2.0$ trace is active, on

If the field containing NSTRC is left blank, then the mode is assumed to be not active (off). If the value of NSTRC is greater than 2.0, the message,

TRACE MODE SWITCH
 IMPROPERLY DEFINED

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The trace logic, if active (on), will cause the name of the subroutine or logical phase just entered to be printed on both the print and message files. These actions are taken in subroutines SBRENT and PHSENT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
3	NSDBG	Debug mode switch. The value of NSDBG specifies whether or not the debug option is active. The value of NSDBG must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 debug is not active, off (default) $= 2.0$ debug is active, on If the field containing NSDBG is left blank, the the debug mode is assumed to be not active (off). If the value of NSDBG is greater than 2.0, the message, DEBUG MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The debug logic, if active (on), will cause the common blocks associated with this input phase to be dumped at the end of each subroutine in the phase and at the end of the logical phase. These actions are taken in subroutines SBREXT and PHSEXT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
4	NSPLT	Plot mode switch. The value of NSPLT specifies whether or not plots will be produced by this generator phase. The value of NSPLT must be integral and less than or equal to 2.0. The following definitions apply: ≤ 1.0 no plots produced, option off (default) $= 2.0$ plots produced, option on

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		If the field containing NSPLT is left blank, then no plots will be produced (off). If the value of NSPLT is greater than 2.0, the message, PLOT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine MATGEN.
5	NSPRT	Print mode switch. The value of NSPRT controls the printing in this generator phase. The value of NSPRT must be integral and less than or equal to 2.0. The following definitions apply: = 1.0 only input records and error messages are printed, option off = 2.0 full printing done, option on (default) If the field containing NSPRT is left blank, full printing is done (option on). If the value of NSPRT is greater than 2.0, the message, PRINT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine MATGEN.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 111 input record specifies the type of equation-of-state model for material MPN. If the 111 input record is omitted, the default value is used. The 111 input record may be used at restart time to change the equation-of-state model type.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	MEOS	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable														
1	MPN	Material property number. The value of MPN uniquely identifies a material model. A model consists of an equation of state and strength, explosive, and thermal descriptions. A single value of MPN links together a set of MAT phase input records for one material model. The value of MPN must be integral and must be greater than or equal to 1 and less than or equal to MAXMAT. (See Appendix "Maximums".) If MPN is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine MATINP. (See Appendix "Messages".)														
2	MEOS	Equation-of-state model type. The value of MEOS uniquely identifies the type of equation-of-state model for material MPN. The equation of state defines a relationship for pressure as a function of relative volume and internal energy density. The value of MEOS must be integral and must be greater than or equal to 1 and less than or equal to MAXEOS. (See Appendix "Maximums".) If MEOS is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine MATINP. (See Appendix "Messages".) The following definitions apply: <table><tr><td>= 1.0</td><td>function of relative volume only (default)</td></tr><tr><td>= 2.0</td><td>function of internal energy density only</td></tr><tr><td>= 3.0</td><td>function of relative volume and internal energy density</td></tr><tr><td>= 4.0</td><td>p-α compaction model (not yet programmed)</td></tr><tr><td>= 5.0</td><td>JWL chemical explosive model (not yet programmed)</td></tr><tr><td>= 6.0-</td><td></td></tr><tr><td>10.0</td><td>user-supplied models</td></tr></table>	= 1.0	function of relative volume only (default)	= 2.0	function of internal energy density only	= 3.0	function of relative volume and internal energy density	= 4.0	p- α compaction model (not yet programmed)	= 5.0	JWL chemical explosive model (not yet programmed)	= 6.0-		10.0	user-supplied models
= 1.0	function of relative volume only (default)															
= 2.0	function of internal energy density only															
= 3.0	function of relative volume and internal energy density															
= 4.0	p- α compaction model (not yet programmed)															
= 5.0	JWL chemical explosive model (not yet programmed)															
= 6.0-																
10.0	user-supplied models															

A description of each model is presented in Appendix "Material Models". Coefficients for a particular model are entered on input records 121, 122, 123.

*Record type 111 is not used for the incompressible flow versions.

Columns →	11	21	31	41	51	61	71	80
	MPN	MEOS	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

<u>Field Number</u>	<u>Input Variable Name</u>	<u>Description of Input Variable</u>
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 112 input record specifies the type of strength model for material MPN. If the 112 input record is omitted, default values are used. The 112 input record may be used at restart time to change the strength/viscosity model types.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	MYLD	MSHR	MSPL	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See field number 1 on TYPE 111 record.
2	MYLD	Yield stress model type. Not used for implicit fluid mechanics versions. Leave blank.
3	MSHR	Shear modulus**/viscosity coefficient model type. For the implicit fluid mechanics versions, MSHR identifies the type of viscosity coefficient model for material MPN. The model defines a relationship for the bulk and shear viscosity coefficients as a function of thermodynamic variables and time. The value of MSHR must be integral and must be greater than or equal to 1 and less than or equal to MAXSHR. (See Appendix "Maximums".) If MSHR is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine MATINP. (See Appendix "Messages".) The following definitions apply: = 1.0 hydrodynamic (default) = 2.0 constant = 3.0 function of pressure only = 4.0 function of internal energy density only = 5.0 function of distortional (viscous) energy density only = 6.0- 10.0 user-supplied models A description of each model is presented in Appendix "Material Models". Coefficients for a particular model are entered on input records 134 and 135.
4	MSPL	Spall model type. Not used for implicit fluid mechanics versions. Leave blank.

*Record type 112 is not used for the inviscid, incompressible flow versions.

**MSHR is used to specify the shear modulus model in the explicit versions.

Columns →	11	21	31	41	51	61	71	80
	MPN	MYLD	MSHR	MSPL	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 113 input record specifies the type of energy release model for material MPN. If the 113 input record is omitted, the default value is used. The 113 input record may be used at restart time to change the energy release model type.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	MERL	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	MERL	Energy release model type. The value of MERL identifies the type of energy release model for material MPN. The energy release model defines a relationship for release of chemical energy as a function of thermodynamic variables and time. The value of MERL must be integral and must be greater than or equal to 1 and less than or equal to MAXERL. (See Appendix "Maximum".) If MERL is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine MATINP. (See Appendix "Messages".) The following definitions apply: = 1.0 no energy release (default) = 2.0 Chapman-Jouguet explosive model (not yet programmed) = 3.0 no model presently defined = 4.0 no model presently defined = 5.0 no model presently defined = 6.0- no model presently defined 10.0 user-supplied models A description of each model is presented in Appendix "Material Models". Coefficients for a particular model are entered on input records 141 and 142.
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*Record type 113 is not used for the incompressible flow versions.

Heat Flow Model Type*

Page 1 of 2

TYPE
114

The 114 input record specifies the type of heat flow model for material MPN. If the 114 input record is omitted, default values are used. The 114 input record may be used at restart time to change heat flow model types.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	MCON	MSHC	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.

2	MCON	Conduction model type. The value of MCON identifies the type of heat conduction model for material MPN. The heat conduction model defines a relationship for heat conductivity as a function of thermodynamic variables and time. The value of MCON must be integral and must be greater than or equal to 1 and less than or equal to MAXCON. (See Appendix "Maximums".) If MCON is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine MATINP. (See Appendix "Messages".) The following definitions apply:

- = 1.0 no heat conduction (default)
- = 2.0 constant heat conduction
- = 3.0 function of temperature only
- = 4.0 no model presently defined
- = 5.0 no model presently defined
- = 6.0-10.0 user-supplied models

A description of each model is presented in Appendix "Material Models". Coefficients for a particular model are entered on input record 152.

*Record type 114 is not used for the incompressible flow versions.

Columns →	11	21	31	41	51	61	71	80
	MPN	MCON	MSHC	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	MSHC	Specific heat capacity model type. The value of MSHC identifies the type of specific heat capacity model for material MPN. The specific heat capacity model defines a relationship for specific heat capacity as a function of thermodynamic variables and time. The value of MSHC must be integral and must be greater than or equal to 1 and less than or equal to MAXSHC. (See Appendix "Maximums".) If MSHC is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine MATINP. (See Appendix "Messages".) The following definitions apply: = 1.0 no specific heat capacity (default) = 2.0 constant specific heat capacity = 3.0 function of temperature only = 4.0 no model presently defined = 5.0 no model presently defined = 6.0-10.0 user-supplied models A description of each model is presented in Appendix "Material Models". Coefficients for a particular model are entered on input record 154.
4-7	--	Fields 4-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Artificial Viscosity Model Type*

Page 1 of 1

TYPE

115

The 115 input record specifies the type of artificial viscosity model for material MPN. If the 115 input record is omitted, the default value is used. The 115 record may be used at restart time to change the artificial viscosity model type.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	MAVS	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	MAVS	Artificial viscosity model type. The value of MAVS identifies the type of artificial viscosity model for material MPN. The artificial viscosity model defines a relationship for linear, quadratic, and tensor artificial viscosities. The value of MAVS must be integral and must be greater than or equal to 1 and less than or equal to 5. If MAVS is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine MATINP. (See Appendix "Messages".) The following definitions apply: = 1.0 quadratic artificial viscosity in compression only (default) = 2.0 quadratic artificial viscosity in compression and linear artificial viscosity always = 3.0 quadratic artificial viscosity in compression and linear artificial viscosity in compression = 4.0 quadratic artificial viscosity in compression and linear artificial viscosity in expansion = 5.0 user-supplied model A description of each model is presented in Appendix "Material Models". Coefficients for a particular model are entered on input record 171.
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Record type 115 is not used in the incompressible flow versions and is generally not used in the implicit, compressible flow versions unless part of the problem is being run explicitly.

Reference Density

Page 1 of 1

TYPE
121

The 121 input record specifies the reference density for the equation of state for material MPN. The 121 record is absolutely required for each equation-of-state model. The 121 input record may be used at restart time to change the reference density.

	min	max
start	1	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	RDN	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	RDN	Reference density. The value of RDN must be a positive number greater than SMLNUM. If RDN is less than SMLNUM a material is assumed not to exist. The value of RDN is often chosen to be that of the initial density. There is no default value.
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 122 input record specifies equation-of-state parameters for the equation-of-state model specified on the 111 input record. If the 122 input record is omitted, default values are used. The 122 input record may be used at restart time to change equation-of-state parameters.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	EOS0	EOS1	EOS2	EOS3	EOS4	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	EOS0	Equation-of-state parameter 0. (See Appendix "Material Models".) Default value is 0.
3	EOS1	Equation-of-state parameter 1. (See Appendix "Material Models".) Default value is 0.
4	EOS2	Equation-of-state parameter 2. (See Appendix "Material Models".) Default value is 0.
5	EOS3	Equation-of-state parameter 3. (See Appendix "Material Models".) Default value is 0.
6	EOS4	Equation-of-state parameter 4. (See Appendix "Material Models".) Default value is 0.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*Record type 122 is not used for the incompressible flow versions.

Equation-of-State Parameters (#2)*

Page 1 of 1

TYPE

123

The 123 input record specifies equation-of-state parameters for the equation-of-state model specified on the 111 input record. If the 123 input record is omitted, default values are used. The 123 input record may be used at restart time to change equation-of-state parameters.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	EOS5	EOS6	EOS7	EOS8	EOS9	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	EOS5	Equation-of-state parameter 5. (See Appendix "Material Models".) Default value is -1.0.
3	EOS6	Equation-of-state parameter 6. (See Appendix "Material Models".) Default value is 100.
4	EOS7	Equation-of-state parameter 7. (See Appendix "Material Models".) Default value is 0.
5	EOS8	Equation-of-state parameter 8. (See Appendix "Material Models".) Default value is 0.
6	EOS9	Equation-of-state parameter 9. (See Appendix "Material Models".) Default value is 0.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*Record type 123 is not used for the incompressible flow versions.

The 134 input record specifies shear viscosity coefficient parameters of the viscosity coefficient model specified on the 112 input record. If the 134 input record is omitted, default values are used. The 134 input record may be used at restart time to change shear viscosity coefficient parameters.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	SHRO	SHR1	SHR2	SHR3	SHR4	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	SHRO	Shear viscosity coefficient parameter 0. (See Appendix "Material Models".) Default value is 0.
3	SHR1	Shear viscosity coefficient parameter 1. (See Appendix "Material Models".) Default value is 0.
4	SHR2	Shear viscosity coefficient parameter 2. (See Appendix "Material Models".) Default value is 0.
5	SHR3	Shear viscosity coefficient parameter 3. (See Appendix "Material Models".) Default value is 0.
6	SHR4	Shear viscosity coefficient parameter 4. (See Appendix "Material Models".) Default value is 0.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* For the implicit, compressible flow versions and the viscous, incompressible flow versions, record type 134 is used to specify parameters for the shear viscosity coefficient model. This is in contrast to the explicit versions where this record type specifies the shear modulus parameters. For the inviscid, incompressible flow versions, record type 134 is not used.

The 135 input record specifies bulk viscosity coefficient parameters for the viscosity coefficient model specified on the 112 input record. If the 135 input record is omitted, default values are used. The 135 input record may be used at restart time to change bulk viscosity coefficient parameters.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	SHR5	SHR6	SHR7	SHR8	SHR9	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	SHR5	Bulk viscosity coefficient parameter 0. (See Appendix "Material Models".) Default value is 0.
3	SHR6	Bulk viscosity coefficient parameter 1. (See Appendix "Material Models".) Default value is 0.
4	SHR7	Bulk viscosity coefficient parameter 2. (See Appendix "Material Models".) Default value is 0.
5	SHR8	Bulk viscosity coefficient parameter 3. (See Appendix "Material Models".) Default value is 0.
6	SHR9	Bulk viscosity coefficient parameter 4. (See Appendix "Material Models".) Default value is 0.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*Record type 135 is not used for the inviscid, incompressible flow versions.

Energy Release Parameters*

Page 1 of 1

TYPE 142

The 142 input record specifies energy release parameters for the energy release model specified on the 113 input record. If the 142 input record is omitted, default values are used. The 142 input record may be used at restart time to change energy release parameters.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	ERL0	ERL1	ERL2	ERL3	ERL4	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	ERL0	Energy release parameter 0. (See Appendix "Material Models".) Default value is 0.
3	ERL1	Energy release parameter 1. (See Appendix "Material Models".) Default value is 0.
4	ERL2	Energy release parameter 2. (See Appendix "Material Models".) Default value is 0.
5	ERL3	Energy release parameter 3. (See Appendix "Material Models".) Default value is 0.
6	ERL4	Energy release parameter 4. (See Appendix "Material Models".) Default value is 0.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*Record type 142 is not used for the incompressible flow versions.

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Heat Conductivity Parameters*

Page 1 of 1

TYPE

152

The 152 input record specifies heat conductivity parameters for the heat conductivity model specified on the 114 input record. If the 152 input record is omitted, default values are used. The 152 input record may be used at restart time to change heat conductivity parameters.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	CON0	CON1	CON2	CON3	CON4	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	CON0	Heat conductivity parameter 0. (See Appendix "Material Models".) Default value is 0.
3	CON1	Heat conductivity parameter 1. (See Appendix "Material Models".) Default value is 0.
4	CON2	Heat conductivity parameter 2. (See Appendix "Material Models".) Default value is 0.
5	CON3	Heat conductivity parameter 3. (See Appendix "Material Models".) Default value is 0.
6	CON4	Heat conductivity parameter 4. (See Appendix "Material Models".) Default value is 0.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*Record type 152 is not used for the incompressible flow versions.

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Specific Heat Capacity Parameters*

Page 1 of 1

TYPE
154

The 154 input record specifies specific heat capacity parameters for the specific heat capacity model specified on the 114 input record. If the 154 input record is omitted, default values are used. The 154 input record may be used at restart time to change specific heat capacity parameters.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	SHCO	SHC1	SHC2	SHC3	SHC4	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	SHCO	Specific heat capacity parameter 0. (See Appendix "Material Models".) Default value is 0.
3	SHC1	Specific heat capacity parameter 1. (See Appendix "Material Models".) Default value is 0.
4	SHC2	Specific heat capacity parameter 2. (See Appendix "Material Models".) Default value is 0.
5	SHC3	Specific heat capacity parameter 3. (See Appendix "Material Models".) Default value is 0.
6	SHC4	Specific heat capacity parameter 4. (See Appendix "Material Models".) Default value is 0.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*Record type 154 is not used for the incompressible flow versions.

Artificial Viscosity Parameters*

Page 1 of 1

TYPE
171

The 171 input record specifies artificial viscosity parameters for the artificial viscosity model specified on the 115 input record. If the 171 input record is omitted, default values are used. The 171 input record may be used at restart time to change artificial viscosity parameters.

	min	max
start	0	MAXMAT
restart	0	MAXMAT

Columns →	11	21	31	41	51	61	71	80
	MPN	CQV	CLV	CTV	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	CQV	Coefficient of quadratic artificial viscosity. The value of CQV must be a positive number greater than SMLNUM or the default value is used. A typical value of CQV is 2.0 for all materials up to 1 Mbar. When the 171 input record is not specified or the field is left blank the default value of 10^{-8} is assumed.
3	CLV	Coefficient of linear artificial viscosity. The value of CLV must be a positive number. Typical values range between 0.0 and 1.0. Default value is 0.0.
4	CTV	Coefficient of tensor viscosity. CTV is applicable only to two-dimensional problems and is ignored for one-dimensional problems.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*Record type 171 is not used for the incompressible flow versions. For the implicit, compressible flow versions, artificial viscosity is generally not used. Therefore, the default values for the coefficients are set so that the magnitude of the artificial viscosity will be essentially zero. However, quadratic and linear artificial viscosity may be needed in some cases, particularly when the implicit, compressible versions are run in their explicit modes. The tensor viscosity may be used to help prevent hourglass distortions in 2D grids; however this can generally be accomplished with the node coupler (see Section 5.6).

End of MAT Phase

Page 1 of 1

TYPE
END

The END input record signifies the end of a block of data for the MAT input phase. It must follow the last MAT input record.

	min	max
start	1	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	--	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1-7	--	Fields 1-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
END

7.2 GRID POINTS SPECIFICATION PHASE (GPT)

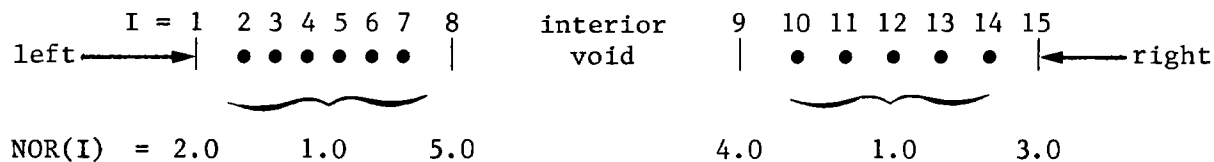
The grid points specification phase (GPT) input block may be located in any position in the input deck after the PRB input block and before the final END record. The purpose of the GPT input block is to specify the location and orientation of grid points and wall points for the problem at start time. The GPT input block may not be used at restart time. The GPT phase input is the same for all versions of STEALTH.

Grid points are specified by "grid" index (LG) and then by grid-point "block" index (L). (Both indexes are local to the GPT phase and are used to locate array elements in the labeled COMMON block/GPTPRM/.) Grids are defined by unique physical boundaries so that grid-point orientation can be determined. Grid-point blocks are defined as convenient groupings of grid points for the purpose of grid-point coordinate generation. From one to MAXBLK grid-point blocks can be specified in from one to MAXGRD grids (see Appendix "Maximums"). Blocks find their way into a particular grid by means of the specification of grid-point block index limits. Block index specification may not overlap two grids.

Grid-point orientation depends on the dimensionality of the PROCESSOR and is determined as a result of the input recorded on record types 21_. The STEALTH 1D processor allows six (6) orientations, as follows:

<u>Orientation Value</u> <u>NOR(I)</u>	<u>Orientation Description</u>
1.0	interior
2.0	outside left
3.0	outside right
4.0	inside left
5.0	inside right
6.0	special

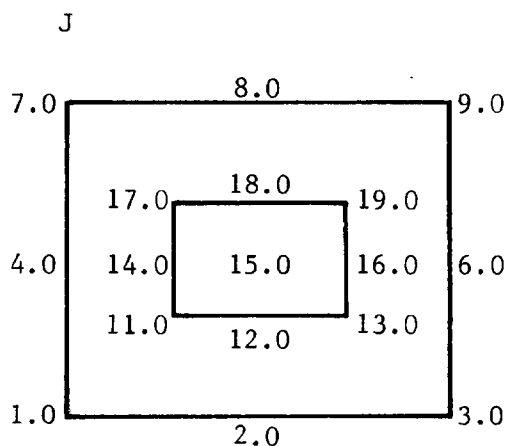
One orientation value is contained in each element of the NOR array. The index of the NOR array is the grid-point index, I. A one-dimensional problem is shown below in index space with appropriate orientation values.



To define the orientations, two grids would be required; on input record type 211, LG = 1.0 would include grid points 1 - 8, while LG = 2.0 would include grid points 9 - 15.

The STEALTH 2D processor allows twenty (20) orientations. The orientations values for a single grid are shown below in index space.

Orientation Value	
NOR(I,J)	Orientation Description
1.0	outside bottom left corner
2.0	outside bottom
3.0	outside bottom right corner
4.0	outside left
5.0	interior
6.0	outside right
7.0	outside top left corner
8.0	outside top
9.0	outside top right corner
10.0	user-supplied
11.0	inside bottom left notch *
12.0	inside bottom (same as 8.0) *
13.0	inside bottom right notch *
14.0	inside left (same as 6.0) *
15.0	nonexistent point
16.0	inside right (same as 4.0) *
17.0	inside top left notch *
18.0	inside top (same as 2.0) *
19.0	inside top right notch *
20.0	outside corner-on-corner *



$$20.0 = \frac{x}{x} \text{ or } \frac{x}{x}$$

Unlike the one-dimensional code, the orientation values are defined similarly for each grid.

The GPT phase input records for one- or two-dimensional coordinate input are divided into the following groups:

<u>Record Identifier</u>	<u>Group Description</u>
22__	Block definition
23__	Point-by-point input algorithms
24__	Equal zone input algorithms
25__	Geometric-ratio zone algorithms
26__	Polar and hyperbolic-elliptic zone algorithms
27__	Equipotential algorithms
28__	Special algorithms

There are no global input defaults in the GPT input block. Variable defaults do exist but are expressly noted in the text of the variable description. A minimum input for a start run consists of one input record to specify grid definition (orientations) and one input record to specify grid-point coordinates. Changing grid-point coordinates and orientation after a problem has started can be done only by rezoning.

A summary of GPT phase input records and input variables appears in Table 7.2.

7.2.1 One-Dimensional Input Blocks. A user may define the positions of mesh points in a grid by dividing the grid into one or more blocks. A block is a set of grid points which are contiguous in index space (see

* Not presently available.

Section 6.2 of Volume 1). The x-positions of the grid points in a block are generated from information supplied by user input.

A block must be one of the following types:

Equally Spaced Points

A block containing equally spaced grid points implies constant zone size in the block. The user may specify equally spaced points in a block in one of three ways. In all cases, the number of zones and the block's leftmost grid-point coordinate value must be specified. One method of specification, which uses the 241 input record, requires the block's rightmost gridpoint coordinate value; the second method of specification, which uses the 242 input record, requires the block width; and the third method, which uses the 234 input record, requires the width of a zone in the block.

Geometrically Spaced Points

A block containing grid points spaced by a geometric ratio also requires that the number of zones in the block, the block's leftmost grid-point coordinate value, and the geometric ratio be specified for all methods of generation. There are four ways to specify geometrically spaced grid points in a block: (1) input record 251 uses the block's rightmost grid point coordinate value; (2) input record 252 uses the width of the block; (3) input record 253 uses the block's leftmost zone width; and (4) input record 254 uses the block's rightmost zone width.

Point-by-Point

The coordinates of each point in a block may be given explicitly.

Special

The user may provide FORTRAN logic in subroutine MYGPT to generate grid points for a block. The subroutine must be programmed so that, for given values of *i* in a block (variable *I*), the subroutine returns the x-coordinates for that block (variables *XPN*). The block number (*NBLK*) is also a parameter, so that the subroutine may contain logic for more than one block. The user-supplied logic should not alter *I* or *NBLK*.

7.2.2 Two-Dimensional Input Blocks. A user may define the positions of mesh points in a grid by dividing the grid into one or more blocks. A block is a set of grid points which are contiguous in index space (see

Section 6.2 of Volume 1). The x- and y-positions of the grid points in a block are generated from information supplied by user input. Only in axial symmetry is there a restriction on the x- and y-values.* In 2D axial symmetry, the x-direction is the radial direction and the y-direction is the axial direction.

A block must be one of the following types:

Quadrilateral

A quadrilateral block is one in which the border of the block in the real space forms a convex quadrilateral. The user provides (1) the coordinates of the lower leftmost grid point (lower left in the i-j space of the block); (2) information about the size of the zones in the block (dimensions of the first zone or dimensions of the entire block); and (3) a pair of geometric ratios used to space grid points along the bottom (lowest value j-line) of the block and on the left (lowest value i-line) of the block. These data are provided on a 246 or 247 input record. If a geometric ratio, r , is provided, then the ratio is used to space grid points such that the distance between grid point 2 and grid point 3 is r times the distance between grid point 1 and grid point 2, the distance between grid point 3 and grid point 4 is r times the distance between grid point 2 and grid point 3, etc.

A 246 or a 247 input record is sufficient to define a rectangular block with i-lines parallel to the y-axis and j-lines parallel to the x-axis. If a more general quadrilateral is desired, a 256 or a 257 input record must augment a 246 or a 247 input record. On the 256 and 257 records, the user may specify (1) angles between the sides of the block; (2) an angle of rotation of the entire block; and (3) information used to space grid points along the rightmost (highest value) i-line. The grid points are generated such that the i- and j-lines are straight line segments in x-y space.

* Certain ALE rezone options may require that x increase in the direction of increasing i and y increase in the direction of increasing j . This restriction is noted in the discussion of the ALE input record (PRB phase) which specifies these options.

Polar

A polar block is one in which the grid points on a given i-line lie on the same circle (or radial line) in x-y space, and the grid points on a given j-line lie on the same radial line (or circle) in x-y space. All circles are concentric and all radial lines pass through their center.

The user provides (1) the coordinates of the center; (2) the radius of the inner circle; (3) the angle that the first radial line (bottommost j-line) makes with the positive x-axis; (4) information about the size of the zones in the block (dimensions of the first zone or dimensions of the entire block); and (5) whether the i-lines or the j-lines are the circles. These data are provided on a 263 input record and either a 261 or a 262 input record. A 261 or a 262 input record is sufficient to define a polar block in which grid points are evenly spaced along i-lines and j-lines. If geometric spacing is desired, ratios must be specified by including a 265 or a 266 input record. The ratios are used to space grid points along circles and radial lines.

Hyperbolic-Elliptic

A hyperbolic-elliptic block is one in which the grid points on a given i-line lie on the same ellipse (or hyperbola) in x-y space and the grid points on a given j-line lie on the same hyperbola (or ellipse) in x-y space. All ellipses and hyperbolas are concentric, and all hyperbolas share the same foci with the innermost ellipse.

Three input records are needed to specify a hyperbolic-elliptic block. On a 263 input record, the user specifies whether the i-lines or the j-lines are ellipses. On a 261 or a 262 input record, the user provides (1) the coordinates of the center; (2) the length of the semi-minor axis of the inner ellipse; (3) the angle which the asymptote of the first hyperbola makes with the semi-major axis of the ellipses and hyperbolas; and (4) information used to space the semi-minor axes of consecutive ellipses (either the difference between the first two, or between the first and last) and the asymptote of consecutive hyperbolas (either the angle between the first two, or between the first and last). On a 266 or a 267 input record, the user provides the semi-major axis of the inner ellipse and information used to space the semi-major axes of consecutive ellipses (either the difference between the first two or between the first and last). Geometric ratios used to space the semi-major axes of the ellipses, semi-minor axis of the ellipses, and asymptotes of the hyperbolas may also be given, as may the rotation of the major axis from the positive x-axis.

Special

The user may provide FORTRAN logic in subroutine MYGPT to generate grid points for a block. The subroutine must be programmed so that for given values of i and j (variables III and JJJ) the subroutine returns the x- and y-coordinates for that point (variables XXX and YYY). The block number (NBLK) is also a parameter so that the subroutine may contain logic for more than one block. The user-supplied logic should not alter III, JJJ, or NBLK.

Grid-point coordinates may also be given explicitly, point by point. Point-by-point coordinates need not be contiguous in index space.

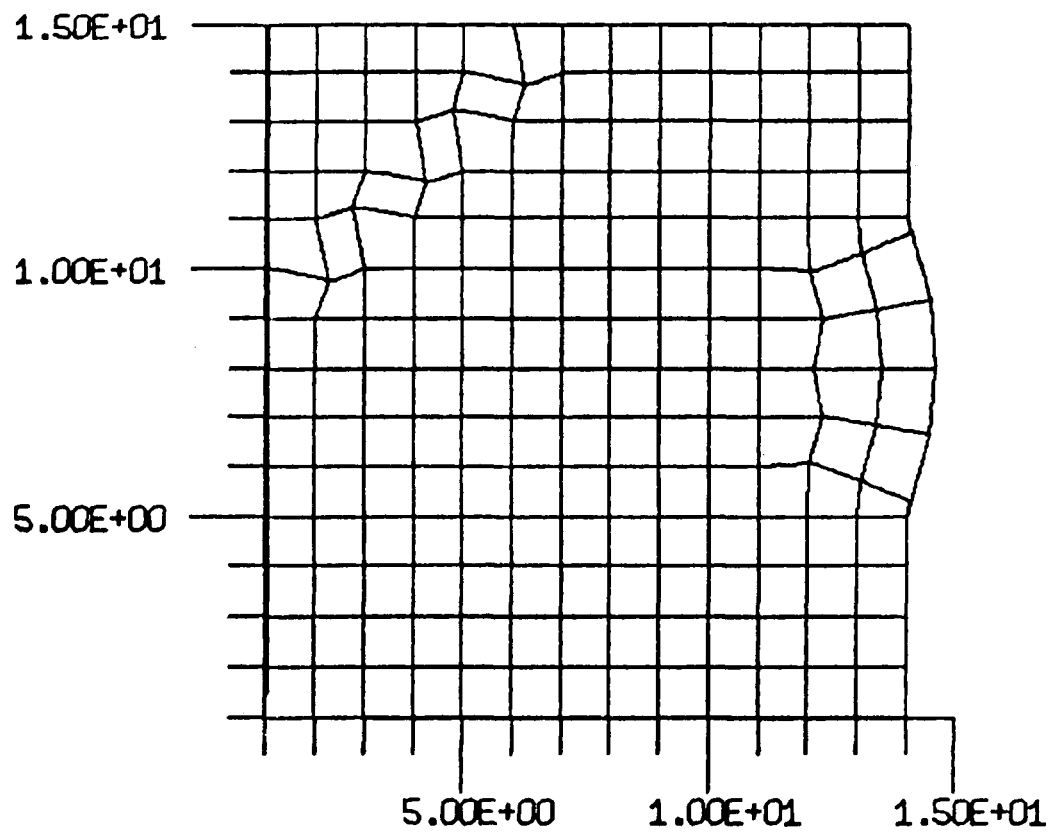
Each block must be given a unique block number from 1 to MAXBLK. (See Appendix "Maximums".) Point-by-point initializations should also be given a unique block number, though they need not form a contiguous set of points. All point-by-point initializations should be associated with the same block number.

If the same point is defined in more than one block, the block with the highest number will be used to define the point. Thus, it is possible, for example, to define a large quadrilateral block, then redefine a few of its points by using point-by-point initializations with a higher block number than the quadrilateral block number. See Page 7.208.

7.2.3 Wall-Point Specification. Wall points define line segments (known as wall segments) which are kinematic constraints for the grid. Wall point values are provided on the 212 input records.

In one-dimensional runs, single wall points may be used to specify kinematic boundaries on the left and right of the grid. In two-dimensional runs, pairs of wall points may be used to define wall segments. Single wall points are not allowed. Two or more wall points form a sequence of wall points. In axial symmetry, at least two wall points are required to define the axis of symmetry.*

*These concepts are described in greater detail in Appendix "Grid point Interactions".



221	BLK	1.0	1.0	14.0	1.0	15.0		
246	QUD	1.0	1.0	1.0	1.0	1.0		
221	BLK	2.0	12.0	14.0	6.0	10.0		
262	POL	2.0	7.0	8.0	5.365	2.231	-21.8	43.6
263	POL	2.0	1.0					
232	PBP	10.0	2.0	10.0	2.25	9.75		
232	PBP	10.0	3.0	11.0	2.75	11.25		
232	PBP	10.0	4.0	12.0	4.25	11.75		
232	PBP	10.0	5.0	13.6	4.75	13.25		
232	PBP	10.0	6.0	14.0	6.25	13.75		

In the above scheme, block number 1 defines a 14 x 15 regular quadrilateral mesh. Block number 2 then redefines the points $\{(i,j): 12 \leq i \leq 14, 6 \leq j \leq 10\}$ to be a polar block. Finally, the points (2,10), (3,11), (4,12), (5,13) and (6,14) are specified explicitly in a point-by-point fashion with block number 10.

TABLE 7.2

SUMMARY OF GPT PHASE INPUT RECORDS AND INPUT VARIABLES

FIELDS 1-7

TYPE	1	2	3	4	5	6	7	
GPT	NSINP	NSTRC	NSDBG	NSPLT	NSPRT			
211	LG	IMIN	JMIN	XMIN	YMIN			
212	LW	XWL	YWL	NWO				
221	L	ILFT	IRHT	JBOT	JTOP			
231	L	IPSN	XPSN	IPSN	XPSN	IPSN	XPSN	1D
232	L	IPSN	JPSN	XPSN	YPSN			2D
241	L	NZON	XLFT	XRHT				1D
242	L	NZON	XLFT	XBLK				1D
243	L	NZON	XLFT	XZON				1D
246	L	XBL	ZONJBL	YBL	ZONIBL	RATJBT	RATILF	2D
247	L	XBL	BLKJBT	YBL	BLKILF	RATJBT	RATILF	2D
251	L	NZON	XLFT	XRHT	XRAT			1D
252	L	NZON	XLFT	XBLK	XRAT			1D
253	L	NZON	XLFT	XZONL	XRAT			1D
254	L	NZON	XLFT	XZONR	XRAT			1D
256	L	ANG1	ANG2	ANG3	ZONIBR	RATIRH		2D
257	L	ANG1	ANG2	ANG3	BLKIRH	RATIRH		2D

TABLE 7.2 (continued)

FIELDS 1-7

[illegible]

Grid Point (GPT) Phase Control

Page 1 of 3

TYPE
GPT

The function of the GPT control record is to activate the GPT input phase. The GPT control record must follow an END input record and is required for all start runs. It may not be used at restart time.

	min	max
start	1	1
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSINP	Input mode switch. The value of NSINP specifies the mode of input to be used in this input phase. The value of NSINP must be integral and less than or equal to 3. The following definitions apply:

≤ 1.0 card input (default)
 $= 2.0$ library input
 $= 3.0$ keyboard input

If the field containing NSINP is left blank, then the mode of input is assumed to be card input. If the value of NSINP is greater than 3.0, the message,

INPUT MODE SWITCH
 IMPROPERLY DEFINED

is written on the print and the message files, and the program terminates immediately in subroutine GENGEN.

2	NSTRC	Trace mode switch. The value of NSTRC specifies whether or not the trace option is active. The value of NSTRC must be integral and less than or equal to 2. The following definitions apply:

≤ 1.0 trace is not active, off (default)
 $= 2.0$ trace is active, on

If the field containing NSTRC is left blank, then the mode is assumed to be not active (off). If the value of NSTRC is greater than 2.0, the message,

TRACE MODE SWITCH
 IMPROPERLY DEFINED

TYPE
GPT

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The trace logic, if active (on), will cause the name of the subroutine or logical phase just entered to be printed on both the print and message files. These actions are taken in subroutines SBRENT and PHSENT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
3	NSDBG	Debug mode switch. The value of NSDBG specifies whether or not the debug option is active. The value of NSDBG must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 debug is not active, off (default) $= 2.0$ debug is active, on If the field containing NSDBG is left blank, the the debug mode is assumed to be not active (off). If the value of NSDBG is greater than 2.0, the message, DEBUG MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The debug logic, if active (on), will cause the common blocks associated with this input phase to be dumped at the end of each subroutine in the phase and at the end of the logical phase. These actions are taken in subroutines SBREXT and PHSEXT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
4	NSPLT	Plot mode switch. The value of NSPLT specifies whether or not plots will be produced by this generator phase. The value of NSPLT must be integral and less than or equal to 2.0. The following definitions apply: ≤ 1.0 no plots produced, option off (default) $= 2.0$ plots produced, option on If the field containing NSPLT is left blank, then no plots will be produced (off). If the value of NSPLT is greater than 2.0, the message, PLOT MODE SWITCH IMPROPERLY DEFINED

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files, and the program terminates immediately in subroutine GPTGEN.
5	NSPRT	Print mode switch. The value of NSPRT controls the printing in this generator phase. The value of NSPRT must be integral and less than or equal to 2.0. The following definitions apply: = 1.0 only input records and error messages are printed, option off = 2.0 full printing done, option on (default) If the field containing NSPRT is left blank, full printing is done (option on). If the value of NSPRT is greater than 2.0, the message, PRINT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine GPTGEN.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Grid Origin Definition

Page 1 of 1

TYPE
211

The 211 input record defines a grid origin. The 211 input record may not be used at restart time.

	min	max
start	1	MAXGRD
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	LG	IMIN	JMIN	XMIN	YMIN	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	LG	Grid number. The value of LG must be a unique number for each grid. The value of LG must be integral and greater than or equal to 1 and less than or equal to MAXGRD. (See Appendix "Maximums".) If LG is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
2	IMIN	Leftmost grid point index of this grid. The value of IMIN must be integral and greater than or equal to 1 and less than or equal to MAXGPT - 1. (See Appendix "Maximums".) If IMIN is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
		$1 \leq \text{IMIN} \leq \text{MAXGPT} - 1$
3	JMIN	Bottommost grid point index of this grid. The value of IMIN must be integral and greater than or equal to 1 and less than or equal to MAXGPT - 1. (See Appendix "Maximums".) If JMIN is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutin GPTINP. (See Appendix "Messages".) JMIN must be left blank in one-dimensional problems.
		$1 \leq \text{JMIN} \leq \text{MAXBUF} - 1$
4	XMIN	x-coordinate for the (IMIN,JMIN) grid point in this grid. The value of XMIN can be any number in problem units for non-divergent symmetries. XMIN cannot be a negative number in divergent symmetries.
5	YMIN	y-coordinate for the (IMIN,JMIN) grid point in this grid. The value of YMIN can be any number in problem units. YMIN must be left blank in one-dimensional problems.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Wall Point Definition

Page 1 of 2

TYPE

212

The 212 input record defines a wall point. The 212 input record may not be used at restart time.

	min	max
start	0	MAXWPT
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	LW	XWL	YWL	NWO	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	LW	Wall point number. The value of LW must be a unique number for each wall point. The value of LW must be integral and greater than or equal to 1 and less than or equal to MAXWPT. (See Appendix "Maximums".) If LW is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".) The values of LW = MAXWPT - 1 and LW = MAXWPT have special meaning for one-dimensional runs. They are the left and right boundary pistons, respectively. Wall point segments are defined as a set of wall points which must be consecutively numbered in increasing integer value. One-dimensional problems may have only one wall point segment composed of up to MAXWPT - 2 wall points. Two-dimensional problems may have up to MAXWPT/2 segments with a sum total of MAXWPT wall points.
2	XWL	x-coordinate for wall point LW. The value of XWL can be any number in problem units for non-divergent symmetries. XWL can not be a negative number in divergent symmetries.
3	YWL	y-coordinate for wall point LW. The value of YWL can be any number in problem units. YWL must be left blank when specifying onedimensional boundary pistons.

Columns →	11	21	31	41	51	61	71	80
	LW	XWL	YWL	NWO	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable										
4	NWO	Wall point orientation number. The value of NWO must be integral and greater than or equal to 1 and less than or equal to 5. The following definitions apply: <table><tr><td>< 1.0</td><td>interior wall point</td></tr><tr><td>= 2.0</td><td>first wall point</td></tr><tr><td>= 3.0</td><td>last wall point</td></tr><tr><td>= 4.0</td><td>piston point on the left for 1D</td></tr><tr><td>= 5.0</td><td>piston point on the right for 1D</td></tr></table> If the field containing NWO is left blank, then NWO is assumed to be equal to 1.0, i.e., an interior wall point. If the value of NWO is greater than 5.0, the message, WALL POINT ORIENTATION IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine GPTINP.	< 1.0	interior wall point	= 2.0	first wall point	= 3.0	last wall point	= 4.0	piston point on the left for 1D	= 5.0	piston point on the right for 1D
< 1.0	interior wall point											
= 2.0	first wall point											
= 3.0	last wall point											
= 4.0	piston point on the left for 1D											
= 5.0	piston point on the right for 1D											
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)										

The 221 input record defines a grid point block for which grid point spacing is described on input records in the GPT input phase. At least one 221 input record is required for a start run to set up grid points. The 221 input record may not be used at restart time.

	min	max
start	1	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	ILFT	IRHT	JBOT	JTOP	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
2	ILFT	Leftmost grid point index for grid point block L. The value of ILFT must be integral and greater than or equal to 1 and less than IRHT. If ILFT is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the GPT GENERATOR phase. (See Appendix "Messages".)
		$1 \leq \text{ILFT} < \text{IRHT}$
3	IRHT	Rightmost grid point index for grid point block L. The value of IRHT must be integral and greater than ILFT and less than or equal to MAXGPT. (See Appendix "Maximums".) If IRHT is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the GPT GENERATOR phase. (See Appendix "Messages".)
		$\text{ILFT} < \text{IRHT} \leq \text{MAXGPT}$

Columns →	11	21	31	41	51	61	71	80
	L	ILFT	IRHT	JBOT	JTOP	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	JBOT [*]	Bottommost grid point index for grid point block L. The value of JBOT must be integral and greater than or equal to 1 and less than JTOP. If JBOT is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the GPT GENERATOR phase. (See Appendix "Messages".)
		$1 \leq \text{JBOT} < \text{JTOP}$
5	JTOP [*]	Topmost grid point index for grid point block L. The value of JTOP must be integral and greater than JBOT and less than or equal to MAXBUF. (See Appendix "Maximums".) If JTOP is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the GPT GENERATOR phase. (See Appendix "Messages".)
		$\text{JBOT} < \text{JTOP} \leq \text{MAXBUF}$
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*JBOT and JTOP are not required for one-dimensional problems and input values in this field will result in the FLDCHK message being written on the print and the message files and the program being terminated at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 231 input record may be used to specify point-by-point grid point input specification for block number L. The 231 input record may not be used at restart time.

	min	max
start	0	MAXGPT
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	IPSN	XPSN	IPSN	XPSN	IPSN	XPSN	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 221 record.
2,4,6	IPSN	Grid point index for the grid point whose x-position is specified in the next field. The value of IPSN must be integral and greater than or equal to 1 and less than or equal to MAXGPT. (See Appendix "Maximums".) If IPSN is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3,5,7	XPSN	x-coordinate for the grid point index specified in the previous field. Its value can be any number in problem units. Values of the XPSN must increase for increasng IPSN; that is, XPSN(IPSN - 1) < XPSN(IPSN) < XPSN(IPSN + 1) ...

The 232 input record may be used to specify point-by-point grid point input. The 232 input record may not be used at restart time.

	min	max
start	0	MAXPBP
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	IPSN	JPSN	XPSN	YPSN	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. The value of L uniquely identifies the set of all point-by-point initializations. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".) L should have the same value on all 232 input records.
2	IPSN	I grid point index for the grid point whose x and y position is specified on this input record. The value of IPSN must be integral and greater than or equal to 1 and less than or equal to MAXGPT. (See Appendix "Maximums".) If IPSN is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3	JPSN	J grid point index for the grid point whose x and y position is specified on this input record. The value of JPSN must be integral and greater than or equal to 1 and less than or equal to MAXBUF. (See Appendix "Maximums".) If JPSN is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
4	XPSN	x-coordinate for the (I,J) grid point specified on this input record. Its value can be any number in problem units for non-divergent symmetries. XPSN cannot be a negative number in divergent symmetry.
5	YPSN	y-coordinate for the (I,J) grid point specified on this input record. Its value can be any number in problem units.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
241

The 241 input record may be used to specify equally spaced grid points for block number L. The 241 input record may not be used at restart time.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	NZON	XLFT	XRHT	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 221 record.
2	NZON	Number of zones in this block, $NZON \equiv IRHT - ILFT$. The value of NZON must be integral and greater than or equal to 1 and less than or equal to MAXZON. (See Appendix "Maximums".) If NZON is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3	XLFT	x-coordinate of the leftmost grid point in this block. The value of XLFT can be any number less than XRHT in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
4	XRHT	x-coordinate of the rightmost grid point in this block. The value of XRHT can be any number greater than XLFT in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
5-7	--	Fields 5-7 must be left blank or FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
241

TYPE
242

The 242 input record may be used to specify equally spaced grid points for block number L. The 242 input record may not be used at restart time.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	NZON	XLFT	XBLK	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 221 record.
2	NZON	Number of zones in this block, $NZON \equiv IRHT - ILFT$. The value of NZON must be integral and greater than or equal to 1 and less than or equal to MAXZON. (See Appendix "Maximums".) If NZON is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3	XLFT	x-coordinate of the leftmost grid point in this block. The value of XLFT can be any number less than $XRHT^*$ in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
4	XBLK	Width of the block. The value of XBLK must be a positive number in problem units.
5-7	--	Fields 5-7 must be left blank or FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* $XHRT \equiv XLFT + XBLK$

TYPE
242

The 243 input record may be used to specify equally spaced grid points for block number L. The 243 input record may not be used at restart time.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	NZON	XLFT	XZON	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 221 record.
2	NZON	Number of zones in this block, $NZON \equiv IRHT - ILFT$. The value of NZON must be integral and greater than or equal to 1 and less than or equal to MAXZON. (See Appendix "Maximums".) If NZON is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3	XLFT	x-coordinate of the leftmost grid point in this block. The value of XLFT can be any number less than XRHT* in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
4	XZON	Width of each zone in this block. The value of XZON must be a positive number in problem units.
5-7	--	Fields 5-7 must be left blank or FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

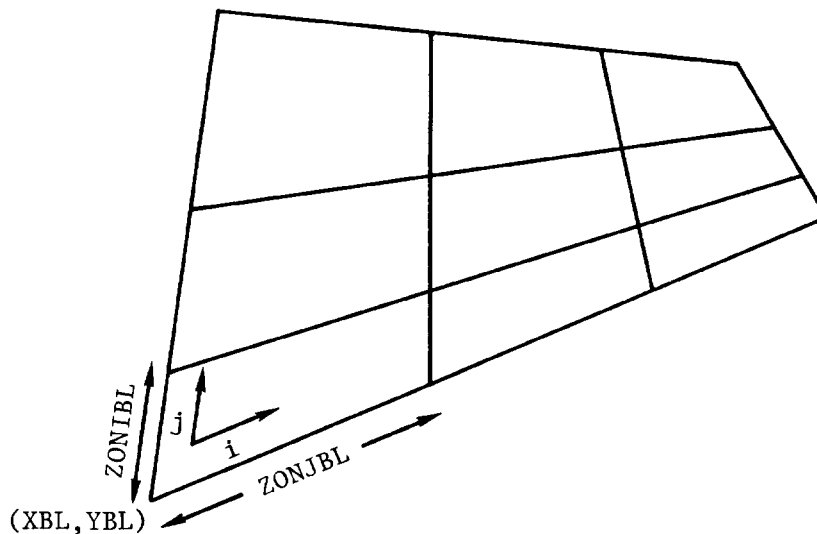
* $XRHT \equiv XLFT + NZON * XZON$

The 246 record may be used alone or in conjunction with a 256 or 257 record to specify quadrilateral zoning for block number L. A 246 record alone is sufficient to specify a block of rectangular zones with sides parallel to the x and y axes.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	XBL	ZONJBL	YBL	ZONIBL	RATJBT	RATILF	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable



1	L	Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
2	XBL	x-coordinate of lower-leftmost grid point (in i-j space) in this block.
3	ZONJBL	Length along bottom j-line of the lower-leftmost zone (in i-j space) in the block (see figure). The value of ZONJBL must be a positive number in problem units.
4	YBL	y-coordinate of the lower-leftmost grid point (in i-j space) in this block.

Columns →	11	21	31	41	51	61	71	80
	L	XBL	ZONJBL	YBL	ZONIBL	RATFBT	RATILF	
Fields →	1	2	3	4	5	6	7	

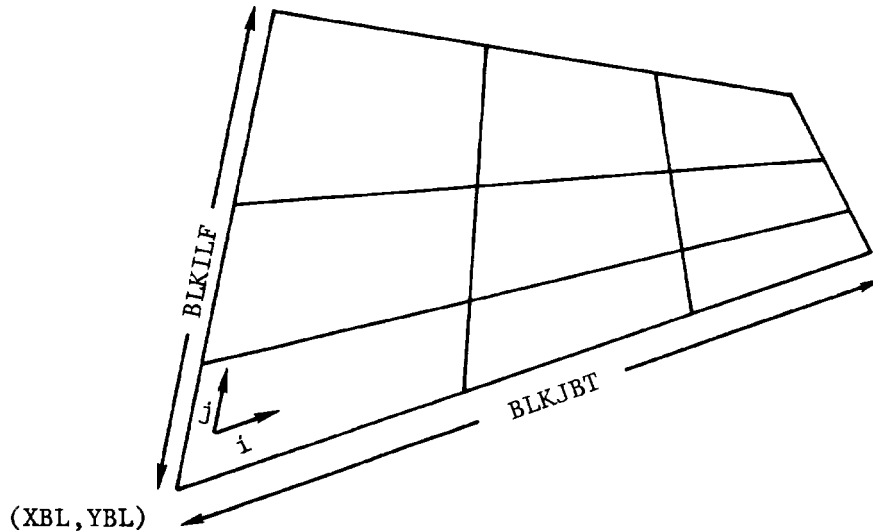
Field Number	Input Variable Name	Description of Input Variable
5	ZONIBL	Length along left i-line of the lower-leftmost zone (in i-j space) in the block (see figure). The value of ZONIBL must be a positive number in problem units.
6	RATJBT	Geometric ratio. The value of RATJBT is used to space grid points along j-lines. The value of RATJBT must be greater than or equal to 0.5 and less than or equal to 1.5, or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine GPTINP. If this field is left blank, a ratio of 1.0 is assumed.
7	RATILF	Geometric ratio. The value of RATILF is used to space grid points along the leftmost i-line (in i-j space). The value of RATILF must be greater than or equal to 0.5 and less than or equal to 1.5 or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine GPTINP. If this field is left blank, a ratio of 1.0 is assumed.

The 247 record may be used alone or in conjunction with a 256 or 257 record, to specify quadrilateral zoning for block number L. A 247 record alone is sufficient to specify a block of rectangular zones with sides parallel to the x and y axes.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	XBL	BLKJBT	YBL	BLKILF	RATJBT	RATILF	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable



1	L	Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
2	XBL	x-coordinate of the lower-leftmost grid point (in i-j space) in this block.
3	BLKJBT	Length of the entire block along the bottommost j-line (in i-j space) (see figure). The value of BLKJBT must be a positive number in problem units.

Columns →	11	21	31	41	51	61	71	80
	L	XBL	BLKJBT	YBL	BLKILF	RATJBT	RATILF	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	YBL	y-coordinate of the lower-leftmost grid point (in i-j space) in this block.
5	BLKILF	Length of the entire block along leftmost i-line (in i-j space) (see figure). The value of BLKILF must be a positive number in problem units.
6	RATJBT	Geometric ratio. The value of RATJBT is used to space grid points along j-lines. The value of RATJBT must be greater than or equal to 0.5 and less than or equal to 1.5, or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine GPTINP. If this field is left blank, a ratio of 1.0 is assumed.
7	RATILF	Geometric ratio. The value of RATILF is used to space grid points along the leftmost i-line (in i-j space). The value of RATILF must be greater than or equal to 0.5 and less than or equal to 1.5, or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine GPTINP. If this field is left blank, a ratio of 1.0 is assumed.

The 251 input record may be used to specify geometrically spaced grid points for block number L. The 251 input record may not be used at restart time.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	NZON	XLFT	XRHT	XRAT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 221 record.
2	NZON	Number of zones in this block, $NZON \equiv IRHT - ILFT$. The value of NZON must be integral and greater than or equal to 1 and less than or equal to MAXZON. (See Appendix "Maximums".) If NZON is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3	XLFT	x-coordinate of the leftmost grid point in this block. The value of XLFT can be any number less than XRHT in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
4	XRHT	x-coordinate of the rightmost grid point in this block. The value of XRHT can be any number greater than XLFT in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
5	XRAT	Geometric ratio. The value of XRAT is used to space grid points from XLFT to XRHT. The value of XRAT must be greater than or equal to 0.5 and less than or equal to 2.0 or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine GPTINP.
5-7	--	Fields 5-7 must be left blank or FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 252 input record may be used to specify geometrically spaced grid points for block number L. The 252 input record may not be used at restart time.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	NZON	XLFT	XBLK	XRAT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 221 record.
2	NZON	Number of zones in this block, $NZON \equiv IRHT - ILFT$. The value of NZON must be integral and greater than or equal to 1 and less than or equal to MAXZON. (See Appendix "Maximums".) If NZON is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3	XLFT	x-coordinate of the leftmost grid point in this block. The value of XLFT can be any number less than XRHT* in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
4	XBLK	Width of the block. The value of XBLK must be a positive number in problem units.
5	XRAT	Geometric ratio. The value of XRAT is used to space grid points from XLFT to XRHT.* The value of XRAT must be greater than or equal to 0.5 and less than or equal to 2.0 or the message,
GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine GPTINP.		
6-7	--	Fields 6-7 must be left blank or FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* $XRHT \equiv XLFT + XBLK$

TYPE
253

The 253 input record may be used to specify geometrically spaced grid points for block number L. The 253 input record may not be used at restart time.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	NZON	XLFT	XZONL	XRAT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 221 record.
2	NZON	Number of zones in this block, $NZON \equiv IRHT - ILFT$. The value of NZON must be integral and greater than or equal to 1 and less than or equal to MAXZON. (See Appendix "Maximums".) If NZON is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3	XLFT	x-coordinate of the leftmost grid point in this block. The value of XLFT can be any number less than XRHT* in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
4	XZONL	Width of the leftmost zone. The value of XZONL must be a positive number in problem units.
5	XRAT	Geometric ratio. The value of XRAT is used to space gid points from XLFT to XRHT.* The value of XRAT must be greater than or equal to 0.5 and less than or equal to 2.0 or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine GPTINP.
6-7	--	Fields 6-7 must be left blank or FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* $XRHT \equiv XLFT + XZONL * (XRAT^{**}NZON - 1.0) / (XRAT - 1.0)$

TYPE
253

The 254 input record may be used to specify geometrically spaced grid points for block number L. The 254 input record may not be used at restart time.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	NZON	XLFT	XZONR	XRAT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 221 record.
2	NZON	Number of zones in this block, $NZON \equiv IRHT - ILFT$. The value of NZON must be integral and greater than or equal to 1 and less than or equal to MAXZON. (See Appendix "Maximums".) If NZON is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3	XLFT	x-coordinate of the leftmost grid point in this block. The value of XLFT can be any number less than XRHT* in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
4	XZONR	Width of the rightmost zone. The value of XZONR must be a positive number in problem units.
5	XRAT	Geometric ratio. The value of XRAT is used to space grid points from XLFT to XRHT.* The value of XRAT must be greater than or equal to 0.5 and less than or equal to 2.0 or the message,
GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine GPTINP.		
6-7	--	Fields 6-7 must be left blank or FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* $XRHT \equiv XLFT + XZONR * (XRAT * NZON - 1.0) / (XRAT - 1.0)$

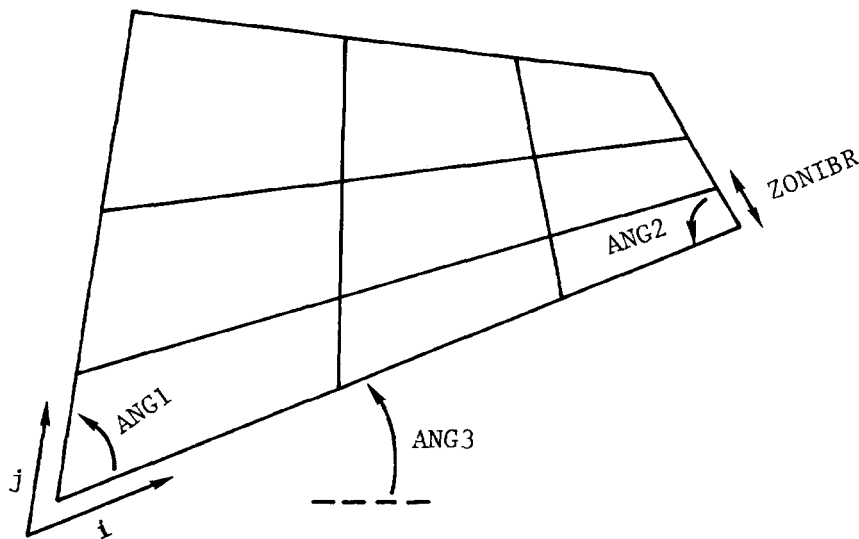
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The 256 input record may be used in conjunction with a 246 or a 247 input record to specify quadrilateral zoning for block number L.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	ANG1	ANG2	ANG3	ZONIBR	RATIRH	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable



1	L	Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
2	ANG1	Angle (expressed in degrees) between the bottommost j-line (in i-j space) and the leftmost i-line (see figure). The value of ANG1 must be greater than 0.0 and less than 180.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, a right angle (90°) is assumed.

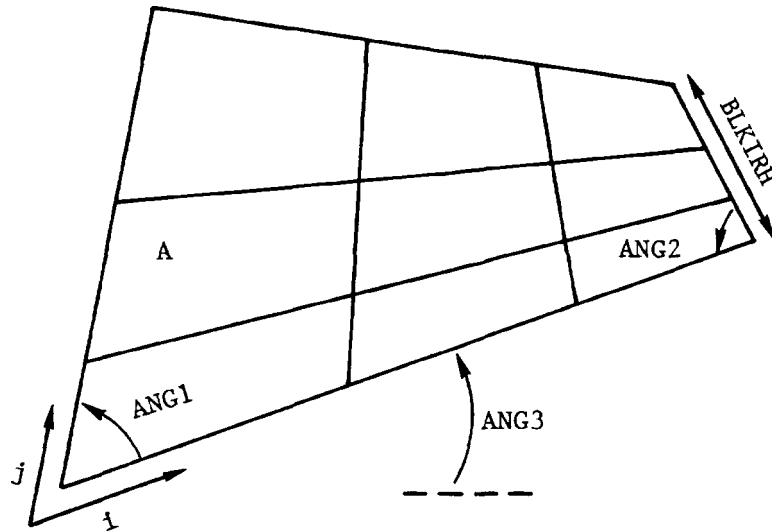
Columns →	11	21	31	41	51	61	71	80
	L	ANG1	ANG2	ANG3	ZONIBR	RATIRH	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	ANG2	Angle (expressed in degrees) between the bottommost j-line and the rightmost i-line (in i-j space) (see figure). The value of ANG2 must be greater than 0.0 and less than 180.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, a right angle (90°) is assumed.
4	ANG3	Angle (expressed in degrees) measured counterclockwise from the x-axis to the bottommost j-line (in i-j space) (see figure). The value of ANG3 must be greater than -360.0 and less than 360.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, an angle of 0° is assumed.
5	ZONIBR	Length along the rightmost i-line of the lower rightmost zone (in i-j space) in the block (see figure). The value of ZONIBR must be a positive number in problem units. If this field is left blank, ZONIBR will be assumed to be the same as ZONIBL (as specified on a 246 input record or implied on a 247 input record).
6	RATIRH	Geometric ratio. The value of RATIRH is used to space grid points along the rightmost i-line (in i-j space). The grid points on the left i-line will be connected to those on the right i-line with straight lines. The value of RATIRH must be greater than or equal to 0.5 and less than or equal to 1.5 or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, RATIRH will be set to the value of RATILF (as specified on a 246 or 247 input record).
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 257 input record may be used in conjunction with a 246 or a 247 input record to specify quadrilateral zoning for block number L.

Columns →	11	21	31	41	51	61	71	80
	L	ANG1	ANG2	ANG3	BLKIRH	RATIRH	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable



1	L	Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
2	ANG1	Angle (expressed in degrees) between the bottommost j-line (in i-j space) and the leftmost i-line (see figure). The value of ANG1 must be greater than 0.0 and less than 180.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, a right angle (90°) is assumed.

Columns →	11	21	31	41	51	61	71	80
	L	ANG1	ANG2	ANG3	BLKIRH	RATIRH	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	ANG2	Angle (expressed in degrees) between the bottommost j-line and the rightmost i-line (in i-j space) (see figure). The value of ANG2 must be greater than 0.0 and less than 180.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, a right angle (90°) is assumed.
4	ANG3	Angle (expressed in degrees) measured counterclockwise from the x-axis to the bottommost j-line (in i-j space) (see figure). The value of ANG3 must be greater than -360.0 and less than 360.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, an angle of 0° is assumed.
5	BLKIRH	Length of the entire block along the rightmost i-line (in i-j space) (see figure). The value of BLKIRH must be a positive number in problem units. If this field is left blank, BLKIRH will be assumed to be the same as BLKILF (as specified on a 247 record or implied on a 246 record).
6	RATIRH	Geometric ratio. The value of RATIRH is used to space grid points along the rightmost i-line (in i-j space). The grid points on the left i-line will be connected to those on the right i-line with straight lines. The value of RATIRH must be greater than or equal to 0.5 and less than or equal to 1.5 or the message GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, RATIRH will be set to the value of RATILF (as specified on a 246 or 247 input record).
7	—	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 261 input record must be used with a 263 input record to specify i-j orientations and with a 266 or a 267 input record to specify polar or hyperbolic-elliptic zoning for block number L. A 261 input record alone is sufficient to specify a polar block with equal zoning, but a 266 or a 267 input record must be included for a hyperbolic-elliptic block or a polar block with geometric zoning.

start
restart

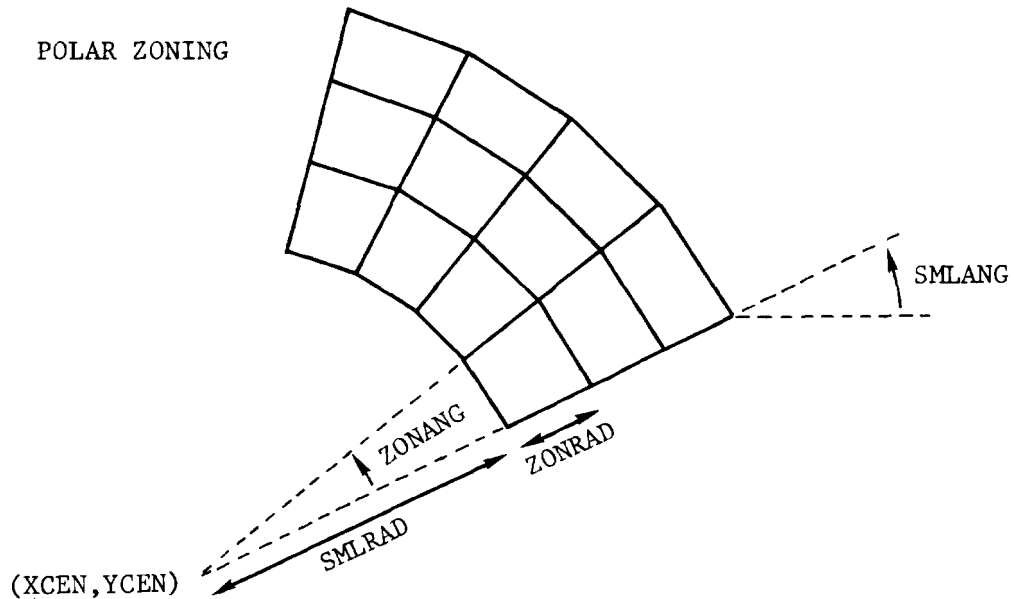
min	max
0	MAXBLK
0	0

Columns →	11	21	31	41	51	61	71	80
	L	XCEN	YCEN	SMLRAD	ZONRAD	SMLANG	ZONANG	
Fields →	1	2	3	4	5	6	7	

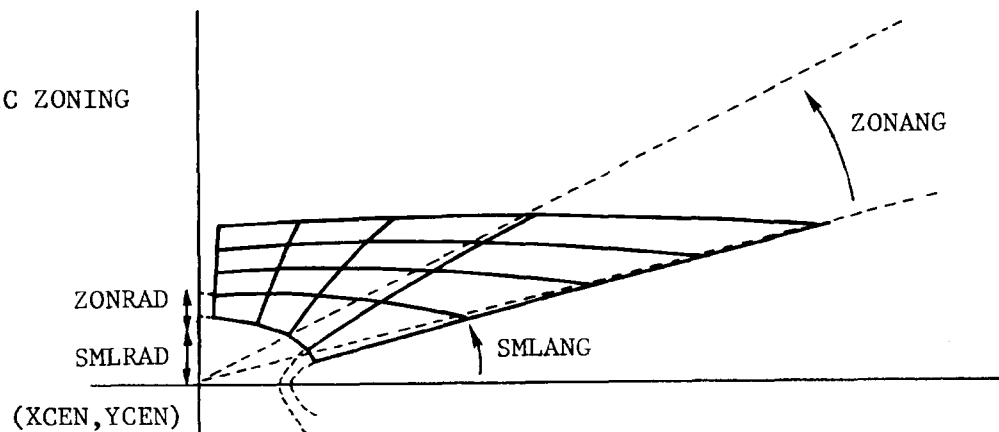
Field Number Input Variable Name

Description of Input Variable

POLAR ZONING



HYPERBOLIC-ELLIPTIC ZONING



Columns →	11	21	31	41	51	61	71	80
	L	XCEN	YCEN	SMLRAD	ZONRAD	SMLANG	ZONANG	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
2	XCEN	x-coordinate of the center of the circles (polar) or ellipses and hyperbolas, expressed in problem units.
3	YCEN	y-coordinate of the center of the circles (polar) or ellipses and hyperbolas, expressed in problem units.
4	SMLRAD	For polar zoning, SMLRAD is the radius of the inner circle. SMLRAD must be a positive number expressed in problem units. For hyperbolic-elliptic zoning, SMLRAD is the length of the <u>semi-minor</u> axis of the smallest ellipse. It may be 0.0.
5	ZONRAD	For Polar zoning, ZONRAD is the distance along a radius from the innermost circle to the next circle (i.e., the width of the first zone) (see figure). For hyperbolic-elliptic zoning, ZONRAD is the difference in length between the <u>semi-minor</u> axis of the smallest ellipse and the <u>semi-minor</u> axis of the next smallest ellipse. ZONRAD should be a positive number expressed in problem units.
6	SMLANG	SMLANG is the angle (expressed in degrees) measured counter-clockwise from the x-axis to the first radial line (polar zoning), or from the major axis to the asymptote of the first hyperbola (hyperbolic-elliptic zoning). The value of SMLANG must be greater than or equal to -360.0 and less than or equal to 360.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP.
7	ZONANG	ZONANG is the angle (expressed in degrees) formed between the first and second radial lines (polar zoning), or the first and second set of asymptotes (hyperbolic-elliptic zoning). The value of ZONANG must be greater than 0.0 and less than or equal to 360.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP.

The 262 input record must be used with a 263 input record to specify i-j orientations and may be used with a 266 or a 267 input record to specify polar or hyperbolic-elliptic zoning for block number L. A 262 input record alone is sufficient to specify a polar block with equal zoning, but a 266 or a 267 input record must be included for hyperbolic-elliptic zoning or for polar zoning with geometric spacing of zones. restart

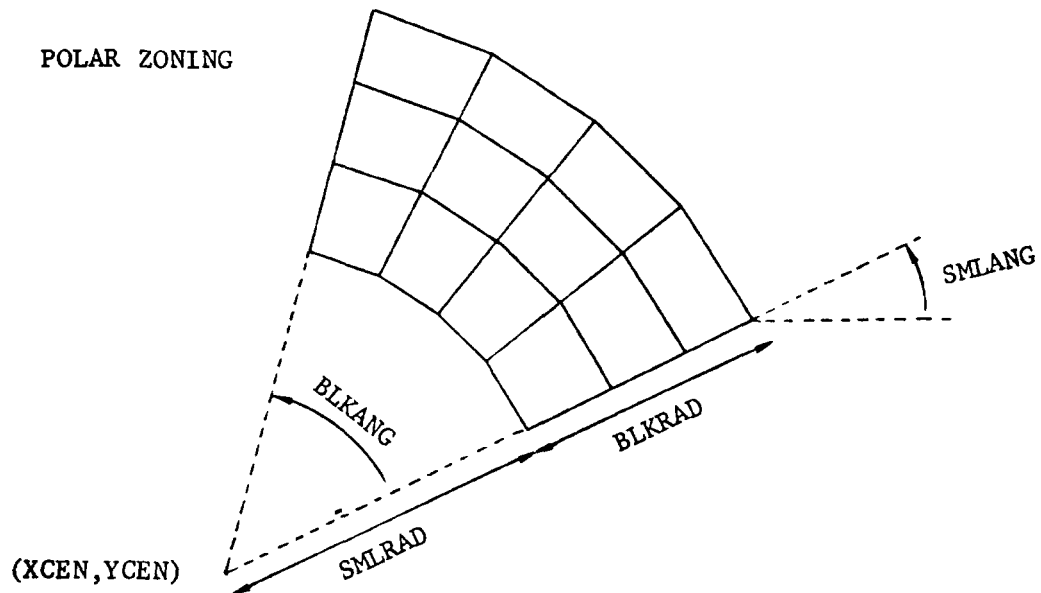
TYPE
262

min	max
0	MAXBLK
0	0

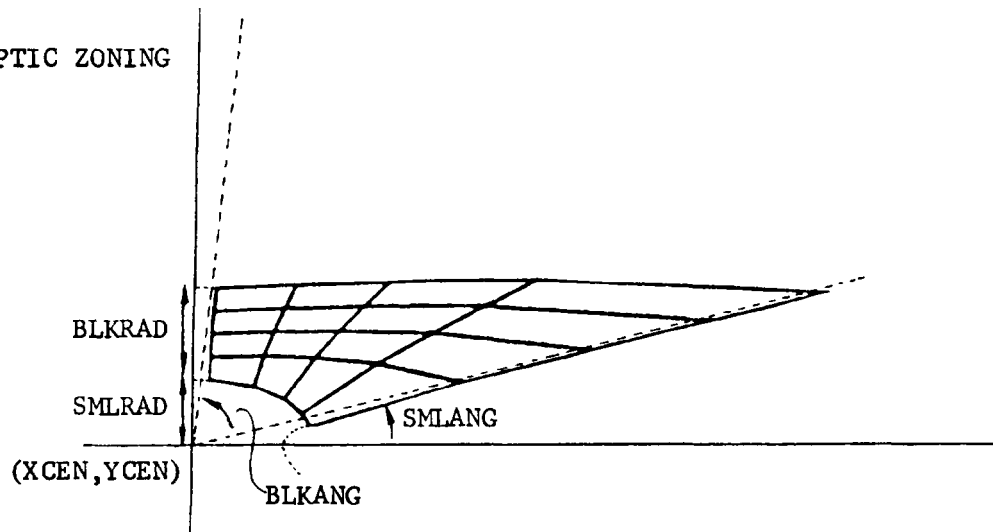
Columns →	11	21	31	41	51	61	71	80
	L	XCEN	YCEN	SMLRAD	BLKRAD	SMLANG	BLKANG	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable

POLAR ZONING



HYPERBOLIC-ELLIPTIC ZONING



Columns →	11	21	31	41	51	61	71	80
	L	XCEN	YCEN	SMLRAD	BLKRAD	SMLANG	BLKANG	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
2	XCEN	x-coordinate of the center of the circles (polar) or ellipses and hyperbolas, expressed in problem units.
3	YCEN	y-coordinate of the center of the circles (polar) or ellipses and hyperbolas, expressed in problem units.
4	SMLRAD	For polar zoning, SMLRAD is the radius of the inner circle. SMLRAD must be a positive number expressed in problem units. For hyperbolic-elliptic zoning, SMLRAD is the length of the <u>semi-minor</u> axis of the smallest ellipse. It may be 0.0.
5	BLKRAD	For polar zoning, BLKRAD is the distance along a radius from the innermost to the outermost radius; i.e., the "length" of the entire block. For hyperbolic-elliptic zoning, BLKRAD is the difference in length between the <u>semi-major</u> axes of the smallest and largest ellipses. BLKRAD should be a positive number expressed in problem units.
6	SMLANG	SMLANG is the angle (expressed in degrees) measured counter-clockwise from the x-axis to the first radial line (polar zoning), or from the major axis to the asymptote of the first hyperbola (hyperbolic-elliptic zoning). The value of SMLANG must be greater than or equal to -360.0 and less than or equal to 360.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP.
7	BLKANG	BLKANG is the angle (expressed in degrees) formed between the outermost radial lines (polar zoning) or the asymptotes of the first and last hyperbolas (hyperbolic-elliptic zoning). The value of BLKANG must be greater than 0.0 and less than 360.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP.

Polar or Hyperbolic-Elliptic Zoning -- i-j Space Orientation

Page 1 of 2

TYPE

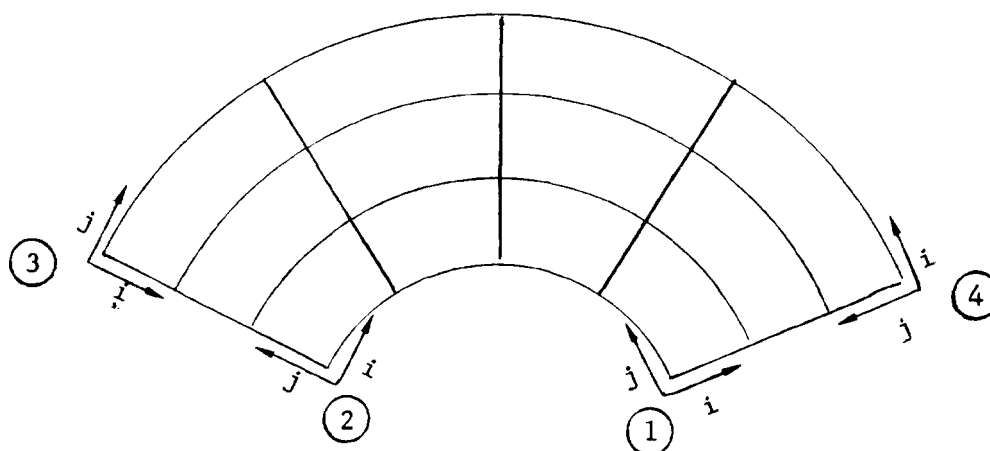
263

A 263 input record defines the i-j space orientation of a polar or hyperbolic-elliptic zone specified with the 261-262 and 266-267 input records. There must be exactly one 263 input record for each polar or hyperbolic-elliptic block.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	IJORN	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable



- 1 L Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)

TYPE

263

Columns →	11	21	31	41	51	61	71	80
	L	IJORN	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

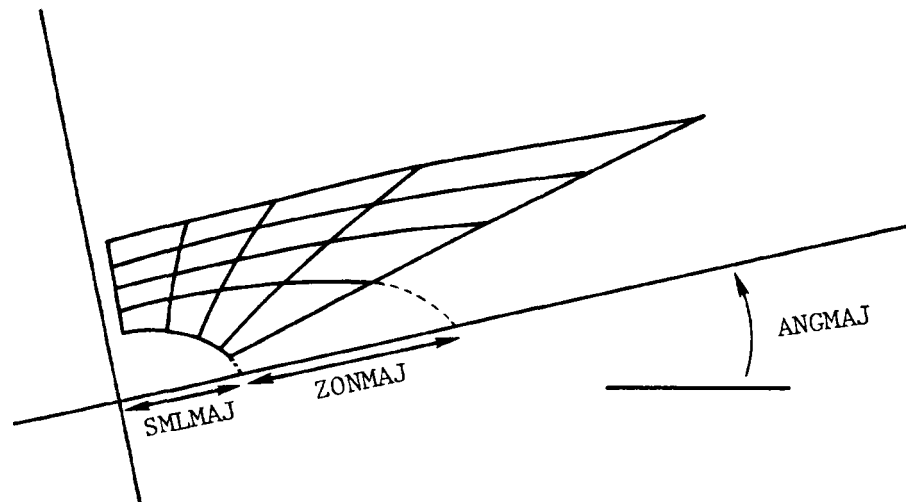
Field Number	Input Variable Name	Description of Input Variable
2	IJORN	i-j space orientation type. The value of IJORN defines the orientation in i-j space of polar of hyperbolic-elliptic block number L. The value of IJORN must be integral and have a value greater than or equal to 1.0 and less than or equal to 4.0. The following definitions apply: = 1.0 circles (polar) or ellipses (hyperbolic-elliptic) are i-lines, and radial lines (polar) or hyperbolas (hyperbolic-elliptic) are j-lines. i increases with increasing radius and j increases with increasing angle (see figure). = 2.0 circles (polar) or ellipses (hyperbolic-elliptic) are j-lines, and radial lines (polar) or ellipses (hyperbolic-elliptic) are i-lines. i increases with decreasing angle and j increases with increasing radius (see figure). = 3.0 circles (polar) or ellipses (hyperbolic-elliptic) are i-lines, and radial lines (polar) or hyperbolas (hyperbolic-elliptic) are j-lines. i increases with decreasing radius and j increases with decreasing angle (see figure). = 4.0 circles (polar) or ellipses (hyperbolic-elliptic) are j-lines, and radial lines (polar) or hyperbolas (hyperbolic-elliptic) are i-lines. i increases with increasing angle and j increases with decreasing radius (see figure).
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 266 input record may be used in conjunction with a 261 or a 262 input record to specify polar or hyperbolic-elliptic zoning.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	RATRAD	RATANG	SMLMAJ	ZONMAJ	RATMAJ	ANGMAJ	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable



- 1 L Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
- 2 RATRAD Geometric ratio. The value of RATRAD is used to space circles (polar zoning) or semi-minor axes (hyperbolic-elliptic zoning). The value of RATRAD must be greater than or equal to 0.5 and less than or equal to 1.5 or the message,

GEOMETRIC RATIO
IMPROPERLY DEFINED

is written on the print and the message files and the program terminates at the end of subroutine GPTINP.

Columns →	11	21	31	41	51	61	71	80
	L	RATRAD	RATANG	SMLMAJ	ZONMAJ	RATMAJ	ANGMAJ	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	RATANG	Geometric ratio. The value of RATANG is used to space radii (polar zoning) or asymptotes (hyperbolic-elliptic zoning). The value of RATRAD must be greater than or equal to 0.5 and less than or equal to 1.5 or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates at the end of subroutine GPTINP.
4	SMLMAJ	For hyperbolic-elliptic zoning, SMLMAJ is the length of the <u>semi-major</u> axis of the smallest ellipse. The value of SMLMAJ must be a positive number in problem units. Leave this field blank for polar zoning.
5	ZONMAJ	For hyperbolic-elliptic zoning, ZONMAJ is the difference in length between the <u>semi-major</u> axes of the smallest and next-smallest ellipses. The value of ZONMAJ must be a positive number in problem units. Leave this field blank for polar zoning.
6	RATMAJ	Geometric ratio. The value of RATMAJ is used to space the <u>semi-major</u> axes in hyperbolic-elliptic zoning. The value of RATMAJ must be greater than or equal to 0.5 and less than or equal to 1.5 or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and on the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, a ratio of 1.0 is assumed. Leave this field blank for polar zoning.
7	ANGMAJ	For hyperbolic-elliptic zoning, ANGMAJ is the angle (expressed in degrees) measured counterclockwise from the x-axis to the line containing the major axes of the ellipses. The value of ANGMAJ must be greater than or equal to -360.0 and less than or equal to 360.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP. Leave this field blank for polar zoning.

Polar or Hyperbolic-Elliptic Zoning -- Additional Specifications

Page 1 of 2

TYPE

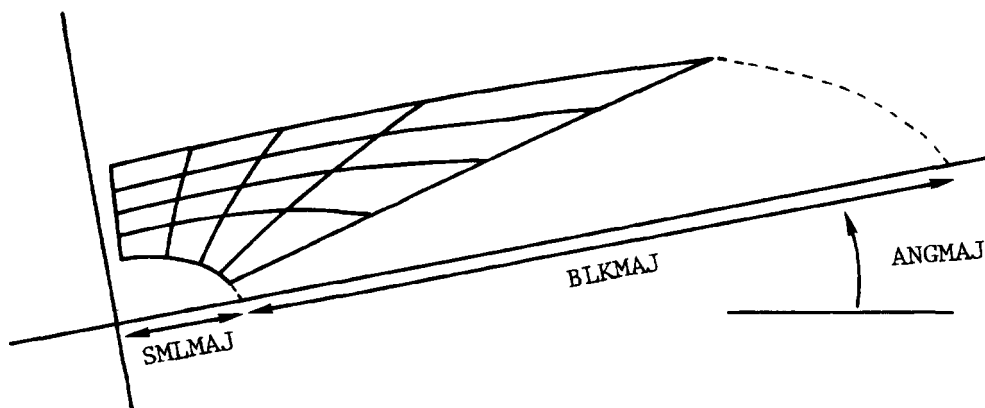
267

The 267 input record may be used in conjunction with a 261 or a 262 input record to specify polar or hyperbolic-elliptic zoning.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	RATRAD	RATANG	SMLMAJ	BLKMAJ	RATMAJ	ANGMAJ	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable



- 1 L Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
- 2 RATRAD Geometric ratio. The value of RATRAD is used to space circles (polar zoning) or semi-minor axes (hyperbolic-elliptic zoning). The value of RATRAD must be greater than or equal to 0.5 and less than or equal to 1.5 or the message,

GEOMETRIC RATIO
IMPROPERLY DEFINED

is written on the print and the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, a ratio of 1.0 is assumed.

Columns →	11	21	31	41	51	61	71	80
	L	RATRAD	RATANG	SMLMAJ	BLKMAJ	RATMAJ	ANGMAJ	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	RATANG	Geometric ratio. The value of RATANG is used to space radii (polar zoning) or asymptotes (hyperbolic-elliptic zoning). The value of RATRAD must be greater than or equal to 0.5 and less than or equal to 1.5 or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and the message files and the program terminates at the end of subroutine GPTINP.
4	SMLMAJ	For hyperbolic-elliptic zoning, SMLMAJ is the length of the <u>semi-major</u> axis of the smallest ellipse. The value of SMLMAJ must be a positive number in problem units. Leave this field blank for polar zoning.
5	BLKMAJ	For hyperbolic-elliptic zoning, BLKMAJ is the difference in length between the <u>semi-major</u> axes of the smallest and largest ellipses. The value of BLKMAJ must be a positive number in problem units. Leave this field blank for polar zoning.
6	RATMAJ	Geometric ratio. The value of RATMAJ is used to space the <u>semi-major</u> axes in hyperbolic-elliptic zoning. The value of RATMAJ must be greater than or equal to 0.5 and less than or equal to 1.5 or the message, GEOMETRIC RATIO IMPROPERLY DEFINED is written on the print and on the message files and the program terminates at the end of subroutine GPTINP. If this field is left blank, a ratio of 1.0 is assumed. Leave this field blank for polar zoning.
7	ANGMAJ	For hyperbolic-elliptic zoning, ANGMAJ is the angle (expressed in degrees) measured counterclockwise from the x-axis to the line containing the major axes of the ellipses. The value of ANGMAJ must be greater than or equal to -360.0 and less than or equal to 360.0 or a message is written on the print and the message files and the program terminates at the end of subroutine GPTINP. Leave this field blank for polar zoning.

Special Zoning #1

Page 1 of 1

TYPE
281

The 281 input record may be used to specify special parameters for block number L. The 281 input record may not be used at restart time.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	NZON	XLFT	XRHT	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 221 record.
2	NZON	Number of zones in this block, NZON IRHT - ILFT. The value of NZON must be integral and greater than or equal to 1 and less than or equal to MAXZON. (See Appendix "Maximums".) If NZON is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3	XLFT	x-coordinate of the leftmost grid point in this block. The value of XLFT can be any number less than XRHT in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
4	XLFT	x-coordinate of the rightmost grid point in this block. The value of XLFT can be any number less than XRHT in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Special Zoning #2

Page 1 of 1

ID ONLY

TYPE

282

The 282 input record may be used to specify special parameters for block number L. The 282 input record may not be used at restart time.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	NZON	XLFT	XBLK	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 221 record.
2	NZON	Number of zones in this block, NZON IRHT - ILFT. The value of NZON must be integral and greater than or equal to 1 and less than or equal to MAXZON. (See Appendix "Maximums".) If NZON is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
3	XLFT	x-coordinate of the leftmost grid point in this block. The value of XLFT can be any number less than XRHT in problem units but must be non-negative when NSSYM = 2, 3, or 5. (The value of NSSYM is specified in input block PRB on the SYM input record.)
4	XBLK	Width of the block. The value of XBLK must be a positive number in problem units.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* XRHT XLFT + XBLK

Special 2D Zoning

Page 1 of 1

TYPE
283

The 283 input record is used to activate special subroutine MYGPT for block number L. The 283 input record may not be used at restart time.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 221. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine GPTINP. (See Appendix "Messages".)
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

End of GPT Phase

Page 1 of 1

TYPE

END

The END input record signifies the end of a block of data for the GPT input phase. It must follow the last GPT input record.

	min	max
start	1	1
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	--	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1-7	--	Fields 1-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE

END

7.3 ZONE SPECIFICATION PHASE (ZON)

The zone specification phase (ZON) input block may be located in any position in the input deck after the PRB input block and before the final END record. The purpose of the ZON input block is to specify initial values for the physics equations in the PROCESSOR -- "Initial" values imply that the ZON input block may not be used at restart time.

Initial-value blocks are specified on input record types 31__ by grid-point index limits. (The block number L is local to phase ZON and is used to locate array elements in the labeled COMMON block /ZONPRM/.) Up to MAXBLK initial-value blocks may be specified to identify variations in initial values. (See Appendix "Maximums".)

Initial values are divided into the following groups:

<u>Record Identifier</u>	<u>Group Description</u>
32_	Initial Scalars
33_	Initial Vectors
34_	Initial Tensors

Initial vectors and tensors have global defaults of zero (0.0) but initial scalars must always be specified.

A minimum input deck for a start run consists of one input record to specify an initial value block of the entire grid and one set of initial scalar input records which specify the material property model of the block and the initial relative volume. Zone values cannot be changed after a problem has started.

Other versions of the STEALTH codes contain a rezoning capability that would normally be specified in the ZON phase input block. In these versions, however, this rezone capability has been replaced by the ALE method which offers some advantages for fluid flow calculations. ALE input is specified in the PRB phase input block.

A summary of ZON phase input records and input variables appears in Table 7.3.

SUMMARY OF ZON PHASE INPUT RECORDS AND INPUT VARIABLES

[illegible]

The function of the ZON control record is to activate the ZON input phase. The ZON control record must follow an END input record and is required for all start runs. It may be used at restart time for rezone specifications only.

	min	max
start	1	1
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSINP	Input mode switch. The value of NSINP specifies the mode of input to be used in this input phase. The value of NSINP must be integral and less than or equal to 3. The following definitions apply:

≤ 1.0 card input (default)
 $= 2.0$ library input
 $= 3.0$ keyboard input

If the field containing NSINP is left blank, then the mode of input is assumed to be card input. If the value of NSINP is greater than 3.0, the message,

INPUT MODE SWITCH
IMPROPERLY DEFINED

is written on the print and the message files, and the program terminates immediately in subroutine GENGEN.

2	NSTRC	Trace mode switch. The value of NSTRC specifies whether or not the trace option is active. The value of NSTRC must be integral and less than or equal to 2. The following definitions apply:

≤ 1.0 trace is not active, off (default)
 $= 2.0$ trace is active, on

If the field containing NSTRC is left blank, then the mode is assumed to be not active (off). If the value of NSTRC is greater than 2.0, the message,

TRACE MODE SWITCH
IMPROPERLY DEFINED

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	SNPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The trace logic, if active (on), will cause the name of the subroutine or logical phase just entered to be printed on both the print and message files. The actions are taken in subroutines SBRENT and PHSENT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
3	NSDBG	Debug mode switch. The value of NSDBG specifies whether or not the debug option is active. The value of NSDBG must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 debug is not active, off (default) $= 2.0$ debug is active, on If the field containing NSDBG is left blank, then the debug mode is assumed to be not active (off). If the value of NSDBG is greater than 2.0, the message, DEBUG MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The debug logic, if active (on), will cause the common blocks associated with this input phase to be dumped at the end of each subroutine in the phase and at the end of the logical phase. These actions are taken in subroutines SBREXT and PHSEXT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
4	NSPLT	Plot mode switch. The value of NSPLT specifies whether or not plots will be produced by this generator phase. The value of NSPLT must be integral and less than or equal to 2.0. The following definitions apply: ≤ 1.0 no plots produced, option off (default) $= 2.0$ plots produced, option on If the field containing NSPLT is left blank, then no plots will be produced (off). If the value of NSPLT is greater than 2.0, the message,

TYPE
ZON

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		PLOT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine ZONGEN.
5	NSPRT	Print mode switch. The value of NSPRT controls the printing in this generator phase. The value of NSPRT must be integral and less than or equal to 2.0. The following definitions apply: = 1.0 only input records and error messages are printed, option off = 2.0 full printing done, option on (default) If the field containing NSPRT is left blank, full printing is done (option on). If the value of NSPRT is greater than 2.0, the message, PRINT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine ZONGEN.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
ZON

Initial Values Block Definition

Page 1 of 2

TYPE 311

The 311 input record defines an initial values block for which initial values are described on input records in the ZON input phase. At least one 311 input record is required for a start run to set up initial values. The 311 input record may not be used at restart time.

	min	max
start	1	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	ILFT	IRHT	JBOT	JTOP	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. The value of L uniquely identifies a block of grid points defined by the grid point limits specified on record type 311. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXBLK. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine ZONINP. (See Appendix "Messages".)
2	ILFT	Leftmost grid point index for initial value block L. The value of ILFT must be integral and greater than or equal to 1 and less than IRHT. If ILFT is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the ZON GENERATOR phase. (See Appendix "Messages".) $1 \leq ILFT < IRHT$
3	IRHT	Rightmost grid point index for initial value block L. The value of IRHT must be integral and greater than ILFT and less than or equal to MAXGPT. (See Appendix "Maximums".) If IRHT is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the ZON GENERATOR phase. (See Appendix "Messages".) $ILFT < IRHT \leq MAXGPT$

Columns →	11	21	31	41	51	61	71	80
	L	ILFT	IRHT	JBOT	JTOP	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	JBOT*	Bottommost grid point index for initial value block L. The value of JBOT must be integral and greater than or equal to 1 and less than JTOP. If JBOT is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the ZON GENERATOR phase. (See Appendix "Messages".) $1 \leq \text{JBOT} < \text{JTOP}$
5	JTOP*	Topmost grid point index for initial value block L. The value of JTOP must be integral and greater than JBOT and less than or equal to MAXBUF. (See Appendix "Maximums".) If JTOP is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the ZON GENERATOR phase. (See Appendix "Messages".) $\text{JBOT} < \text{JTOP} \leq \text{MAXBUF}$
6-7	--	Fields 6-7 must be left blank of the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*JBOT and JTOP are not required for one-dimensional problems and input values in this field will result in the FLDCHK message being written on the print and the message files and the program being terminated at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 321 input record specifies the material property number for zones in block number L. At least one 321 input record is required for all start runs. It may not be used at restart time.

	min	max
start	1	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	MPNBLK	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 311 record.
2	MPNBLK	Material property number. The value of MPNBLK uniquely identifies a material property model. In the incompressible flow versions, a model consists only of a reference density. The value of MPNBLK must be integral and must be greater than or equal to 1 and less than or equal to MAXMAT. (See Appendix "Maximums".) If MPNBLK is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine ZONINP. (See Appendix "Messages".)
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Initial Scalars Specification

Page 1 of 1

TYPE

322

The 322 input record specifies the initial relative volume, internal energy density, temperature, and heat energy density for zones in block number L. At least one 322 input record is required for all start runs. It may not be used at restart time.

	min	max
start	1	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	RLVBLK	ZIEBLK	TMPBLK	ZHEBLK	PRHBLK	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 311 record.
2	RLVBLK	Initial relative volume. RLVBLK is related to the reference density defined for the material model specified on the 321 input record for this block. The value of RLVBLK must be a positive number greater than SMLNUM or the message, INITIAL RELATIVE VOLUME OF BLOCK <u>11</u> MUST BE A NONZERO POSITIVE NUMBER ITS VALUE IS RLVBLK = <u>eeeeeeeeeeee</u> is written on the print and the message files and the program terminates immediately in subroutine ZONINP. For the incompressible flow versions, RLVBLK should be set equal to 1.0.
3	ZIEBLK	Initial internal energy density.*
4	TMPBLK	Initial temperature.*
5	ZHEBLK	Initial heat energy density.*
6	PRHBLK	Initial pressure.**
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Not used for the incompressible flow versions. Leave blank.

** Not used for implicit, compressible flow versions. In these versions the initial pressure is determined from the equation of state using the initial relative volume and initial internal energy density.

TYPE

322

Initial Velocity Specification

Page 1 of 1

TYPE
331

The 331 input record specifies the initial velocity for zones in block number L. The 331 input record may not be used at restart time. If the 331 input record is omitted, the initial velocity is assumed to be the default value.

	min	max
start	0	MAXBLK
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	L	XVLBLK	YVLBLK	ZVLBLK	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 311 record.
2	XVLBLK	Initial x-velocity. The value of XVLBLK can be any number in problem units. The default value is zero.
3	YVLBLK	Initial y-velocity. The value of YVLBLK can be any number in problem units. The default value is zero. (Only needed for two-dimensional problems.)
4	ZVLBLK	Initial z-velocity. The value of ZVLBLK can be any number in problem units. The default value is zero. (Only needed for three-dimensional problems.)
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Initial Total Stress Tensor Specification*

Page 1 of 1

TYPE
341

The 341 input record specifies the initial total stress tensor for zones in block number L. The 341 input record may not be used at restart time. If the 341 input record is omitted, the initial total stresses are assumed to be the default values.

	min	max
start	0	MAXBLK
restart	0	0

Columns → 11 21 31 41 51 61 71 80

L	TXXBLK	TYYBLK	TZZBLK	TXYBLK	TYZBLK	TXZBLK

Fields → 1 2 3 4 5 6 7

Field Number	Input Variable Name	Description of Input Variable
1	L	Block number. See Field Number 1 on TYPE 311 record.
2	TXXBLK	Initial xx-total stress. The value of TXXBLK can be any number in problem units. The default value is zero.**
3	TYYBLK	Initial yy-total stress. The value of TYYBLK can be any number in problem units. The default value is zero.**
4	TZZBLK	Initial zz-total stress. The value of TZZBLK can be any number in problem units. The default value is zero.**
5	TXYBLK	Initial xy-shear stress. The value of TXYBLK can be any number in problem units. The default value is zero. This field will be ignored in one-dimensional problems.
6	TYZBLK	Initial yz-total stress. The value of TYZBLK can be any number in problem units. The default value is zero. This field will be ignored in one- and two-dimensional problems.
7	TXZBLK	Initial xz-shear stress. The value of TXZBLK can be any number in problem units. The default value is zero. This field will be ignored in one- and two-dimensional problems.

* Not used for the inviscid, incompressible flow versions.

** If the initial relative volume and internal energy density are specified such that a non-zero initial pressure is produced, or if an initial pressure is specified on the 322 input record, the default value for the diagonal components of the stress tensor is the negative of the pressure.

End of ZON Phase

Page 1 of 1

TYPE
END

The END input record signifies the end of a block of data for the ZON input phase. It must follow the last ZON input record.

	min	max
start	1	1
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	--	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1-7	--	Fields 1-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
END

7.4 BOUNDARY CONDITIONS SPECIFICATIONS PHASE (BDY)

The boundary specifications phase (BDY) input block may be located in any position in the input deck after the PRB input block and before the final END record. The purpose of the BDY input block is to specify time-dependent boundary conditions for the physics equations in the PROCESSOR. Boundary conditions may be changed at restart time.

Boundary conditions must be specified for grid points as well as wall points. Usually, only boundary grid points require explicit boundary conditions, but there are circumstances in which an interior grid point requires a boundary condition. All wall points need boundary conditions.

Boundary conditions are specified point-by-point in one-dimensional problems and by line segment (two points in space) in two-dimensional problems. Only the points which require boundary values (momentum or thermal) need be specified. Specifications of the type of boundary point is done by grid-point index on input record groups 41_ and 42_.

Boundary conditions fall into two distinct categories: momentum and thermal. These categories may be further classified as directional (vector) or non-directional (non-vector). Directional boundary conditions are centered at a point (i.e., a boundary grid point) while non-directional boundary conditions are centered between grid points. For momentum boundary conditions, velocity, displacement, acceleration, and force are the typical directional boundary conditions; pressure is a non-directional boundary condition. For thermal boundary conditions, heat flux is directional and temperature is non-directional.* Grid and wall point boundary conditions require both momentum and thermal specifications.

* Thermal boundary conditions are not used with the incompressible flow versions.

However, when a directional quantity is used to specify a momentum condition, then a non-directional quantity may not be used at that point, and vice versa. Similar remarks apply to thermal boundary conditions.

All boundary conditions require boundary data. These data may come by prescription or from an interaction calculation. Prescribed data are usually in the form of a history or a constant. Interactive conditions require the proper "interaction" algorithm.*

Input specifications in the BDY GENERATOR phase are grouped into categories which reflect the concepts described above. The 411 and 412 input records assign momentum and thermal boundary properties to each boundary point (denoted by its index space location). The 411 input record defines the boundary point (or segment) and the 412 input record defines the properties. The properties are composed of the momentum boundary number (NBM), the thermal boundary number (NBT), the boundary value number (NBV), the boundary rezone number (NBR), and a material model specification (MPN). There are eight types of boundary conditions each for momentum and thermal boundary conditions. They are summarized below.

<u>NBM</u>	<u>Momentum Boundary Condition</u>
1.0	interior
2.0	pressure history
3.0	free (pressure = 0)
4.0	velocity history
5.0	fixed (velocity = 0)
6.0	wall interaction (rigid)
7.0	grid interaction*
8.0	user-supplied special

*Not available in the implicit, fluid mechanics versions.

<u>NBT</u>	<u>Thermal Boundary Condition</u>
1.0	interior
2.0	temperature history
3.0	isothermal (temperature = 0)
4.0	heat flow history
5.0	adiabatic (heat flow = 0)
6.0	wall interaction (adiabatic)
7.0	grid interaction*
8.0	user-supplied special

For certain boundary conditions, no more data need be specified than that contained on input records 411 and 412. For example, a free, adiabatic boundary requires no more input. However, if boundary history data are necessary for either the momentum or the thermal type of boundary condition, then a 422 and/or a 423 input record corresponding to the momentum and thermal boundary conditions, respectively, must be specified to identify which history data are to be used. The momentum boundary data number (MBD) and/or the thermal boundary data number (TBD) are set equal to the correct history data model number. The 422 and 423 input records connect a specific boundary condition on the 411 and 412 input records to a particular model that has been specified on input records 431-469.

History data are input through input records 431-469 as shown below.

Record	
<u>Identifier</u>	<u>Group Description</u>
43_	Pressure conditions
44_	Velocity conditions
45_	Temperature conditions
46_	Heat flow conditions
	momentum values
	thermal values

Non-directional momentum data are specified on input records 431-439. For example, pressure history data are provided on records 431 and 432. Directional momentum data are specified on records 441-449; x-velocity on the 441 and 442 records, and y-velocity on the 443-444 records. Non-directional thermal data are specified on input records 451-459; temperature history data appear on the 451-452 input records. Directional thermal data are specified on records 461-469; x-heat flux on records 461-462 and y-heat flux on records 463-464.

If a wall interaction momentum condition has been specified for a particular boundary grid point, then the boundary specifications for the wall are required. Wall boundary conditions are specified on input records 481-489.

Minimum input is simply a set of appropriate 41_ input records for each boundary point (1D) or each boundary segment or group of boundary segments (2D). At restart time, BDY records need only be input if a boundary type or function is to be changed. In this case, all of the parameters on the affected record must be specified again. New boundaries may not be specified at restart time.

A summary of BDY phase input records and input variables appears in Table 7.4.

TABLE 7.4

SUMMARY OF BDY PHASE INPUT RECORDS AND INPUT VARIABLES

FIELDS 1-7

TYPE	1	2	3	4	5	6	7
BDY	NSINP	NSTRC	NSDBG	NSPLT	NSPRT		
411	LS	IBBGN	JBBGN	IBEND	JBEND		2D
412	LS	MPNBSG.	NBMBSG	NBTBSG	NBVBSG	NBRBSG	2D
421	I	NBM	NBT	NBV			1D
422	NBV	MMBD					
431	MMBD	PRHFNC	PRHS	PRHE			
432	MMBD	PRH1	PRH2	PRH3	PRH4		
441	MMBD	XVLFNC	XVLS	XVLE			
442	MMBD	XVL1	XVL2	XVL3	XVL4		
443	MMBD	YVLFNC	YVLS	YVLE			
444	MMBD	YVL1	YVL2	YVL3	YVL4		
481	LS	IWBGN	IWEND				
482	LS	MPNWSG	NBMWSG	NBTWSG	NBVWSG	DWLWSG	
483	NMW	NTW	NVW	MWL			1D
484	NMW	NTW	NVW	MWL			1D
END							

The function of the BDY control record is to activate the BDY input phase. The BDY control record must follow an END input record and is required for all start runs. It may be used at restart time to change data.

	min	max
start	1	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSINP	Input mode switch. The value of NSINP specifies the mode of input to be used in this input phase. The value of NSINP must be integral and less than or equal to 3. The following definitions apply:

≤ 1.0 card input (default)
 $= 2.0$ library input
 $= 3.0$ keyboard input

If the field containing NSINP is left blank, then the mode of input is assumed to be card input. If the value of NSINP is greater than 3.0, the message,

INPUT MODE SWITCH
IMPROPERLY DEFINED

is written on the print and the message files, and the program terminates immediately in subroutine GENGEN.

2	NSTRC	Trace mode switch. The value of NSTRC specifies whether or not the trace option is active. The value of NSTRC must be integral and less than or equal to 2. The following definitions apply:

≤ 1.0 trace is not active, off (default)
 $= 2.0$ trace is active, on

If the field containing NSTRC is left blank, then the mode is assumed to be not active (off). If the value of NSTRC is greater than 2.0, the message,

TRACE MODE SWITCH
IMPROPERLY DEFINED

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The trace logic, if active (on), will cause the name of the subroutine of logical phase just entered to be printed on both the print and message files. These actions are taken in subroutines SBRENT and PHSENT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
3	NSDBG	Debug mode switch. The value of NSDBG specifies whether or not the debug option is active. The value of NSDBG must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 debug is not active, off (default) $= 2.0$ debug is active, on If the field containing NSDBG is left blank, then the debug mode is assumed to be not active (off). If the value of NSDBG is greater than 2.0, the message, DEBUG MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The debug logic, if active (on), will cause the common blocks associated with this input phase to be dumped at the end of each subroutine in the phase and at the end of the logical phase. These actions are taken in subroutines SBREXT and PHSEXT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
4	NSPLT	Plot mode switch. The value of NSPLT specifies whether or not plots will be produced by this generator phase. The value of NSPLT must be integral and less than or equal to 2.0. The following definitions apply: ≤ 1.0 no plots produced, option off (default) $= 2.0$ plots produced, option on If the field containing NSPLT is left blank, then no plots will be produced (off). If the value of NSPLT is greater than 2.0, the message, PLOT MODE SWITCH IMPROPERLY DEFINED

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files, and the program terminates immediately in subroutine BDYGEN.
5	NSPRT	Print mode switch. The value of NSPRT controls the printing in this generator phase. The value of NSPRT must be integral and less than or equal to 2.0. The following definitions apply: = 1.0 only input records and error messages are printed, option off = 2.0 full printing done, option on (default) If the field containing NSPRT is left blank, full printing is done (option on). If the value of NSPRT is greater than 2.0, the message, PRINT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine BDYGEN.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Boundary Point Segment Definition

Page 1 of 2

TYPE
411

The 411 input record defines a sequence of contiguous boundary points for which unique boundary properties are described on input record 412. A boundary point segment may be composed of one or more boundary points. Undefined boundary points are assumed to be mechanically free and thermally adiabatic.

	min	max
start	0	MAXSEG
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	LS	IBBGN	JBBGN	IBEND	JBEND	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	LS	Segment number. The value of LS uniquely identifies a sequence of boundary points defined by the grid point limits specified on record type 411. The value of LS must be integral and greater than or equal to 1 and less than or equal to MAXSEG. (See Appendix "Maximums".) If LS is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Message".) If the segment is composed of only one point, then IBBGFN = IBEND and JBBFN = JBEND. In one-dimensional problems, JBBGN and JBEND are ignored. In two-dimensional problems, the boundary point limits must be defined counterclockwise in a righthanded i,j space and must not cross a grid corner in i,j space.
2	IBBGN	I index of first boundary point in a sequence of boundary points. The value of IBBGN must be integral and greater than or equal to 1 and less than or equal to MAXGPT. (See Appendix "Maximumx".) If IBBGN is out of this range, a RGEERR message is written on the print and the message files and the program terminates in subroutine BDYINP. (See Appendix "Messages".)
3	JBBGN	J index of first boundary point in a sequence of boundary points. The value of JBBGN must be integral and greater than or equal to 1 and less than or equal to MAXBUF. (See Appendix "Maximums".) If JBBGN is out of this range, a RGEERR message is written on the print and the message files and the program terminates in subroutine BDYINP. (See Appendix "Messages".)

Columns →	11	21	31	41	51	61	71	80
	LS	IBBGN	JBBGN	IBEND	JBEND	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	IBEND	I index of last boundary point in a sequence of boundary points. The value of IBEND must be integral and greater than or equal to 1 and less than or equal to MAXGPT. (See Appendix "Maximums".) If IBEND is out of this range, a RGEERR message is written on the print and the message files and the program terminates in subroutine BDYINP. (See Appendix "Messages".)
5	JBEND	J index of last boundary point in a sequence of boundary points. The value of JBEND must be integral and greater than or equal to 1 and less than or equal to MAXBUF. (See Appendix "Maximums".) If JBEND is out of this range, a RGEERR message is written on the print and the message files and the program terminates in subroutine BDYINP. (See Appendix "Messages".)
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 412 input record describes the properties of a contiguous sequence of boundary segments defined on the 411 input record.

	min	max
start	0	MAXSEG
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	LS	MPNBSG	NBMBSG	NBTBSG	NBVBSG	NBRBSG	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	LS	Segment number. The value of LS uniquely identifies a sequence of boundary points defined by the grid point limits specified on record type 411. The value of LS must be integral and greater than or equal to 1 and less than or equal to MAXSEG. (See Appendix "Maximums".) If LS is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) If the segment is composed of only one point, then IBBGN = IBEND and JBBGN = JBEND. In two-dimensional problems, the boundary point limits must be defined counterclockwise in a righthanded i,j space and must not cross a grid corner in i,j space.
2	MPNBSG	Material property number for this segment. The value of MPNBSG uniquely identifies a material model. A model may consist of a reference density, an equation of state, viscosity coefficients, and thermal descriptions; however, only the mechanical and thermal surface properties will be used. The value of MPNBSG must be integral and must be greater than or equal to 1 and less than or equal to MAXMAT. (See Appendix "Maximums".) If MPNBSG is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
3	NBMBSG	Momentum boundary number for this segment. The value of NBMBSG identifies the momentum boundary condition type. The value of NBMBSG must be integral and greater than or equal to 1 and less than or equal to 9. If NBMBSG is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply:

Columns →	11	21	31	41	51	61	71	80
	LS	MPNBSG	NBMBSG	NBTBSG	NBVBSG	NBRBSG	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable

= 1.0	interior
= 2.0	pressure history*
= 3.0	free, p = 0.0
= 4.0	velocity history*
= 5.0	fixed (rigid)
= 6.0	wall interaction**
= 7.0	grid interaction**
= 8.0	special
= 9.0	continuative outflow

- 4 NBTBSG Thermal boundary number for this segment. The value of NBTBSG identifies the thermal boundary condition type. The value of NBTBSG must be integral and greater than or equal to 1 and less than or equal to 8. If NBTBSG is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply:

= 1.0	interior
= 2.0	temperature history***
= 3.0	isothermal, T = 0.0
= 4.0	heat flux history***
= 5.0	adiabatic
= 6.0	wall interaction
= 7.0	grid interaction
= 8.0	special

Thermal boundary conditions are not used with the incompressible flow versions.

*When a pressure history boundary point in a particular cycle is outside of the range of the function defined on the 431 input record, it automatically becomes a free point for that cycle. When a velocity history point is outside of its range as defined on the 441 input record, it is permanently changed to a free point for all time.

**Not available in implicit fluid mechanics.

***When a temperature history boundary point in a particular cycle is outside of the range of the function defined on the 451 input record, it automatically becomes an isothermal point where T = 0 for that cycle. When a heat flux history point is outside of its range as defined on the 461 input record, it is permanently changed to an isothermal point where T = 0 for all time.

Columns →	11	21	31	41	51	61	71	80
	LS	MPNBSG	NBMBSG	NBTBSG	NBVBSG	NBRBSG	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
5	NBVBSG	Index of boundary array. The parameter NBVBSG has a different function depending on the type of momentum boundary condition specified for the boundary segment LS. The different functions are as follows: 1. For boundary segments which have a pressure or velocity history specification (NBMBSG = 2.0 or 4.0), the value of NBVBSG specifies the index location of boundary history model data for each grid point on that segment. 2. For boundary segments that interact with wall points (NBMBSG = 6.0), the value of NBVBSG specifies the greater wall point number of the closest wall point segment. 3. For boundary segments that interact with another grid (NBMBSG = 7.0), the value of NBVBSG specifies the closest i,j point in the other grid. The format for NBVBSG in this case is IIIJJJ.* When none of the above boundary conditions are specified for the segment, leave NBVBSG blank. The value of NBVBSG must be integral and greater than or equal to 0. For case 1 above, the value must be less than or equal to MAXBDY; for case 2 it must be less than MAXWPT. (See Appendix "Maximums".) If NBVBSG is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
6	NBRBSG	Boundary rezone number.** The value of NBRBSG specifies the type of rezoning to be used in the ALE mesh rezoner for the grid points on the boundary segment LS. The value of NBRBSG must be integral and greater than or equal to 1 and less than or equal to 3. If NBRBSG is out of this range, a RGEERR message is written on the print and message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply:

* Not available in the implicit fluid mechanics versions.

** Required only for rezone options specified by NSALE = 4.0 - 8.0 on record type ALE in the PRB input block.

Columns →	11	21	31	41	51	61	71	80
	LS	MPNBSG	NBMBSG	NBTBSG	NBVBSG	NBRBSG	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		= 1.0 Lagrangian
		= 2.0 Eulerian
		= 3.0 Same rezone model as used for interior grid points
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Boundary LocationTYPE
421

Each 421 input record specifies the boundary conditions for a particular boundary point. A 421 input record is required for each boundary point in a grid. There are no default values and the 421 input record may be used at restart time to change boundary conditions.

	min	max
start	2	MAXGPT
restart	1	MAXGPT

Columns →	11	21	31	41	51	61	71	80
	I	NBM	NBT	NBV	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	I	Index of grid point. The value of I specifies a grid point index location that requires boundary conditions to be specified. The value of I must be integral and greater than or equal to 1 and less than or equal to MAXGPT. (See Appendix "Maximums".) If I is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	NBM	Momentum boundary number. The value of NBM identifies the momentum boundary condition type. The value of NBM must be integral and greater than or equal to 1 and less than or equal to 8. If NBM is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 1.0 interior = 2.0 pressure history* = 3.0 free, p = 0.0 = 4.0 velocity history* = 5.0 fixed (rigid) = 6.0 wall interaction = 7.0 grid interaction = 8.0 special

* When a pressure history boundary point in a particular cycle is outside of the range of the function defined on the 431 input record, it automatically becomes a free point for that cycle. When a velocity history point is outside of its range as defined on the 441 input record, it is permanently changed to a free point for all time.

TYPE
421

Columns →	11	21	31	41	51	61	71	80
	I	NBM	NBT	NBV	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	NBT	Thermal boundary number. The value of NBT identifies the thermal boundary condition type. The value of NBT must be integral and greater than or equal to 1 and less than or equal to 8. If NBT is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 1.0 interior = 2.0 temperature history* = 3.0 isothermal, $T = 0$* = 4.0 heat flux history* = 5.0 adiabatic = 6.0 wall interaction = 7.0 grid interaction = 8.0 special Thermal boundary conditions are not used with the incompressible flow versions.
4	NBV	Index of boundary array. The value of NBV specifies the index location of boundary history model data for a grid point in the boundary values array. When no history data is required, leave NBV blank. The value of NBV must be integral and greater than or equal to 0 and less than or equal to MAXBDY. (See Appendix "Maximums".) If NBV is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* When a temperature history boundary point in a particular cycle is outside of the range of the function defined on the 451 input record, it automatically becomes an isothermal point where $T = 0$ for that cycle. When a heat flux history point is outside of its range as defined on the 461 input record, it is permanently changed to an isothermal point where $T = 0$ for all time.

A 422 input record is required for each boundary point whose momentum boundary is a specified time history input. It is used in conjunction with the 421 input record in 1D and the 412 and 482 input records in 2D.

	min	max
start	0	MAXBDY
restart	0	MAXBDY

Columns →	11	21	31	41	51	61	71	80
	NBV	MMBD	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NBV	Index of boundary array. The value of NBV specifies the index location of boundary history model data for a grid point in the boundary values array. When no history data are required, NBV is left blank. The value of NBV must be integral and greater than or equal to 0 and less than or equal to MAXBDY. (See Appendix "Maximums".) If NBV is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	MMBD	Momentum boundary model number. The value of MMBD defines the array location of the function coefficients, model, and range defined on input records 431, 432, 441 thru 444. The value of MMBD must be integral and greater than or equal to 1 and less than or equal to MAXMBD. (See Appendix "Maximums".) If MMBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 423 input record is required for each boundary point whose thermal boundary is a specified time history input. It is used in conjunction with the 421 input record in 1D and the 412 input record in 2D.

	min	max
start	0	MAXBDY
restart	0	MAXBDY

Columns →	11	21	31	41	51	61	71	80
	NBV	MTBD	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NBV	Index of boundary array. The value of NBV specifies the index location of boundary history model data for a grid point in the boundary values array. When no history data is required, NBV is left blank. The value of NBV must be integral and greater than or equal to 0 and less than or equal to MAXBDY. (See Appendix "Maximums".) If NBV is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	MTBD	Thermal boundary model number. The value of MTBD defines the array location of the function coefficients, model, and range defined on input records 451, 452, 461, and 462. The value of MTBD must be integral and greater than or equal to 1 and less than or equal to MAXTBD. (See Appendix "Maximums".) If MTBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*Not used with the incompressible flow versions.

A 431 input record is required to specify a function type and a range for a pressure boundary.

	min	max
start	0	MAXMBD
restart	0	MAXMBD

Columns →	11	21	31	41	51	61	71	80
	MMBD	PRHFNC	PRHS	PRHE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MMBD	Momentum boundary model number. The value of MMBD defines the array location of the function coefficients, model, and range defined on input records 431, 432, 441 thru 444. The value of MMBD must be integral and greater than or equal to 1 and less than or equal to MAXMBD. (See Appendix "Maximums".) If MMBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	PRHFNC	Function type for pressure history modeling. The value of PRHFNC specifies the type of function of time. The value of PRHFNC must be integral and greater than 1 and less than or equal to 10. If PRHFNC is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 1.0 polynomial = 2.0 rational = 3.0 exponential #1 = 4.0 exponential #2 = 5.0 exponential #3 = 6.0 trigonometric #1 = 7.0 trigonometric #2 = 8.0 (none) = 9.0 user-supplied = 10.0 user-supplied See Appendix "Functions" for a description of the available function types.
3	PRHS	Start of time range for pressure function. The value of PRHS is a positive number. The value of problem time must be greater than or equal to PRHS and less than PRHE for the function to be activated.

Columns →	11	21	31	41	51	61	71	90
	MMBD	PRHFNC	PRHS	PRHE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	PRHE	End of time range for pressure function. The value of PRHE is a positive number. The value of problem time must be greater than or equal to PRHS and less than PRHE for the function to be activated.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 432 input record is required to specify function coefficients for a pressure boundary.

	min	max
start	0	MAXMBD
restart	0	MAXMBD

Columns →	11	21	31	41	51	61	71	80
	MMBD	PRH1	PRH2	PRH3	PRH4	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MMBD	Momentum boundary model number. The value of MMBD defines the array location of the function coefficients, model, and range defined on input records 431, 432, 441 thru 444. The value of MMBD must be integral and greater than or equal to 1 and less than or equal to MAXMBD. (See Appendix "Maximums".) If MMBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	PRH1	Pressure coefficient number 1. Default value is 0.
3	PRH2	Pressure coefficient number 2. Default value is 0.
4	PRH3	Pressure coefficient number 3. Default value is 0.
5	PRH4	Pressure coefficient number 4. Default value is 0.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

A 441 input record is required to specify a function type and a range for an x-velocity boundary.

	min	max
start	0	MAXMBD
restart	0	MAXMBD

Columns →	11	21	31	41	51	61	71	80
	MMBD	XVLFNC	XVLS	XVLE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MMBD	Momentum boundary model number. The value of MMBD defines the array location of the function coefficients, model, and range defined on input records 431, 432, 441 thru 444. The value of MMBD must be integral and greater than or equal to 1 and less than or equal to MAXMBD. (See Appendix "Maximums".) If MMBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	XVLFNC	Function type for x-velocity history modeling. The value of XVLFNC specifies the type of function of time. The value of XVLFNC must be integral and greater than or equal to 1 and less than or equal to 10. If XVLFNC is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 1.0 polynomial = 2.0 rational = 3.0 exponential #1 = 4.0 exponential #2 = 5.0 exponential #3 = 6.0 trigonometric #1 = 7.0 trigonometric #2 = 8.0 (none) = 9.0 user-supplied = 10.0 user-supplied See Appendix "Functions" for a description of available function types.
3	XVLS	Start of time range of x-velocity function. The value of XVLS is a positive number. The value of problem time must be greater than or equal to XVLS and less than XVLE for the function to be activated.

Columns →	11	21	31	41	51	61	71	80
	MMBD	XVLFNC	XVLS	XVLE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	XVLE	End of time range of x-velocity function. The value of XVLE is a positive number. The value of problem time must be greater than or equal to XVLS and less than XVLE for the function to be activated.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

x-Velocity History Coefficients

Page 1 of 1

TYPE
442

The 442 input record is required to specify function coefficients for an x-velocity boundary.

	min	max
start	0	MAXMBD
restart	0	MAXMBD

Columns →	11	21	31	41	51	61	71	80
	MMBD	XVL1	XVL2	XVL3	XVL4	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MMBD	Momentum boundary model number. The value of MMBD defines the array location of the function coefficients, model, and range defined on input records 431, 432, 441 thru 444. The value of MMBD must be integral and greater than or equal to 1 and less than or equal to MAXMBD. (See Appendix "Maximums".) If MMBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	XVL1	x-velocity coefficient number 1. Default value is 0.
3	XVL2	x-velocity coefficient number 2. Default value is 0.
4	XVL3	x-velocity coefficient number 3. Default value is 0.
5	XVL4	x-velocity coefficient number 4. Default value is 0.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

A 443 input record is required to specify a function type and a range for a y-velocity boundary.

	min	max
start	0	MAXMBD
restart	0	MAXMBD

Columns →	11	21	31	41	51	61	71	80
	MMBD	YVLFNC	YVLS	YVLE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MMBD	Momentum boundary model number. The value of MMBD defines the array location of the function coefficients, model, and range defined on input records 431, 432, 441 thru 444. The value of MMBD must be integral and greater than or equal to 1 and less than or equal to MAXMBD. (See Appendix "Maximums".) If MMBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	YVLFNC	Function type for y-velocity history modeling. The value of YVLFNC specifies the type of function of time. The value of YVLFNC must be integral and greater than or equal to 1 and less than or equal to 10. If YVLFNC is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 1.0 polynomial = 2.0 rational = 3.0 exponential #1 = 4.0 exponential #2 = 5.0 exponential #3 = 6.0 trigonometric #1 = 7.0 trigonometric #2 = 8.0 (none) = 9.0 user-supplied = 10.0 user-supplied

See Appendix "Functions" for a description of available function types.

3	YVLS	Start of time range of y-velocity function. The value of YVLS is a positive number. The value of problem time must be greater than or equal to YVLS and less than YVLE for the function to be activated.

Columns →	11	21	31	41	51	61	71	80
	MMBD	YVLFNC	YVLS	YVLE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	YVLE	End of time range of y-velocity function. The value of YVLE is a positive number. The value of problem time must be greater than or equal to YVLS and less than YVLE for the function to be activated.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

y-Velocity History Coefficients

Page 1 of 1

TYPE

444

The 444 input record is required to specify function coefficients for a y-velocity boundary.

	min	max
start	0	MAXMBD
restart	0	MAXMBD

Columns →	11	21	31	41	51	61	71	80
	MMBD	YVL1	YVL2	YVL3	YVL4	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MMBD	Momentum boundary model number. The value of MMBD defines the array location of the function coefficients, model, and range defined on input records 431, 432, 441 thru 444. The value of MMBD must be integral and greater than or equal to 1 and less than or equal to MAXMBD. (See Appendix "Maximums".) If MMBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	YVL1	y-velocity coefficient number 1. Default value is 0.
3	YVL2	y-velocity coefficient number 2. Default value is 0.
4	YVL3	y-velocity coefficient number 3. Default value is 0.
5	YVL4	y-velocity coefficient number 4. Default value is 0.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

A 451 input record is required to specify a function type and a range for a temperature boundary.

	min	max
start	0	MAXTBD
restart	0	MAXTBD

Columns →	11	21	31	41	51	61	71	80
	MTBD	TMPFNC	TMPS	TMPE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MTBD	Thermal boundary model number. The value of MTBD defines the array location of the function coefficients, model, and range defined on input records 451,452, 461 thru 464. The value of MMBD must be integral and greater than or equal to 1 and less than or equal to MAXTBD. (See Appendix "Maximums".) If MMBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	TMPFNC	Function type for temperature history modeling. The value of TMPFNC specifies the type of function of time. The value of TMPFNC must be integral and greater than or equal to 1 and less than or equal to 10. If TMPFNC is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 1.0 polynomial = 2.0 rational = 3.0 exponential #1 = 4.0 exponential #2 = 5.0 exponential #3 = 6.0 trigonometric #1 = 7.0 trigonometric #2 = 8.0 (none) = 9.0 user-supplied = 10.0 user-supplied

See Appendix "Functions" for a description of available function types.

* Not used with the incompressible flow versions.

Columns →	11	21	31	41	51	61	71	80
	MTBD	TMPFNC	TMPS	TMPE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	TMPS	Start of time range of temperature function. The value of TMPS is a positive number. The value of problem time must be greater than or equal to TMPS and less than TMPE for the function to be activated.
4	TMPE	End of time range of temperature function. The value of TMPE is a positive number. The value of problem time must be greater than or equal to TMPS and less than TMPE for the function to be activated.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 452 input record is required to specify function coefficients for a temperature boundary.

	min	max
start	0	MAXTBD
restart	0	MAXTBD

Columns →	11	21	31	41	51	61	71	80
	MTBD	TMP1	TMP2	TMP3	TMP4	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MTBD	Thermal boundary model number. The value of MTBD defines the array location of the function coefficients, model, and range defined on input records 451, 452, 461 thru 464. The value of MTBD must be integral and greater than or equal to 1 and less than or equal to MAXMBD. (See Appendix "Maximums".) If MTBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	TMP1	Temperature coefficient number 1. Default value is 0.
3	TMP2	Temperature coefficient number 2. Default value is 0.
4	TMP3	Temperature coefficient number 3. Default value is 0.
5	TMP4	Temperature coefficient number 4. Default value is 0.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Not used with the incompressible flow versions.

A 451 input record is required to specify a function type and a range for an x-heat flux boundary.

	min	max
start	0	MAXTBD
restart	0	MAXTBD

Columns →	11	21	31	41	51	61	71	80
	MTBD	XHFFNC	XHFS	XHFE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MTBD	Thermal boundary model number. The value of MTBD defines the array location of the function coefficients, model, and range defined on input records 451,452, 461 thru 464. The value of MTBD must be integral and greater than or equal to 1 and less than or equal to MAXTBD. (See Appendix "Maximums".) If MMBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	TMPFNC	Function type for x-heat flux history modeling. The value of TMPFNC specifies the type of function of time. The value of TMPFNC must be integral and greater than or equal to 1 and less than or equal to 10. If TMPFNC is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 1.0 polynomial = 2.0 rational = 3.0 exponential #1 = 4.0 exponential #2 = 5.0 exponential #3 = 6.0 trigonometric #1 = 7.0 trigonometric #2 = 8.0 (none) = 9.0 user-supplied = 10.0 user-supplied

See Appendix "Functions" for a description of available function types.

*Not used with the incompressible flow versions.

Columns →	11	21	31	41	51	61	71	80
	MTBD	XHFFNC	XHFS	XHFE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	TMPS	Start of time range of x-heat flux function. The value of TMPS is a positive number. The value of problem time must be greater than or equal to TMPS and less than TMPE for the function to be activated.
4	TMPE	End of time range of x-heat flux function. The value of TMPE is a positive number. The value of problem time must be greater than or equal to TMPS and less than TMPE for the function to be activated.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 462 input record is required to specify function coefficients for an x-heat flux boundary.

	min	max
start	0	MAXTBD
restart	0	MAXTBD

Columns →	11	21	31	41	51	61	71	80
	MTBD	XHF1	XHF2	XHF3	XHF4	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MTBD	Momentum boundary model number. The value of MTBD defines the array location of the function coefficients, model, and range defined on input records 451, 452, 461 thru 464. The value of MTBD must be integral and greater than or equal to 1 and less than or equal to MAXTBD. (See Appendix "Maximums".) If MTBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	XVL1	x-heat flux coefficient number 1. Default value is 0.
3	XVL2	x-heat flux coefficient number 2. Default value is 0.
4	XVL3	x-heat flux coefficient number 3. Default value is 0.
5	XVL4	x-heat flux coefficient number 4. Default value is 0.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Not used with the incompressible flow versions.

A 463 input record is required to specify a function type and a range for an y-heat flux boundary.

	min	max
start	0	MAXTBD
restart	0	MAXTBD

Columns →	11	21	31	41	51	61	71	80
	MTBD	YHFFNC	YHFS	YHFE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MTBD	Thermal boundary model number. The value of MTBD defines the array location of the function coefficients, model, and range defined on input records 451,452, 461 thru 464. The value of MTBD must be integral and greater than or equal to 1 and less than or equal to MAXTBD. (See Appendix "Maximums".) If MMBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	YHFFNC	Function type for y-heat flux history modeling. The value of YHFFNC specifies the type of function of time. The value of YHFFNC must be integral and greater than or equal to 1 and less than or equal to 10. If YHFFNC is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 1.0 polynomial = 2.0 rational = 3.0 exponential #1 = 4.0 exponential #2 = 5.0 exponential #3 = 6.0 trigonometric #1 = 7.0 trigonometric #2 = 8.0 (none) = 9.0 user-supplied = 10.0 user-supplied

See Appendix "Functions" for a description of available function types.

* Not used with the incompressible flow versions.

Columns →	11	21	31	41	51	61	71	80
	MTBD	YHFFNC	YHFS	YHFE	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	YHFS	Start of time range of y-heat flux function. The value of YHFS is a positive number. The value of problem time must be greater than or equal to YHFS and less than YHFE for the function to be activated.
4	YHFE	End of time range of y-heat flux function. The value of YHFE is a positive number. The value of problem time must be greater than or equal to YHFS and less than YHFE for the function to be activated.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

y-Heat Flux History Coefficients*

Page 1 of 1

TYPE 464

The 464 input record is required to specify function coefficients for an y-heat flux boundary.

	min	max
start	0	MAXTBD
restart	0	MAXTBD

Columns →	11	21	31	41	51	61	71	80
	MTBD	YHF1	YHF2	YHF3	YHF4	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MTBD	Momentum boundary model number. The value of MTBD defines the array location of the function coefficients, model, and range defined on input records 451, 452, 461 thru 464. The value of MTBD must be integral and greater than or equal to 1 and less than or equal to MAXTBD. (See Appendix "Maximums".) If MTBD is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
2	YHF1	y-heat flux coefficient number 1. Default value is 0.
3	YHF2	y-heat flux coefficient number 2. Default value is 0.
4	YHF3	y-heat flux coefficient number 3. Default value is 0.
5	YHF4	y-heat flux coefficient number 4. Default value is 0.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Not used with the incompressible flow versions.

Wall Point Sequence Definition

Page 1 of 1

TYPE
481

The 481 input record defines a sequence of contiguous wall points for which unique boundary properties are described on input record 482.

	min	max
start	0	MAXSEG
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	LS	IWBGN	IWEND	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	LS	Sequence number. The value of LS uniquely identifies the sequence of wall points defined by the wall point limits specified on this record. The value of LS must be integral and greater than or equal to 1 and less than or equal to MAXSEG. (See Appendix "Maximums".) If LS is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) A sequence may be composed of only one point, i.e., IWBGN- <u>≤</u> IWEND.
2	IWBGN	Wall point number (as specified on record type 212) of the first wall point in a sequence of wall points. The value of IWBGN must be integral and greater than or equal to 1 and less than or equal to MAXWPT. (See Appendix "Maximums".) If IWBGN is out of this range, a RGEERR message is written on the print and the message files and the program terminates in subroutine BDYINP. (See Appendix "Messages".)
3	IWEND	Wall point number (as specified on record type 212) of the last wall point in a sequence of wall points. The value of IWEND must be integral and greater than or equal to 1 and less than or equal to MAXWPT. (See Appendix "Maximums".) If IWEND is out of this range, a RGEERR message is written on the print and the message files and the program terminates in subroutine BDYINP. (See Appendix "Messages".)
4-7	--	Fields 4-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Wall Point Sequence Properties

Page 1 of 3

TYPE 482

The 482 input record describes the properties of a contiguous sequence of wall point segments defined on the 481 input record. The 482 input record may not be used at restart time.

	min	max
start	0	MAXSEG
restart	0	0

Columns →	11	21	31	41	51	61	71	80
	LS	MPNWSG	NBMWSG	NBTWSG	NBVWSG	DWLWSG	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	LS	Sequence number. The value of LS uniquely identifies a sequence of wall points defined by the wall point limits specified on record type 481. The value of LS must be integral and greater than or equal to 1 and less than or equal to MAXSEG. (See Appendix "Maximums".) If LS is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) A sequence may be composed of only one point, i.e., $IWBGN \leq IBEND$.
2	MPNWSG	Material property number for this sequence. The value of MPNWSG uniquely identifies a material model. A model may consist of a reference density, an equation of state, viscosity coefficients, and thermal descriptions; however, only the mechanical and thermal surface properties will be used. The value of MPNWSG must be integral and must be greater than or equal to 1 and less than or equal to MAXMAT. (See Appendix "Maximums".) If MPNWSG is out of this range, a RGEERR message is written on the print and the message files and the program terminates in subroutine BDYINP. (See Appendix "Messages".)
3	NBMWSG	Momentum boundary number for this sequence. The value of NBMWSG identifies the momentum boundary condition type. The value of NBMWSG must be integral and greater than or equal to 4 and less than or equal to 5 or equal to 8. If NBMWSG is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 4.0 velocity history* = 5.0 fixed (rigid) = 8.0 special

*When a velocity history wall point is outside of its range as defined on the 441 input record, it is permanently changed to a fixed wall point for all time.

Columns →	11	21	31	41	51	61	71	80
	LS	MPNWSG	NBMWSG	NBTWSG	NBVWSG	DWLWSG	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	NBTWSG	Thermal boundary number for this sequence. The value of NBTWSG identifies the thermal boundary condition type. The value of NBTWSG must be integral and greater than or equal to 4 and less than or equal to 5 or equal to 8. If NBTWSG is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 4.0 heat flux history* = 5.0 adiabatic = 8.0 special Thermal boundary conditions are not used with the incompressible flow versions.
5	NBVWSG	Index of boundary array. The value of NBVWSG specifies the index location of boundary history model data for a wall point in the boundary values array. When no history data is required, leave NBVWSG blank. The value of NBVWSG must be integral and greater than or equal to 0 and less than or equal to MAXBDY. (See Appendix "Maximums".) If NBVWSG is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
6	DWLWSG	Minimum distance to this sequence. The value of DWLWSG specifies the minimum distance between wall interaction boundary grid points and this boundary sequence. If the distance is less than DWLWSG, the grid points are placed on the wall. The value of DWLWSG should be set equal to 10% of the distance across typical boundary zones that will interact with this sequence. The default value is the value specified for DSTMIN on record type MIN in the PRB input block.

* When a heat flux history wall point is outside of its range as defined on the 461 input record, it is permanently changed to an adiabatic wall point for all time.

** 10% of the distance across a typical boundary zone should be used in fluid flow problems where it is desirable to avoid separation between the fluid and the constraining wall. If it is desirable to allow separation, a value of 1% should be used; however, this could retard convergence of the iteration in the implicit versions and in some cases could lead to an unstable iteration.

Columns →	11	21	31	41	51	61	71	80
	LS	MPNWSG	NBMWSG	NBTWSG	NSBWSG	DWLWSG	--	
Fields →	1	2	3	4	5	6	7	

<u>Field Number</u>	<u>Input Variable Name</u>	<u>Description of Input Variable</u>
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Left Wall Point Boundary

Page 1 of 2

TYPE
483

A 483 input record is used to specify the boundary conditions for a left wall point. There are no default values and the 483 input record may be used at restart time to change boundary conditions. The data on this record are stored in boundary array location MAXWPT - 1.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	NMW	NTW	NVW	MWL	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NMW	Momentum boundary number. The value of NMW identifies the momentum boundary condition type. The value of NMW must be integral and greater than or equal to 4 and less than or equal to 5 or equal to 8. If NMW is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 4.0 velocity history* = 5.0 fixed (rigid) = 8.0 special
2	NTW	Thermal boundary number. The value of NTW identifies the thermal boundary condition type. The value of NTW must be integral and greater than or equal to 4 and less than or equal to 5 or equal to 8. If NTW is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 4.0 heat flux history** = 5.0 adiabatic = 8.0 special Thermal boundary conditions are not used with the incompressible flow versions.

* When a velocity history wall point is outside of its range as defined on the 441 input record, it is permanently changed to a fixed wall point for all time.

** When a heat flux history wall point is outside of its range as defined on the 461 input record, it is permanently changed to an adiabatic wall point for all time.

Columns →	11	21	31	41	51	61	71	80
	NMW	NTW	NVW	MWL	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	NVW	Index of boundary array. The value of NVW specifies the index location of boundary history model data for a grid point in the boundary values array. When no history data is required, leave NVW blank. The value of NVW must be integral and greater than or equal to 0 and less than or equal to MAXBDY. (See Appendix "Maximums".) If NVW is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
4	MWL	Material property number for this wall point. The value of MWL uniquely identifies a material model. A model may consist of a reference density, an equation of state, viscosity coefficients, and thermal descriptions; however, only the mechanical and thermal surface properties will be used. The value of MWL must be integral and must be greater than or equal to 1 and less than or equal to MAXMAT. (See Appendix "Maximums".) If MWL is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

A 484 input record is used to specify the boundary conditions for a right wall point. There are no default values and the 484 input record may be used at restart time to change boundary conditions. The data on this record are stored in boundary array location MAXWPT.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	NMW	NTW	NVW	MWL	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NMW	Momentum boundary number. The value of NMW identifies the momentum boundary condition type. The value of NMW must be integral and greater than or equal to 4 and less than or equal to 5 or equal to 8. If NMW is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 4.0 velocity history* = 5.0 fixed (rigid) = 8.0 special
2	NTW	Thermal boundary number. The value of NTW identifies the thermal boundary condition type. The value of NTW must be integral and greater than or equal to 4 and less than or equal to 5 or equal to 8. If NTW is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".) The following definitions apply: = 4.0 heat flux history** = 5.0 adiabatic = 8.0 special

Thermal boundary conditions are not used with the incompressible flow versions.

*When a velocity history wall point is outside of its range as defined on the 441 input record, it is permanently changed to a fixed wall point for all time.

**When a heat flux history wall point is outside of its range as defined on the 461 input record, it is permanently changed to an adiabatic wall point for all time.

Columns →	11	21	31	41	51	61	71	80
	NMW	NTW	NVW	MWL	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
3	NVW	Index of boundary array. The value of NVW specifies the index location of boundary history model data for a grid point in the boundary values array. When no history data is required, leave NVW blank. The value of NVW must be integral and greater than or equal to 0 and less than or equal to MAXBDY. (See Appendix "Maximums".) If NVW is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
4	MWL	Material property number for this wall point. The value of MWL uniquely identifies a material model. A model may consist of a reference density, an equation of state, viscosity coefficients, and thermal descriptions; however, only the mechanical and thermal surface properties will be used. The value of MWL must be integral and must be greater than or equal to 1 and less than or equal to MAXMAT. (See Appendix "Maximums".) If MWL is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine BDYINP. (See Appendix "Messages".)
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

End of BDY Phase

Page 1 of 1

TYPE
END

The END input record signifies the end of a block of data for the BDY input phase. It must follow the last BDY input record.

	min	max
start	1	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	--	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1-7	--	Fields 1-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
END

7.5 TIME SPECIFICATION PHASE (TIM)

The time specification phase (TIM) input block may be located in any position in the input deck after the PRB input block and before the final END record. The purpose of the TIM input block is to specify time step and problem time related information. TIM phase information may be changed at restart time.

Only the 513 input record has a default value. All other TIM phase input records are required for start runs and at least the 521 input record is also required at restart time.

The TIM phase input consists of two types of parameters: (1) those that control the time step and (2) those that control the termination of the calculation. A summary of these parameters appears in Table 7.5. The parameters on record types 511-513 fall into the first category above, while those on record type 521 fall into the second category. These parameters are specified according to the following considerations.

An automatic time step calculation determines the maximum stable time step based on the material velocity and the zone size (see Sections 4.5 and 5.5). However, in most instances it may not be desirable from an accuracy point of view to run with the maximum stable time step. In those cases the time step can be specified by the proper combination of the parameters DLTSOR, DLTGRF, GRFBGN, and DLTMAX.

For a start run the initial time step DLTSOR should be less than or equal to the maximum time step DLTMAX. Beginning at some time GRFBGN, the growth factor DLTGRF will allow the time step to grow to this maximum value. Thereafter, the time step will remain constant at DLTMAX unless it is limited by the internally calculated stable time step.

The value of DLTSOR relative to DLTMAX is determined by how benign the initial conditions are. For the incompressible flow versions, the initial conditions can be considered benign if they approximately satisfy the incompressibility condition, $\nabla \cdot \underline{y} = 0$. For the implicit, compressible flow versions the initial conditions are benign if they do not contain any large pressure or velocity gradients. In those cases DLTSOR can be set equal to DLTMAX. If, as is more often the case, the initial conditions do not satisfy these criteria, then a smaller time step should be used in order to avoid an unstable iteration on the first cycle as the code attempts to find a solution corresponding to the input conditions. Typically, DLTSOR is taken to be one-tenth (0.1) of the maximum time step DLTMAX in this case. The parameters GRFBGN and DLTGRF may then be chosen to tailor the growth of the timestep. In most cases, particularly with the incompressible flow versions, the default values for these quantities will be adequate.

For a restart run, the best value of DLTSOR is the time step that was used on the last cycle. This value should be used unless the solution has been modified in some way by new input data. The values for DLTGRF, GRFBGN, and DLTMAX may be changed at restart time if it is desirable to let the time step grow to a larger value.

The minimum time step DLTMIN comes into play only if the time step is limited by the automatic time step calculation. Its value usually should be chosen to be just slightly smaller than the initial time step. It can be increased or decreased at restart time to better control the economics of the problem. However, it can never be greater than or equal to DLTSOR or the problem will terminate immediately.

The time step safety factor DLTSFR is used in the automatic calculation of the stable time step and should be chosen to provide some conservatism in that calculation. In some cases values near 1.0 may be

used, but in general a value on the order of 0.25 or less should be used to provide maximum accuracy and stability.

Both the maximum time TIMMAX and the maximum number of cycles (time steps) MAXCYC can be used to specify when a calculation should be terminated. In general TIMMAX is chosen from physics considerations while MAXCYC is based on economic considerations. When the time step is constant and therefore is known, either can be used. When the time step is variable, either because of the use of a programmed growth or because of being limited by the internal stable time step calculation, MAXCYC should be determined from cost considerations (to prevent running an excessively large number of cycles with an unexpectedly small time step). For the explicit versions of the codes, cost is proportional to the number of grid points in a mesh multiplied by the number of cycles. For a particular problem the number of grid points is usually fixed so that the cost is directly proportional to the number of cycles. However, with these implicit versions there is no one-to-one correspondence between cost and number of cycles because the number of iterations in the implicit phase may vary from cycle to cycle. Therefore, the maximum number of iterations MAXITR (on the ITR record in the PRB phase) should be used in conjunction with MAXCYC to control the cost of the problem.

TABLE 7.5

SUMMARY OF TIM PHASE INPUT RECORDS AND INPUT VARIABLES

FIELDS 1-7

TYPE	1	2	3	4	5	6	7
TIM	NSINP	NSTRC	NSDBG	NSPLT	NSPRT		
511	DLTSOR						
512	DLTMIN	DLTMAX					
513	DLTGRF	DLTSFR	GRFBGN				
521	TIMMAX	MAXCYC					
END							

The function of the TIM control record is to activate the TIM input phase. The TIM control record must follow an END input record and is required for all start runs. It may be used at restart time to change data.

	min	max
start	1	1
restart	1	1

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSINP	Input mode switch. The value of NSINP specifies the mode of input to be used in this input phase. The value of NSINP must be integral and less than or equal to 3. The following definitions apply:

≤ 1.0 card input (default)
 $= 2.0$ library input
 $= 3.0$ keyboard input

If the field containing NSINP is left blank, then the mode of input is assumed to be card input. If the value of NSINP is greater than 3.0, the message,

INPUT MODE SWITCH
IMPROPERLY DEFINED

is written on the print and the message files, and the program terminates immediately in subroutine GENGEN.

2	NSTRC	Trace mode switch. The value of NSTRC specifies whether or not the trace option is active. The value of NSTRC must be integral and less than or equal to 2. The following definitions apply:

≤ 1.0 trace is not active, off (default)
 $= 2.0$ trace is active, on

If the field containing NSTRC is left blank, then the mode is assumed to be not active (off). If the value of NSTRC is greater than 2.0, the message,

TRACE MODE SWITCH
IMPROPERLY DEFINED

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The trace logic, if active (on), will cause the name of the subroutine or logical phase just entered to be printed on both the print and message files. These actions are taken in subroutines SBRENT and PHSENT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
3	NSDBG	Debug mode switch. The value of NSDBG specifies whether or not the debug option is active. The value of NSDBG must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 debug is not active, off (default) $= 2.0$ debug is active, on If the field containing NSDBG is left blank, then the debug mode is assumed to be not active (off). If the value of NSDBG is greater than 2.0, the message, DEBUG MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The debug logic, if active (on), will cause the common blocks associated with this input phase to be dumped at the end of each subroutine in the phase and at the end of the logical phase. These actions are taken in subroutines SBREXT and PHSEXT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
4	NSPLT	Plot mode switch. The value of NSPLT specifies whether or not plots will be produced by this generator phase. The value of NSPLT must be integral and less than or equal to 2.0 The following definitions apply: ≤ 1.0 no plots produced, option off (default) $= 2.0$ plots produced, option on If the field containing NSPLT is left blank, then no plots will be produced (off). If the value of NSPLT is greater than 2.0, the message, PLOT MODE SWITCH IMPROPERLY DEFINED

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

<u>Field Number</u>	<u>Input Variable Name</u>	<u>Description of Input Variable</u>
		is written on the print and the message files, and the program terminates immediately in subroutine TIMGEN.
5	NSPRT	Print mode switch. The value of NSPRT controls the printing in this generator phase. The value of NSPRT must be integral and less than or equal to 2.0. The following definitions apply: = 1.0 only input records and error messages are printed, option off = 2.0 full printing done, option on (default) If the field containing NSPRT is left blank, full printing is done (option on). If the value of NSPRT is greater than 2.0, the message, PRINT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files and the program terminates immediately in subroutine TIMGEN.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Start or Restart Time Step

Page 1 of 1

TYPE
511

The 511 input record specifies the initial time step for a run. The 511 input record is required in all start runs and is optional in a restart run.

	min	max
start	1	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	DLTSOR	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	DLTSOR	Start or restart time step. The value of DLTSOR must be a positive number greater than the "zero tolerance", SMLNUM, greater than or equal to the minimum time step, DLTMIN, and smaller than or equal to the maximum time step, DLTMAX, or the messages, START OR RESTART TIME STEP, DLTSOR, MUST BE GREATER THAN OR EQUAL TO ZERO TOLERANCE, SMLNUM DLTSOR = <u>eeeeeeeeeeeeee</u> SMLNUM = <u>eeeeeeeeeeeeee</u> START OR RESTART TIME STEP, DLTSOR, MUST BE GREATER THAN OR EQUAL TO MINIMUM TIME STEP, DLTMIN DLTSOR = <u>eeeeeeeeeeeeee</u> DLTMIN = <u>eeeeeeeeeeeeee</u> START OR RESTART TIME STEP, DLTSOR MUST BE SMALLER THAN OR EQUAL TO MAXIMUM TIME STEP, DLTMAX DLTSOR = <u>eeeeeeeeeeeeee</u> DLTMIN = <u>eeeeeeeeeeeeee</u> are written on the print and the message files and the program terminates at the end of the GENERATOR phase group.
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 512 input record specifies time step limits for a run. The 512 input record is required in all start runs and is optional in a restart run.

	min	max
start	1	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	DLTMIN	DLTMAX	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	DLTMIN	Minimum time step. The problem time step, $DLTH (\Delta t^{n+1/2})$, may be equal to but never be smaller than DLTMIN. The value of DLTMIN must be a positive number greater than the "zero tolerance", SMLNUM, or the message, MINIMUM TIME STEP, DLTMIN MUST BE GREATER THAN OR EQUAL TO ZERO TOLERANCE, SMLNUM DLTMIN = <u>eeeeeeeeeeee</u> SMLNUM = <u>eeeeeeeeeeee</u> is written on the print and the message files and the program terminates at the end of the GENERATOR phase group.
2	DLTMAX	Maximum time step. The problem step, $DLTH (\Delta t^{n+1/2})$, may be equal to but never be greater than DLTMAX. The value of DLTMAX must be a positive number greater than or equal to DLTMIN, or the message, MAXIMUM TIME STEP, DLTMAX, MUST BE GREATER THAN OR EQUAL TO MINIMUM TIME STEP, DLTMIN DLTMAX = <u>eeeeeeeeeeee</u> DLTMIN = <u>eeeeeeeeeeee</u> is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. In many cases, when a smaller time step is desired than would be required for stability, the value for DLTMAX is chosen to be the constant time step to be used for the calculation after a possible initial transient period (if DLTSOR is less than DLTMAX). The value for DLTMAX should be determined from accuracy considerations as discussed in the beginning of this section and in Section 6.3.
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 513 input record specifies time step factors for a run. If the 513 input record is omitted, default values are used. Default for DLTGRF is 1.2, for DLTSFR is 0.25, and for GRFBGN is 0.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	DLTGRF	DLTSFR	GRFBGN	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	DLTGRF	Time step growth factor. Problem time step, $\Delta t^{n+1/2}$, is limited to grow only as fast as the DLTGRF value allows. The value of DLTGRF must be a positive number between 1.0 (no growth) and 1.2 (20% growth). If the field containing DLTGRF is left blank or a value is used that is less than 1.0, then DLTGRF is assumed to be equal to 1.2. If the value of DLTGRF is greater than 1.2, the message, TIME STEP GROWTH FACTOR, DLTGRF, MUST BE GREATER THAN OR EQUAL TO ZERO TOLERANCE, SMLNUM, AND MUST BE SMALLER THAN OR EQUAL TO 20 PERCENT GROWTH (1.2) DLTGRF = <u>eeeeeeeeeeee</u> SMLNUM = <u>eeeeeeeeeeee</u> is written on the print and the message files and the program terminates at the end of the GENERATOR phase group.
2	DLTSFR	Time step safety factor. The calculated stable time step is multiplied by DLTSFR. The value of DLTSFR must be a positive number greater than or equal to the "zero tolerance", SMLNUM, and less than or equal to 1.0. If the field containing DLTSFR is left blank or a value is used that is less than the "zero tolerance", SMLNUM, then DLTSFR is assumed to be 0.25. If the value of DLTSFR is greater than 1.0, the message, TIME STEP SAFETY FACTOR, DLTSFR, MUST BE GREATER THAN OR EQUAL TO ZERO TOLERANCE, SMLNUM, AND MUST BE SMALLER THAN OR EQUAL TO UNITY (1.0) DLTSFR = <u>eeeeeeeeeeee</u> SMLNUM = <u>eeeeeeeeeeee</u>

Columns →	11	21	31	41	51	61	71	80
	DLTGRF	DLTSFR	GRFBGN	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files and the program terminates at the end of the GENERATOR phase group.
3	GRFBGN	Time to start time step growth. The problem time step, $\Delta t^{n+1/2}$, will grow each cycle by a factor DLTSFR beginning at a problem time equal to GRFBGN. The value of GRFBGN must be a positive number greater than or equal to the "zero tolerance", SMLNUM. If the field containing GRFBGN is left blank or a value is used that is less than the "zero tolerance", SMLNUM, then GRFBGN is assumed to be zero.
4-7	--	Fields 4-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Problem Temporal Limits

Page 1 of 1

TYPE

521

The 521 input record specifies the time and cycle limits of the problem. One and only one record is required in every start and restart run.

	min	max
start	1	1
restart	1	1

Columns →	11	21	31	41	51	61	71	80
	TIMMAX	MAXCYC	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	TIMMAX	Problem time limit. The value of TIMMAX specifies the maximum problem time to which the calculation will be allowed to proceed. When problem time, TIMN (t^{n+1}), is equal to or greater than TIMMAX, the problem terminates. The value of TIMMAX must be a positive number in problem units greater than the start or restart time.
2	MAXCYC	Problem cycle limit. The value of MAXCYC specifies the maximum cycle to which the calculation will be allowed to proceed. When the cycle counter, NCCYC ($n+1$), is equal to or greater than MAXCYC, the problem terminates. The value of MAXCYC must be integral and greater than the start or restart number.
3-7	--	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

End of TIM Phase

Page 1 of 1

TYPE
END

The END input record signifies the end of a block of data for the TIM input phase. It must follow the last TIM input record.

	min	max
start	1	1
restart	1	1

Columns →	11	21	31	41	51	61	71	80
	--	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1-7	--	Fields 1-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
END

7.6 EDIT SPECIFICATION PHASE (EDT)

The edit specification phase (EDT) input block may be located in any position in the input deck after the PRB input block and before the final END record. The purpose of the EDT input block is to specify output edits. EDT phase information may be changed at restart time.

EDT phase data are divided into the following groups:

<u>Record Identifier</u>	<u>Group Description</u>
61_	Output mode type
62_	Print output parameters
63_	Regional summary output parameters
64_	Restart output parameters
65_	Archive output parameters
66_	Debug, trace, and storage output parameters
67_	Plot output parameters

The six edit output modes correspond to the following files and output media:

<u>Edit Mode</u>	<u>File Name</u> *	<u>Output Medium</u>
Print	NFPRT,NFMSG	Printer
Regional summary	NFPRT,NFMSG	Printer
Restart	NFRSO	Tape
Archive	NFARV	Tape
Debug	NFDBG	Printer
Trace	NFTRC	Printer
Storage	NFSTG	Printer
Plot	NFPLT	Plotter or printer

* See Appendix "Files".

Each output mode can offer several forms of output, including user-supplied forms. For example, in print mode it is possible to get "complete" edits which print all zone and grid-point data or "short" edits which print only selected variables. Complete edits are usually a minimum of six pages per edit, while short edits can be as short as one page. (See Appendix "Output" in Volume 1.)

Whether or not edits are specified, a certain number of edits will be written automatically on the output files. These edits need not be specified through input records. The automatic edits are:

<u>Edit Mode</u>	<u>Cycles at Which Automatic Edits Occur</u>
Print	0, 1, last, restart zero, restart first
Regional summary	1, last, restart first
Restart	Last
Archive	Last
Debug	1, last, restart first
Plot	GENERATOR data on printer

The files containing restart and archive data must be saved in order to be used. Restart data are read by STEALTH 1D and 2D and archive data are read by ADAPRO.

A summary of EDT phase input records and input variables appears in Table 7.6.

TABLE 7.6

SUMMARY OF EDT PHASE INPUT RECORDS AND INPUT VARIABLES

FIELDS 1-7

TYPE	1	2	3	4	5	6	7
EDT	NSINP	NSTRC	NSDBG	NSPLT	NSPRT		
611	MPRT						
612	MRSY						
613	MRST						
614	MARV						
615	MSTG						
616	MPLT						
617	MPET						
618	MTRC						
619	MDBG						
621	L	PRTBGN	PRTRGE	PRTINC			
622	MINIPR	MAXIPR	MINJPR	MAXJPR			
623	LP	IDPRT					
624	MOPT						
631	L	RSYBGN	RSYRGE	RSYINC			
632	LREG	ILFT	IRHT	JBOT	JTOP		

ADP

TABLE 7.6 (continued)

FIELDS 1-7

TYPE	1	2	3	4	5	6	7	
641	L	RSTBGN	RSTRGE	RSTINC				
651	L	ARVBGN	ARVRGE	ARVINC				
652	MINIAR	MAXIAR	MINFAR	MAXJAR				
653	IDARV	IDARV	IDARV	IDARV	IDARV	IDARV	IDARV	
654	MARLIM	MINARC	MAXARC	ARCMIN	ARCMAX			ADP
661	L	STGBGN	STGRGE	STGINC				
662	L	TRCBGN	TRCRGE	TRCINC				
663	L	DBGBGN	DBGRGE	DBGINC				
671	L	PLTBGN	PLTRGE	PLTINC				
672	NPLT	IDPLT	IDORD	IDABC	IDLOC	TODLOC		1D
674	NPLT	IDPLT	IDORD	IDABC	IDLOC	TODLOC	IDROW	2D
675	NPLT	IDPLT	IDORD		IDLOC	TODLOC		2D
677	NPLT	PETBGN	PETRGE	PETINC				ADP
END								

The function of the EDT control record is to activate the EDT input phase. The EDT control record must follow an END input record and is required for all start runs. It may be used at restart time to change data.

	min	max
start	1	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NSINP	Input mode switch. The value of NSINP specifies the mode of input to be used in this input phase. The value of NSINP must be integral and less than or equal to 3. The following definitions apply:

≤ 1.0 card input (default)
 $= 2.0$ library input
 $= 3.0$ keyboard input

If the field containing NSINP is left blank, then the mode of input is assumed to be card input. If the value of NSINP is greater than 3.0, the message,

INPUT MODE SWITCH
IMPROPERLY DEFINED

is written on the print and the message files, and the program terminates immediately in subroutine GENGEN.

2	NSTRC	Trace mode switch. The value of NSTRC specifies whether or not the trace option is active. The value of NSTRC must be integral and less than or equal to 2. The following definitions apply:

≤ 1.0 trace is not active, off (default)
 $= 2.0$ trace is active, on

If the field containing NSTRC is left blank, then the mode is assumed to be not active (off). If the value of NSTRC is greater than 2.0, the message,

TRACE MODE SWITCH
IMPROPERLY DEFINED

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The trace logic, if active (on), will cause the name of the subroutine or logical phase just entered to be printed on both the print and message files. These actions are taken in subroutines SBRENT and PHSENT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
3	NSDBG	Debug mode switch. The value of NSDBG specifies whether or not the debug option is active. The value of NSDBG must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 debug is not active, off (default) $= 2.0$ debug is active, on If the field containing NSDBG is left blank, then the debug mode is assumed to be not active (off). If the value of NSDBG is greater than 2.0, the message, DEBUG MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine GENGEN. The debug logic, if active (on), will cause the common blocks associated with this input phase to be dumped at the end of each subroutine in the phase and at the end of the logical phase. These actions are taken in subroutines SBREXT and PHSEXT. USE OF THIS OPTION WILL RESULT IN AN ENORMOUS AMOUNT OF PRINTED OUTPUT. PLEASE USE WITH CAUTION.
4	NSPLT	Plot mode switch. The value of NSPLT specifies whether or not plots will be produced by this generator phase. The value of NSPLT must be integral and less than or equal to 2.0. The following definitions apply: ≤ 1.0 no plots produced, option off (default) $= 2.0$ plots produced, option on If the field containing NSPLT is left blank, then no plots will be produced (off). If the value of NSPLT is greater than 2.0, the message,

Columns →	11	21	31	41	51	61	71	80
	NSINP	NSTRC	NSDBG	NSPLT	NSPRT	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		PLOT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine EDTGEN.
5	NSPRT	Print mode switch. The value of NSPRT controls the printing in this generator phase. The value of NSPRT must be integral and less than or equal to 2.0. The following definitions apply: = 1.0 only input records and error messages are printed, option off = 2.0 full printing done, option on (default) If the field containing NSPRT is left blank, full printing is done (option on). If the value of NSPRT is greater than 2.0, the message, PRINT MODE SWITCH IMPROPERLY DEFINED is written on the print and the message files, and the program terminates immediately in subroutine EDTGEN.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 611 input record specifies the type of print edits, time or cycle, required. If the 611 input record is omitted, print edits* by time will be put on print file, NFPRT. (See Appendix "Files".) The 611 input record may be used at restart time to re-specify print edit mode.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MPRT	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPRT	Print edit mode. The value of MPRT specifies the mode of print edits to be used. The value of MPRT must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 print edits by time (default) $= 2.0$ print edits by cycle
2-7	--	If the field containing MPRT is left blank, then the mode of print edits is assumed to be edits by time. If the value of MPRT is greater than 2.0, the RGEERR message is written on the print and the message files and the program terminates in subroutine EDTINP. (See Appendix "Messages".) Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*The start or restart cycle, as well as the first and last cycles calculated are automatically put on the print file, NFPRT. (See Appendix "Files".) Additional print edits are specified on the 621 input record.

The 612 input record specifies the type of regional summary edits, time or cycle, required. If the 612 input record is omitted, regional summary edits* by time will be put on regional file, NFPRT. (See Appendix "Files".) The 612 input record may be used at restart time to re-specify regional edit mode.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MRSY	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MRSY	Regional summary edit mode. The value of MRSY specifies the mode of regional summary edits to be used. The value of MRSY must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 regional summary edits by time (default) $= 2.0$ regional summary edits by cycle
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*The start or restart cycle, as well as the first and last cycles calculated are automatically put on the regional file, NFPRT. (See Appendix "Files".) Additional regional summary edits are specified on the 631 input record.

The 613 input record specifies the type of restart edits, time or cycle, required. If the 613 input record is omitted, restart edits* by time will be put on restart file, NFPRT. (See Appendix "Files".) The 613 input record may be used at restart time to re-specify restart edit mode.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MRST	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MRST	Restart edit mode. The value of MRST specifies the mode of restart edits to be used. The value of MRST must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 restart edits by time (default) $= 2.0$ restart edits by cycle If the field containing MRST is left blank, then the mode of restart edits is assumed to be edits by time. If the value of MRST is greater than 2.0, the RGEERR message is written on the print and the message files and the program terminates in subroutine EDTINP. (See Appendix "Messages".)
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*The start or restart cycle, as well as the first and last cycles calculated are automatically put on the restart file, NFPRT. (See Appendix "Files".) Additional restart edits are specified on the 641 input record.

The 614 input record specifies the type of archive edits, time or cycle, required. If the 614 input record is omitted, archive edits* by time will be put on archive file, NFPRT. (See Appendix "Files".) The 614 input record may be used at restart time to re-specify restart edit mode.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MARV	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MARV	Archive edit mode. The value of MARV specifies the mode of archive edits to be used. The value of MARV must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 archive edits by time (default) $= 2.0$ archive edits by cycle
2-7	--	If the field containing MARV is left blank, then the mode of archive edits is assumed to be edits by time. If the value of MARV is greater than 2.0, the RGEERR message is written on the print and the message files and the program terminates in sub-routine EDTINP. (See Appendix "Messages".) Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* There are no default archive edits. All archive edits are specified on the 651 input record and are written on file NFARV. (See Appendix "Files".)

The 615 input record specifies the type of storage edits, time or cycle, required. If the 615 input record is omitted, storage edits* by time will be put on storage file, NFPRT. (See Appendix "Files".) The 615 input record may be used at storage time to re-specify storage edit mode.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MSTG	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MSTG	Storage edit mode. The value of MSTG specifies the mode of storage edits to be used. The value of MSTG must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 storage edits by time (default) $= 2.0$ storage edits by cycle If the field containing MSTG is left blank, then the mode of storage edits is assumed to be edits by time. If the value of MSTG is greater than 2.0, the RGEERR message is written on the print and the message files and the program terminates in subroutine EDTINP. (See Appendix "Messages".)
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*There are no default storage edits. All storage edits are specified on the 661 input record and are written on file NFSTG. (See Appendix "Files".)

The 616 input record specifies the type of plot history edits, time or cycle, required. If the 616 input record is omitted, plot history edits* by time will be put on plot file, NFPRT. (See Appendix "Files".) The 616 input record may be used at plot time to re-specify plot edit mode.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MPLT	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPLT	Plot edit mode. The value of MPLT specifies the mode of plot history edits to be used. The value of MPLT must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 plot history edits by time (default) $= 2.0$ plot history edits by cycle
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*There are no default plot edits. All plot edits are specified on the 671 input record and are written on file NFPLT. (See Appendix "Files".) Actual plots are specified on the 672 input record.

Multiple Plot Edit Mode

Page 1 of 1

TYPE
617

The 617 input record specifies the type of multiple plots edits, time or cycle, required. If the 617 input record is omitted, multiple plot edits will be assumed to be by time. The 617 input record only applies to data specified on 677 input records.

	min	max
start	0	1
restart	N/A	N/A

Columns →	11	21	31	41	51	61	71	80
	MPET	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPET	Multiple plot edit mode. The value of MPET specifies the mode of multiple plot edits to be used. The value of MPET must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 multiple plot edits by time (default) $= 2.0$ multiple plot edits by cycle If the field containing MPET is left blank, then the mode of multiple plot edits is assumed to be edits by time. If the value of MPET is greater than 2.0, a RGEERR message is written on the print and the message files and the program terminates in subroutine EDTINP. (See Appendix "Messages".)
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 618 input record specifies the type of trace edits, time or cycle, required. If the 618 input record is omitted, trace edits by time will be put on trace file, NFPRT. (See Appendix "Files".) The 618 input record may be used at restart time to re-specify trace edit mode.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MTRC	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MTRC	Trace edit mode. The value of MTRC specifies the mode of trace edits to be used. The value of MTRC must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 trace edits by time (default) $= 2.0$ trace edits by cycle If the field containing MTRC is left blank, then the mode of trace edits is assumed to be edits by time. If the value of MTRC is greater than 2.0, the RGEERR message is written on the print and the message files and the program terminates in subroutine EDTINP. (See Appendix "Messages".)
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*There are no default trace edits. All trace edits are specified on the 662 input record and are written on file NFPRT and NFMSG. (See Appendix "Files".)

The 619 input record specifies the type of debug edits, time or cycle, required. If the 619 input record is omitted, debug edits* by time will be put on debug file, NFPRT. (See Appendix "Files".) The 619 input record may be used at restart time to re-specify debug edit mode.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MDBG	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MDBG	Debug edit mode. The value of MDBG specifies the mode of debug edits to be used. The value of MDBG must be integral and less than or equal to 2. The following definitions apply: ≤ 1.0 debug edits by time (default) $= 2.0$ debug edits by cycle If the field containing MDBG is left blank, then the mode of debug edits is assumed to be edits by time. If the value of MDBG is greater than 2.0, the RGEERR message is written on the print and the message files and the program terminates in subroutine EDTINP. (See Appendix "Messages".)
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* There are no default debug edits. All debug edits are specified on the 663 input record and are written on file NFPRT and NFMSG. (See Appendix "Files".)

The 621 input record identifies a unique set of print edits.

		min		max	
start		0		MAXEDT	
restart		0		MAXEDT	

Columns →	11	21	31	41	51	61	71	80
	L	PRTBGN	PRTRGE	PRTINC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Print edit index. The value of L uniquely identifies the data on this input record. The value of L must be integral and less than or equal to MAXEDT. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	PRTBGN	Beginning of print edits.* The value of PRTBGN gives a start time or start cycle (depending on MPRT**) from which the print edits on this record are computed. The value of PRTBGN must be greater than or equal to zero.
3	PRTRGE	Range of print edits.* The value of PRTRGE gives the time range or cycle range (depending on MPRT**) from which the print edits on this record are computed. The value of PRTRGE must be a positive number.
4	PRTINC	Increment of print edits.* The value of PRTINC gives the time increments or cycle increments (depending on MPRT**) from which the print edits on this record are computed. The value of PRTINC must be a positive number.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Edits occur at $PRTBGN + (i \times PRTINC)$ where i goes from 1 to n ($n = PRTRGE/PRTINC$). Thus, the first print edit occurs at $(PRTBGN + PRTINC)$ while the last print edit occurs at $(PRTBGN + PRTRGE)$. Intermediate print edits are $PRTINC$ apart. The total number of print edits defined cannot exceed MAXPRT. (See Appendix "Maximums".)

** See 611 input record.

The 622 input record defines the grid point and row print limits for grid point variables printed on the message file. If the 622 input record is omitted, there will be no grid point variables printed on the message file. When the 622 input record is used, $MINIPR \leq MAXIPR$ and $MINJPR \leq MAXJPR$.** The 622 input record may be used at restart time.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MINIPR	MAXIPR	MINJPR	MAXJPR	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MINIPR	Minimum grid point number to be printed on file NFMSG. (See Appendix "Files".) The value of MINIPR must be integral and greater than or equal to 1 and less than or equal to MAXGPT. (See Appendix "Maximums".) If MINIPR is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	MAXIPR	Maximum grid point number to be printed on file NFMSG. (See Appendix "Files".) The value of MAXIPR must be integral and greater than or equal to 1 and less than or equal to MAXGPT. (See Appendix "Maximums".) If MAXIPR is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
3	MINJPR	Minimum row number to be printed on file NFMSG. (See Appendix "Files".) The value of MINJPR must be integral and greater than or equal to 1 and less than or equal to MAXROW. (See Appendix "Maximums".) If MINJPR is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
4	MAXJPR	Maximum row number to be printed on file NFMSG. (See Appendix "Files".) The value of MAXJPR must be integral and greater than or equal to 1 and less than or equal to MAXROW. (See Appendix "Maximums".) If MAXJPR is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)

* Or zone.

** If $MINIPR > MAXIPR$ or $MINJPR > MAXJPR$, a LIMERR message is printed on the print and the message files and the program terminates at the end of the EDT GENERATOR phase. (See Appendix "Messages".)

Columns →	11	21	31	41	51	61	71	80
	MINIPR	MAXIPR	MINJPR	MAXJPR	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Each 623 input record defines a grid point variable to be printed on the message file. Grid point number (GPT), material property number (MPN), and material state indicator (IND) are automatically printed when a 622 input record is used. All other variables each require a 623 input record. The 623 input record may be used at restart time.

	min	max
start	0	MAXVAR
restart	0	MAXVAR

Columns →	11	21	31	41	51	61	71	80
	LP	IDPRT	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	LP	Variable print location. The value of LP identifies the sequential location of the variable defined in the next field of this input record. Variables must be specified in an unbroken sequence. Eight variables will be printed per page in the order of the sequence number LP. Variables 1, 9, 17, etc., will always be the first variables on a new page. (See Appendix "Output".) The value of LP must be integral and greater than or equal to 1 and less than or equal to MAXVAR. (See Appendix "Maximums".) If LP is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	IDPRT	Variable identifier. The value of IDPRT corresponds to a grid point variable identifier. (See Appendix "Identifiers".) The the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Or zone.

The 624 input record specifies the files on which STEALTH print edits are to be made. If the 624 input record is omitted, edits will be on file NFMSG only. (See Appendix "Files".) The 624 input record may be used at restart time to re-specify the output mode.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MOPT	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MOPT	Mode of output. The value of MOPT determines on which files STEALTH print edits will be printed. The following definitions apply: = 1.0 output on files NFPRT and NFMSG = 2.0 output on file NFMSG only (default) If the field containing MOPT is left blank, print edits will be on file NFMSG only. If the value of MOPT is greater than 2.0, the RGEERR message is written on the print and the message files and the program terminates in subroutine EDTINP. (See Appendix "Messages".)
2-7	--	Fields 2-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 631 input record identifies a unique set of regional summary edits.

	min	max
start	0	MAXEDT
restart	0	MAXEDT

Columns →	11	21	31	41	51	61	71	80
	L	RSYBGN	RSYRGE	RSYINC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Regional summary edit index. The value of L uniquely identifies the data on this input record. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXEDT. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	RSYBGN	Beginning of regional summary edits.* The value of RSYBGN gives a start time or start cycle (depending on MRSY**) from which the regional summary edits on this record are computed. The value of RSYBGN must be greater than or equal to zero.
3	RSYRGE	Range of regional summary edits.* The value of RSYRGE gives the time range or cycle range (depending on MRSY**) from which the regional summary edits on this record are computed. The value of RSYRGE must be a positive number.
4	RSYINC	Increment of regional summary edits.* The value of RSYINC gives the time increments or cycle increments (depending on MRSY**) from which the regional summary edits on this record are computed. The value of RSYINC must be a positive number.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Edits occur at $RSYBGN + (i \times RSYINC)$ where i goes from 1 to n ($n = RSYRGE/RSYINC$). Thus, the first regional summary edit occurs at $(RSYBGN + RSYINC)$ while the last regional summary edit occurs at $(RSYBGN + RSYRGE)$. Intermediate regional summary edits are $RSYINC$ apart. The total number of regional summary edits defined cannot exceed $MAXRSY$. (See Appendix "Maximums".)

** See 612 input record.

The 632 input record defines a regional summary region. The 632 input record may be used at restart time.

	min	max
start	0	MAXREG-1
restart	0	MAXREG-1

Columns →	11	21	31	41	51	61	71	80
	LREG	ILFT	IRHT	JBOT	JTOP	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	LREG	Region number. The value of LREG uniquely identifies a region of grid points defined by the grid point limits specified on record type 632. The value of LREG must be integral and greater than or equal to 1 and less than or equal to MAXREG - 1. (See Appendix "Maximums".) If LREG is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine ZONINP. (See Appendix "Messages".)
2	ILFT	Leftmost grid point index for regional summary region LREG. The value of ILFT must be integral and greater than or equal to 1 and less than IRHT. If ILFT is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the EDT GENERATOR phase. (See Appendix "Messages".)
		$1 \leq \text{ILFT} < \text{IRHT}$
3	IRHT	Rightmost grid point index for regional summary region LREG. IRHT must be integral and greater than ILFT and less than or equal to MAXGPT. (See Appendix "Maximums".) If IRHT is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the EDT GENERATOR phase. (See Appendix "Messages".)
		$\text{ILFT} < \text{IRHT} \leq \text{MAXGPT}$

Columns →	11	21	31	41	51	61	71	80
	LREG	ILFT	IRHT	JBOT	JTOP	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	JBOT*	Bottommost grid point index for regional summary region LREG. The value of JBOT must be integral and greater than or equal to 1 and less than JTOP. If JBOT is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the EDT GENERATOR phase. (See Appendix "Messages".) $1 \leq \text{JBOT} < \text{JTOP}$
5	JTOP*	Topmost grid point index for regional summary region LREG. The value of JTOP must be integral and greater than JBOT and less than or equal to MAXBUF. (See Appendix "Maximums".) If JTOP is out of this range, a LIMERR message is written on the print and the message files and the program terminates at the end of the EDT GENERATOR phase. (See Appendix "Messages".) $\text{JBOT} < \text{JTOP} \leq \text{MAXBUF}$
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

*JBOT and JTOP are not required for one-dimensional problems and input values in this field will result in the FLDCHK message being written on the print and the message files and the program being terminated at the end of the GENERATOR phase group. (See Appendix "Messages".)

The 641 input record identifies a unique set of restart edits.

	min	max
start	0	MAXEDT
restart	0	MAXEDT

Columns →	11	21	31	41	51	61	71	80
	L	RSTBGN	RSTRGE	RSTINC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Restart edit index. The value of L uniquely identifies the data on this input record. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXEDT. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	RSTBGN	Beginning of restart edits.* The value of RSTBGN gives a start time or start cycle (depending on MRST**) from which the restart edits on this record are computed. The value of RSTBGN must be greater than or equal to zero.
3	RSTRGE	Range of restart edits.* The value of RSTRGE gives the time range or cycle range (depending on MRST**) from which the restart edits on this record are computed. The value of RSTRGE must be a positive number.
4	RSTINC	Increment of restart edits.* The value of RSTINC gives the time increments or cycle increments (depending on MRST**) from which the restart edits on this record are computed. The value of RSTINC must be a positive number.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Edits occur at $RSTBGN + (i \times RSTINC)$ where i goes from 1 to n ($n = RSTRGE/RSTINC$). Thus, the first restart edit occurs at $(RSTBGN + RSTINC)$ while the last restart edit occurs at $(RSTBGN + RSTRGE)$. Intermediate restart edits are $RSTINC$ apart. The total number of restart edits defined cannot exceed MAXRST. (See Appendix "Maximums".)

**See 613 input record.

The 651 input record identifies a unique set of archive edits.

	min	max
start	0	MAXEDT
restart	0	MAXEDT

Columns →	11	21	31	41	51	61	71	80
	L	ARVBGN	ARVRGE	ARVINC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Archive edit index. The value of L uniquely identifies the data on this input record. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXEDT. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	ARVBGN	Beginning of archive edits.* The value of ARVBGN gives a start time or start cycle (depending on MARV**) from which the archive edits on this record are computed. The value of ARVBGN must be greater than or equal to zero.
3	ARVRGE	Range of archive edits.* The value of ARVRGE gives the time range or cycle range (depending on MARV**) from which the archive edits on this record are computed. The value of ARVRGE must be a positive number.
4	ARVINC	Increment of archive edits.* The value of ARVINC gives the time increments or cycle increments (depending on MARV**) from which the archive edits on this record are computed. The value of ARVINC must be a positive number.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Edits occur at $ARVBGN + (i \times ARVINC)$ where i goes from 1 to n ($n = ARVRGE/ARVINC$). Thus, the first archive edit occurs at $(ARVBGN + ARVINC)$ while the last archive edit occurs at $(ARVBGN + ARVRGE)$. Intermediate archive edits are ARVINC apart. The total number of archive edits defined cannot exceed MAXARV. (See Appendix "Maximums".)

**See 614 input record.

The 652 input record defines the grid point and row edit limits for grid point and zone variables saved on the archive file. If the 652 input record is omitted, the archive file will not be written. When the 652 input record is used, $\text{MINIAR} < \text{MAXIAR}$ and $\text{MINJAR} \leq \text{MAXJAR}$.** The 652 input record may be used at restart time.

	min	max
start	0	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	MINIAR	MAXIAR	MINJAR	MAXJAR	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MINIAR	Minimum grid point number to be saved on file NFARV. (See Appendix "Files".) The value of MINIAR must be integral, greater than or equal to 1, and less than or equal to MAXGPT. (See Appendix "Maximums".) If MINIAR is out of this range, a RGEERR messages is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	MAXIAR	Maximum grid point number to be saved on file NFARV. (See Appendix "Files".) The value of MAXIAR must be integral, greater than or equal to 1 and less than or equal to MAXGPT. (See Appendix "Maximums".) If MAXIAR is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
3	MINJAR***	Minimum row to be saved on file NFARV. (See Appendix "Files".) The value of MINJAR must be integral, greater than or equal to 1, and less than or equal to MAXROW. (See Appendix "Maximums".) If MINJAR is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)

* Or zone.

**If $\text{MINIAR} \geq \text{MAXIAR}$ or $\text{MINJAR} > \text{MAXJAR}$, a LIMERR message is printed on the print and the message files and the program terminates at the end of the EDT GENERATOR phase. (See Appendix "Messages".)

***MINJAR and MAXJAR are not required for one-dimensional problems and input values in this field will result in the FLDCHK message being written on the print and message files and the program being terminated at the end of the GENERATOR phase group. (See Appendix "Messages".)

Columns →	11	21	31	41	51	61	71	80
	MINIAR	MAXIAR	MINJAR	MAXJAR	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	MAXJAR*	Maximum row to be saved on file NFARV. (See Appendix "Files".) The value of MAXJAR must be integral, greater than or equal to 1, and less than or equal to MAXROW. (See Appendix "Maximums".) If MAXJAR is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* MINJAR and MAXJAR are not required for one-dimensional problems and input values in this field will result in the FLDCHK message being written on the print and the message files and the program being terminated at the end of the GENERATOR phase group. (See Appendix "Messages".)

Each 653 input record defines a set of grid point and zone variables to be saved on the archive data file. Variables may be requested in any order (up to 7 per input record) and blank fields will be ignored. If no variables are requested, a set of default variables will be saved.

	min	max
start	0	MAXVAR
restart	0	MAXVAR

Columns →	11	21	31	41	51	61	71	80
	IDARV	IDARV	IDARV	IDARV	IDARV	IDARV	IDARV	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1-7	IDARV	Archive data identifiers. Each value of IDARV corresponds to a grid point or zone variable identifier. (See Appendix "Identifiers".) Up to seven identifiers may be specified with each 653 input record and blank fields will be ignored. If the total number of variables requested by all 653 input records exceeds MAXVAR (see Appendix "Maximums"), a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".) If no variables are requested, a set of default variables will be saved. (See list below). The value of IDARV must be integral, greater than or equal to 1, and less than or equal to MAXVAR. If IDARV is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)

Default Variables List (52)

XPN	XVL	XAC	YPN	YVL	YAC	RLV
VSR	GXK	GYK	XHF	YHF	TXY	SKY
PRH	AVS	TXX	TYT	TZZ	SXX	SYT
SZZ	ZIE	ZDE	ZHE	ZSE	ZKE	ZMS
TRV	SSP	YLD	SHR	DNS	TMP	CON
SHC	ACT	BFS	IGN	EX1	EX2	EX3
EX4	EX5	EX6	NOR	NBM	NBT	NBV
ZPN	ZVL	ZAC				

* Or zone.

Archive Processor Limits

Page 1 of 2

TYPE
654

The 654 input record specifies the range of archive data to be processed during an ADAPRO run. This range can be supplied in terms of either a minimum and a maximum time or a minimum and a maximum cycle. If the 654 input record is omitted, every archive data record up to and including the largest time or cycle for which there is an edit request will be processed.

	min	max
start	0	1
restart	N/A	N/A

Columns →	11	21	31	41	51	61	71	80
	MARLIM	MINARC	MAXARC	ARCMIN	ARCMAX	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MARLIM	Archive data limit mode. The value of MARLIM specifies the mode in which the archive data limits are expressed. The following definitions apply: = 1.0 archive data limits by time = 2.0 archive data limits by cycle If the value of MARLIM is 1.0, the archive data limits must be supplied in the fields containing ARCMIN and ARCMAX. If the value of MARLIM is 2.0, the archive data limits must be supplied in the fields containing MINARC and MAXARC. If the value of MARLIM is either less than 1.0 or greater than 2.0, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	MINARC	Minimum cycle to be processed by ADAPRO. The value of MINARC must be integral, greater than or equal to 1, and less than or equal to MAXARC. If MINARC is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
3	MAXARC	Maximum cycle to be processed by ADAPRO. The value of MAXARC must be integral and greater than or equal to MINARC. If MAXARC is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix Messages".)
4	ARCMIN	Minimum time to be processed by ADAPRO. The value of ARCMIN must be greater than or equal to 0 and less than or equal to ARCMAX. If the value of ARCMIN is out of this range, an error message is written on the print and the message files and the program terminates immediately in subroutine EDTINP.

TYPE
654

Columns →	11	21	31	41	51	61	71	80
	MARLIM	MINARC	MAXARC	ARCMIN	ARCMAX	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
5	ARCMAX	Maximum time to be processed by ADAPRO. If the value of ARCMAX is less than ARCMIN, an error message is written on the print and the message files and the program terminates immediately in subroutine EDTINP.
6-7	--	Fields 6-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
654

The 661 input record identifies a unique set of storage edits.

	min	max
start	0	MAXEDT
restart	0	MAXEDT

Columns →	11	21	31	41	51	61	71	80
	L	STGBGN	STGRGE	STGINC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Storage edit index. The value of L uniquely identifies the data on this input record. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXEDT. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	STGBGN	Beginning of storage edits.* The value of STGBGN gives a start time or start cycle (depending on MSTG**) from which the storage edits on this record are computed. The value of STGBGN must be greater than or equal to zero.
3	STGRGE	Range of storage edits.* The value of STGRGE gives the time range or cycle range (depending on MSTG**) from which the storage edits on this record are computed. The value of STGRGE must be a positive number.
4	STGINC	Increment of storage edits.* The value of STGINC gives the time increments or cycle increments (depending on MSTG**) from which the storage edits on this record are computed. The value of STGINC must be a positive number.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Edits occur at $STGBGN + (i \times STGINC)$ where i goes from 1 to n ($n = STGRGE/STGINC$). Thus, the first storage edit occurs at $(STGBGN + STGINC)$, while the last storage edit occurs at $(STGBGN + STGRGE)$. Intermediate storage edits are $STGINC$ apart. The maximum number of storage edits cannot exceed MAXSTG. (See Appendix "Maximums".)

**See 615 input record.

The 662 input record identifies a unique set of trace edits.

	min	max
start	0	MAXEDT
restart	0	MAXEDT

Columns →	11	21	31	41	51	61	71	80
	L	TRCBGN	TRCRGE	TRCINC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Trace edit index. The value of L uniquely identifies the data on this input record. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXEDT. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	TRCBGN	Beginning of trace edits.* The value of TRCBGN gives a start time or start cycle (depending on MTRC**) from which the trace edits on this record are computed. The value of TRCBGN must be greater than or equal to zero.
3	TRCRGE	Range of trace edits.* The value of TRCRGE gives the time range or cycle range (depending on MTRC**) from which the trace edits on this record are computed. The value of TRCRGE must be a positive number.
4	TRCINC	Increment of trace edits.* The value of TRCINC gives the time increments or cycle increments (depending on MTRC**) from which the trace edits on this record are computed. The value of TRCINC must be a positive number.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Edits occur at $TRCBGN + (i \times TRCINC)$ where i goes from 1 to n ($n = TRCRGE/TRCINC$). Thus, the first trace edit occurs at $(TRCBGN + TRCINC)$, while the last trace edit occurs at $(TRCBGN + TRCRGE)$. Intermediate trace edits are $TRCINC$ apart. The maximum number of trace edits cannot exceed MAXTRC. (See Appendix "Maximums".)

**See 618 input record.

The 663 input record identifies a unique set of debug edits.

	min	max
start	0	MAXEDT
restart	0	MAXEDT

Columns →	11	21	31	41	51	61	71	80
	L	DBGBGN	DBGRGE	DBGINC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Debug edit index. The value of L uniquely identifies the data on this input record. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXEDT. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	DBGBGN	Beginning of debug edits.* The value of DBGBGN gives a start time or start cycle (depending on MDBG**) from which the debug edits on this record are computed. The value of DBGBGN must be greater than or equal to zero.
3	DBGRGE	Range of debug edits.* The value of DBGRGE gives the time range or cycle range (depending on MDBG**) from which the debug edits on this record are computed. The value of DBGRGE must be a positive number.
4	DBGINC	Increment of debug edits.* The value of DBGINC gives the time increments or cycle increments (depending on MDBG**) from which the debug edits on this record are computed. The value of DBGINC must be a positive number.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Edits occur at $DBGBGN + (i \times DBGINC)$ where i goes from 1 to n ($n = DBGRGE/DBGINC$). Thus, the first debug edit occurs at $(DBGBGN + DBGINC)$, while the last debug edit occurs at $(DBGBGN + DBGRGE)$. Intermediate debug edits are $DBGINC$ apart. The maximum number of debug edits cannot exceed MAXDBG. (See Appendix "Maximums".)

**See 619 input record.

The 671 input record identifies a unique set of plot history edits.

	min	max
start	0	MAXEDT
restart	0	MAXEDT

Columns →	11	21	31	41	51	61	71	80
	L	PLTBGN	PLTRGE	PLTINC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	L	Plot history edit index. The value of L uniquely identifies the data on this input record. The value of L must be integral and greater than or equal to 1 and less than or equal to MAXEDT. (See Appendix "Maximums".) If L is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".)
2	PLTBGN	Beginning of plot history edits.* The value of PLTBGN gives a start time or start cycle (depending on MPLT**) from which the plot history edits on this record are computed. The value of PLTBGN must be greater than or equal to zero.
3	PLTRGE	Range of plot history edits.* The value of PLTRGE gives the time range or cycle range (depending on MPLT**) from which the plot history edits on this record are computed. The value of PLTRGE must be a positive number.
4	PLTINC	Increment of plot history edits.* The value of PLTINC gives the time increments or cycle increments (depending on MPLT**) from which the plot history edits on this record are computed. The value of PLTINC must be a positive number.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

* Edits occur at $PLTBGN + (i \times PLTINC)$ where i goes from 1 to n ($n = PLTRGE/PLTINC$). Thus, the first plot history edit occurs at $(PLTBGN + PLTINC)$, while the last plot history edit occurs at $(PLTBGN + PLTRGE)$. Intermediate plot history edits are $PLTINC$ apart. The maximum number of plot history edits cannot exceed MAXPLT. (See Appendix "Maximums".)

**See 616 input record.

Plot Definition

Page 1 of 3

1D ONLY

TYPE
672

A 672 input record is required to specify a 1D plot. Each 672 input record defines a unique time history, snapshot, or mesh plot. Plots may be defined at start or restart time.

	min	max
start	0	MAXEDT
restart	0	MAXEDT

Columns →	11	21	31	41	51	61	71	80
	NPLT	IDPLT	IDORD	IDABC	IDLOC	TODLOC	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NPLT	Plot number. The value of NPLT defines the array location of the plot parameters in this record. The value of NPLT must be integral and greater than or equal to 1 and less than or equal to MAXEDT. (See Appendix "Maximums".) If NPLT is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".) Plot numbers do not have to be consecutive.
2	IDPLT	Plot type. The value of IDPLT identifies the type of plot specified on this record. The value of IDPLT must be integral and greater than or equal to 1.0 and less than or equal to 3.0. The following definitions apply: = 1.0 time history = 2.0 snapshot = 3.0 mesh If the field containing IDPLT is left blank, then the plot is assumed not to exist. If the value of IDPLT is greater than 3.0, the message, PLOT TYPE IMPROPERLY DEFINED is written on the print and the message files, and the program terminates at the end of the GENERATOR phase group.
3	IDORD	Ordinate identifier. The value of IDORD identifies the variable to be plotted on the ordinate of a time history or a snapshot plot. A list of identifier values appears in Appendix "Identifiers". The value of IDORD must be integral and must correspond to a legitimate variable or the message,

Columns →	11	21	31	41	51	61	71	80
	NPLT	IDPLT	IDORD	IDABC	IDLOC	TODLOC	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		ORDINATE IDENTIFIER IMPROPERLY DEFINED VALUE = <u>eeeeeeeeeeee</u> is written on the print and the message files, and the value of IDPLT is set equal to zero so that no plot will be made. Leave this field blank for a mesh plot.
4	IDABC	Abscissa identifier. The value of IDABC identifies the variable to be plotted on the abscissa of a time history or a snapshot plot. A list of identifier values appears in Appendix "Identifiers". The value of IDABC must be integral and must correspond to a legitimate variable or the message, ABSCISSA IDENTIFIER IMPROPERLY DEFINED VALUE = <u>eeeeeeeeeeee</u> is written on the print and the message files, and the value of IDPLT is set equal to zero so that no plot will be made. Leave this field blank for a mesh plot.
5	IDLOC	Zone index or cycle number. The value of IDLOC depends on the value of IDPLT. If IDPLT = 1.0, the value of IDLOC is the zone or grid-point where the time history is to be made. If IDPLT = 2.0 or 3.0, the value of IDLOC is the cycle number at which the snapshot or mesh plot is to be made. The value of IDLOC must be integral and greater than or equal to 1.0 and less than or equal to NCGPT (for zone or grid-point specification) or less than or equal to MAXCYC (for cycle specification). If IDLOC is less than 1.0, the zone index or cycle number will be calculated using the TODLOC specification.

Columns →	11	21	31	41	51	61	71	80
	NPLT	IDPLT	IDORD	IDABC	IDLOC	TODLOC	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
6	TODLOC	Plot time or location. The value of TODLOC depends on the value of IDPLT. If IDPLT = 1.0, the value of TODLOC is the initial position of the zone or grid point where the time history is to be made. If IDPLT = 2.0 or 3.0, the value of TODLOC is the time at which the snapshot or mesh plot is to be made. The value of TODLOC is used only when IDLOC is less than 1.0.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Plot Definition

Page 1 of 2

2D ONLY

TYPE
674

A 674 input record is required to specify a 2D function plot. Each 674 input record defines a unique time history or snapshot plot. Plots may be defined at start or restart time.

	min	max
start	0	MAXEDT
restart	0	MAXEDT

Columns →	11	21	31	41	51	61	71	80
	NPLT	IDPLT	IDORD	IDABC	IDLOC	TODLOC	IDROW	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NPLT	Plot number. The value of NPLT defines the array location of the plot parameters on this record. The value of NPLT must be integral and greater than or equal to 1 and less than or equal to MAXEDT. (See Appendix "Maximums".) If NPLT is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".) Plot numbers do not have to be consecutive.
2	IDPLT	Plot type. The value of IDPLT identifies the type of plot specified on this record. The value of IDPLT must be integral and have a value of 1.0 or 2.0. The following definitions apply: = 1.0 time history = 2.0 snapshot If the value of IDPLT is not 1.0 or 2.0, the message, PLOT TYPE IMPROPERLY DEFINED is written on the print and the message files, and the program terminates at the end of the GENERATOR phase group.
3	IDORD	Ordinate identifier. The value of IDORD identifies the variable to be plotted on the ordinate of a time history or a snapshot plot. A list of identifier values appears in Appendix "Identifiers". The value of IDORD must be integral and must correspond to a legitimate variable or the message, ORDINATE IDENTIFIER IMPROPERLY DEFINED VALUE = <u>eeeeeeeeeeeeee</u> is written on the print and the message files, and the value of IDPLT is set equal to zero so that no plot will be made.

Columns →	11	21	31	41	51	61	71	80
	NPLT	IDPLT	IDORD	IDABC	IDLOC	TODLOC	IDROW	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
4	IDABC	Abscissa identifier. The value of IDABC identifies the variable to be plotted on the abscissa of a time history plot. A list of identifier values appears in Appendix "Identifiers". The value of IDABC must be integral and must correspond to a legitimate variable or the message, ABSCISSA IDENTIFIER IMPROPERLY DEFINED VALUE = <u>eeeeeeeeeeee</u> is written on the print and the message files, and the value of IDPLT is set equal to zero so that no plot will be made. Leave this field blank for a snapshot plot.
5	IDLOC	Zone index or cycle number. The value of IDLOC depends on the value of IDPLT. IDPLT = 1.0; the value of IDLOC is the six-digit number IIIJJJ, where III is the column number (i-index), and JJJ is the row number (j-index) of the zone where the time history is to be made. IDPLT = 2.0; the value of IDLOC is the cycle number at which the snapshot is to be made. The value of IDLOC must be such that $1 \leq III \leq NCGPT$ and $1 \leq JJJ \leq NCROW$ (for the zone or grid-point specification) or less than or equal to MAXCYC (for cycle specification). If IDPLT = 2.0 and IDLOC is less than 1.0, the cycle number will be calculated using TODLOC specification.
6	TODLOC	Plot time. If IDLPT = 2.0 and IDLOC = 0.0, the value of TODLOC is the time at which the snapshot is to be made. Leave this field blank for a time history plot.
7	IDROW	Row or column number. This is the row (j-index) or column (i-index) for which a snapshot will be made. The value of IDROW should be a six-digit number of the form IIIJJJ. If a snapshot of a row is to be made, JJJ should be the row number, III should be zero, and $1 \leq JJJ \leq NCROW$. If a snapshot of a column is to be made, III should be the column number, JJJ should be zero, and $1 \leq III \leq NCGPT$. Leave this field blank for a time history plot.

Plot Definition

Page 1 Of 2

TYPE
675

A 675 input record is required to specify a 2D grid-type plot. Each 675 record defines a unique mesh, contour, vector (velocity), tensor (stress), or isometric contour plot.

	min	max
start	0	MAXEDT
restart	0	MAXEDT

Columns →	11	21	31	41	51	61	71	80
	NPLT	IDPLT	IDORD	--	IDLOC	TODLOC	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NPLT	Plot number. The value of NPLT defines the array location of the plot parameters in this record. The value of NPLT must be integral and greater than or equal to 1 and less than or equal to MAXEDT. (See Appendix "Maximums".) If NPLT is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".) Plot numbers do not have to be consecutive.
2	IDPLT	Plot type. The value of IDPLT identifies the type of plot specified on this record. The value of IDPLT must be integral and have a value greater than or equal to 3.0 and less than or equal to 7.0. The following definitions apply: = 3.0 mesh plot = 4.0 contour plot = 5.0 vector plot (velocity) = 6.0 tensor plot (stress) = 7.0 isometric contour If the value of IDPLT is not one of the above, a message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group.
3	IDORD	Ordinate identifier. For contour or isometric contour plots, the value of IDORD specifies the variable to be contoured.* A list of variable identifiers appears in Appendix "Identifiers". The value of IDORD must be integral and must correspond to a legitimate variable or the message, ORDINATE IDENTIFIER IMPROPERLY DEFINED VALUE = <u>eeeeeeeeeeee</u>

* For isometric contour plots, the value of IDORD specifies the value to be displayed as a "z"-value above the grid.

Columns →	11	21	31	41	51	61	71	80
	NPLT	IDPLT	IDORD	--	IDLOC	TODLOC	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
		is written on the print and the message files, and the value of IDPLT is set to zero so that no plot will be made. Leave this field blank for a mesh, vector, or tensor plot.
4	--	Field 4 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)
5	IDLOC	Cycle number. The value of IDLOC is the cycle number at which the plot is to be made. It must be integral and less than or equal to MAXCYC. If the value of IDLOC is 0.0, the cycle number will be calculated using the TODLOC specification.
6	TODLOC	Plot time. If IDLOC is 0.0, TODLOC is the time at which the plot is to be made.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

Multiple Plot Edit Specification

Page 1 of 2

TYPE
677

A 677 input record specifies a set of multiple plot edits for a plot defined by a 672, a 674, or a 675 input record. Multiple plot edits can be specified for any plot type except time histories and column snapshots. Since each plot edit results in the generation of a complete plot, the 677 input record can be used to generate plot movies.

	min	max
start	0	MAXEDT
restart	N/A	N/A

Columns →	11	21	31	41	51	61	71	80
	NPLT	PETBGN	PETRGE	PETINC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	NPLT	Plot number. The value of NPLT identifies the plot for which the specified multiple plot edits are to apply. The value of NPLT must be integral, greater than or equal to 1, and less than or equal to MAXEDT. (See Appendix "Maximums".) If NPLT is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine EDTINP. (See Appendix "Messages".) The corresponding plot can be of any type except time history or column snapshot. If multiple plot edits are supplied for a time history plot or for a column snapshot, a TYPERR message is written on the print and the message files and the program terminates immediately in subroutine EDTCHK. (See Appendix "Messages".)
2	PETBGN	Beginning of multiple plot edits.* The value of PETBGN gives a start time or start cycle (depending on MPET**) from which the multiple plot edits for plot number NPLT are computed. The value of PETBGN must be greater than or equal to zero.
3	PETRGE	Range of multiple plot edits.* The value of PETRGE gives the time range or cycle range (depending on MPET**) from which the multiple plot edits for plot number NPLT are computed. The value of PETRGE must be a positive number.
4	PETINC	Increments of plot edits. The value of PETINC gives the time increments or cycle increments (depending on MPET**) from which the multiple plot edits for plot number are computed. The value of PETINC must be a positive number.

* Edits occur at $PETBGN + (i \times PETINC)$ where i goes from 1 to n ($n = PETRGE/PETINC$). Thus, the first plot edit occurs at $(PETBGN + PETINC)$ while the last plot edit occurs at $(PETBGN + PETRGE)$. Intermediate plot edits are $PETINC$ apart.

** See 617 input record.

TYPE
677

Columns →	11	21	31	41	51	61	71	80
	NPLT	PETBGN	PETRGE	PETINC	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
677

End of EDT Phase

Page 1 of 1

TYPE
END

The END input record signifies the end of a block of data for the EDT input phase. It must follow the last EDT input record.

	min	max
start	1	1
restart	0	1

Columns →	11	21	31	41	51	61	71	80
	--	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1-7	--	Fields 1-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
END

7.7 END OF INPUT DATA DECK (END)

The last input record in every data deck, start or restart, must be and END record. This END record must follow another END record, which is the end-of-data record of the last input block in the data deck.

End of Input Data Deck

Page 1 of 1

TYPE
END

This END input record signifies the end of all blocks of data in the input data deck. It must follow the last END input record of the last input data block.

	min	max
start	1	1
restart	1	1

Columns →	11	21	31	41	51	61	71	80
	--	--	--	--	--	--	--	
Fields →	1	2	3	4	5	6	7	

Field Number	Input Variable Name

Description of Input Variable

1-7	--	Fields 1-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages".)

TYPE
END

SECTION 8

TEST AND EXAMPLE PROBLEMS

8.1 INTRODUCTION

In this section, we discuss several calculations that have been performed with the implicit fluid dynamics versions of STEALTH. These problems have two purposes. The first is to demonstrate the general capabilities and limitations of the codes, while the second is to provide test problems that a new user could use to help familiarize himself with the use of the codes. While all the problems discussed here are intended to serve the first purpose, cost considerations will probably preclude the use of some of these problems as test problems. In particular, the calculations of the growth of a Rayleigh-Taylor instability (incompressible), the thermally driven cavity (compressible), and the explosion in a rigid, water-filled container (compressible) may be too costly for use as a test problem. On the other hand, the 1D incompressible flow calculations, the 1D implicit, compressible flow calculations of the pipe depressurization with a shortened pipe, and the 2D calculation of the undular bore are fairly inexpensive to run.

8.2 INCOMPRESSIBLE FLOW TEST PROBLEMS

8.2.1 1D Incompressible Flow

8.2.1.1 Problem Description. Three similar calculations were performed to test the three symmetries of the 1D incompressible flow code. These calculations were run as part of the initial check-out of the 1D incompressible code and are intended as test problems to be used by new users of the codes. The problems consist of a constant pressure boundary condition acting on the left with a free surface on the right. For planar symmetry, the physical problem that this represents is an infinite incom-

pressible slab that is free on one side and has a constant pressure reservoir on the other. For cylindircal symmetry, it represents an infinite, incompressible cylindrical shell with a constant pressure in the center cavity and a free outer surface. For spherical symmetry, it represents an incompressible spherical shell with a constant pressure on the inside and a free surface on the outside.

The form of the velocity field for the three different symmetries can be determined by integrating the incompressibility condition, $\nabla \cdot \underline{v} = 0$. In 1D, this can be written

$$\begin{aligned}\frac{\partial \dot{x}}{\partial x} &= 0 && \text{(planar symmetry),} \\ \frac{\partial \dot{r}}{\partial r} + \frac{\dot{r}}{r} &= 0 && \text{(cylindrical symmetry),} \\ \frac{\partial \dot{r}}{\partial r} + \frac{2\dot{r}}{r} &= 0 && \text{(spherical symmetry),} \quad (8.1)\end{aligned}$$

which can be integrated to give

$$\begin{aligned}\dot{x} &= c_1 && \text{(planar),} \\ \dot{x} &= c_2/r && \text{(cylindrical),} \\ \dot{x} &= c_3/r^2 && \text{(spherical).} \quad (8.2)\end{aligned}$$

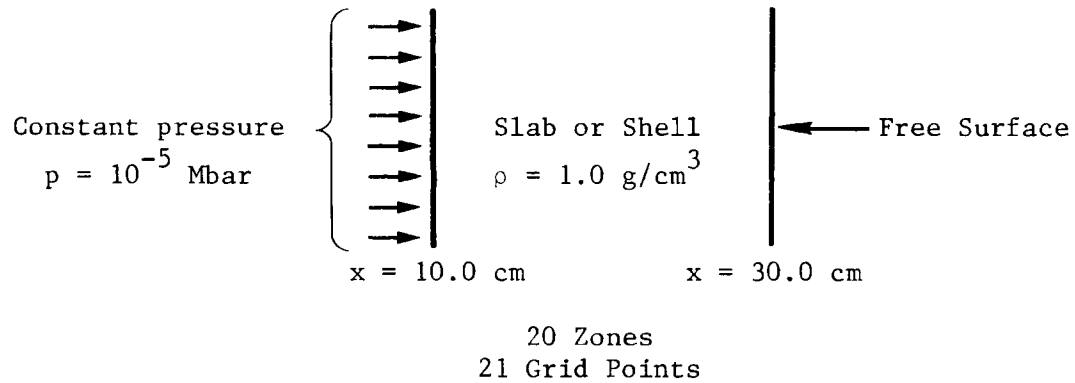
Here, c_1 , c_2 , and c_3 are integration constants. Thus, for planar symmetry the velocity is constant over the entire fluid as one would expect. For cylindrical symmetry the velocity decreases as $1/r$, while for spherical symmetry it decreases as $1/r^2$.

In plane symmetry, it is a simple matter to evaluate the integration constant c_1 from the boundary conditions and the momentum equation. When this is done, the expression for the velocity becomes

$$\dot{x} = \frac{P_o t}{\rho \Delta \ell} \quad (8.3)$$

where P_o is the pressure on the boundary, t is the time, ρ is the density of the fluid and $\Delta \ell$ is the thickness. In our numerical computations, we are interested in making sure that our solutions satisfy both Eqs.(8.2) and (8.3).

8.2.1.2 Problem Set-Up. A schematic of the configuration used for the three calculations is shown below.



A constant pressure boundary condition of 10 bars is applied to the left (inner) boundary. The slab (shell) is 20.0 centimeters thick with a density of 1.0 g/cm^3 . The right (outer) boundary is free. Twenty constant-width zones are used in the slab for a zone width of 1.0 cm. The slab is initially at rest.

During the first time step of the calculation, the code should calculate the steadystate velocity field corresponding to Eqs.(8.2), and thereafter the form of the velocity field should remain essentially unchanged as the slab as a whole is accelerated uniformly. Since we are interested primarily in the form of the velocity field that is established initially, the size of the time step is not too important. A value of 25 μ s was arbitrarily chosen. This is well within the stable value determined from the velocity condition, Eq. (6.2).

Similarly, the selection of the convergence criterion is not very important in this problem as long as it is small enough to give a reasonable level of accuracy. Equation (6.4) can be used to select a reasonable value. To estimate $\frac{\partial v}{\partial x}$ for that equation, we need to estimate a typical Δv and Δx for the problem. We can take Δv to be on the order of the velocity of the inner surface [Eq.(8.3) gives the right order of magnitude for all three symmetries] and Δx can be taken to be the thickness of the slab or shell. Thus,

$$\frac{\partial v}{\partial x} \sim 10^{-6}$$

so that a reasonable value of ϵ is 10^{-8} .

The problem was run for a total of 10 cycles or to a time of 250 μ s. This is sufficient time to be sure that a steady-state solution has been obtained and that the uniform acceleration of the slab (shell) is being calculated properly.

8.2.1.3 Results. Figures 8.1 and 8.2 show velocity as a function of distance for the three calculations at two different times. At both times Eqs.(8.2) are satisfied for all three symmetries. In addition, the velocity for the planar case satisfies Eq.(8.3).

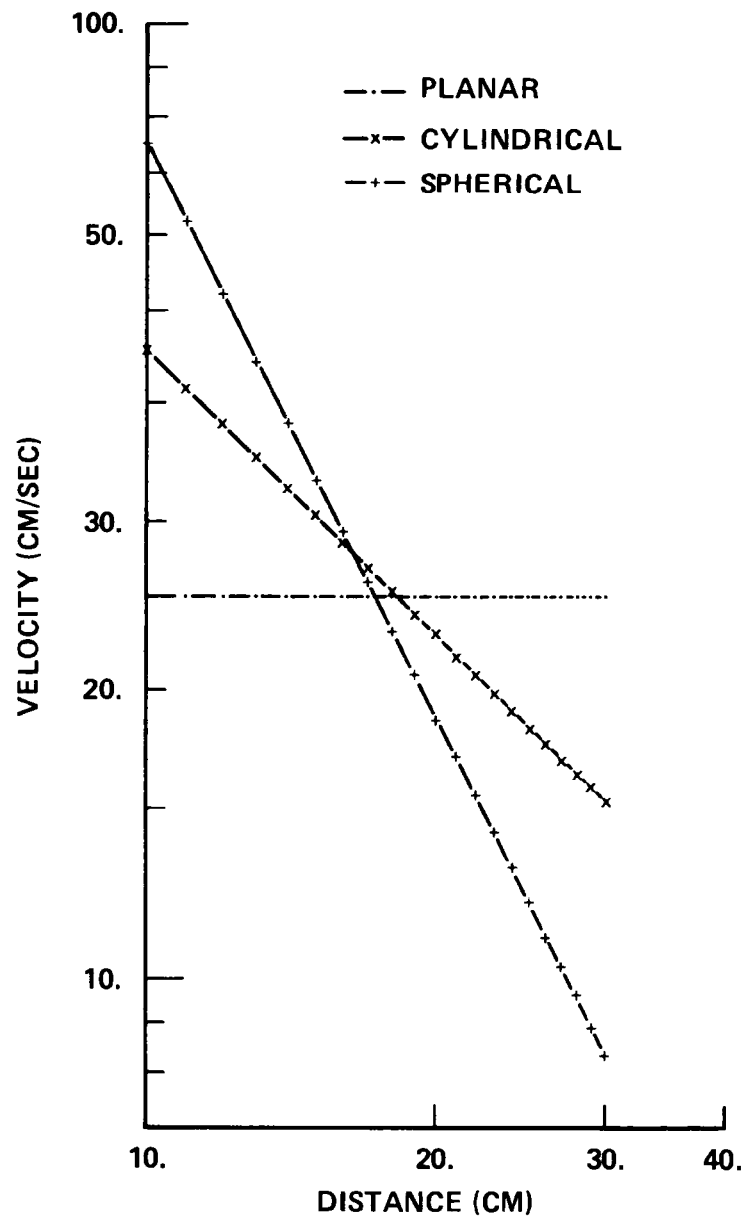


Figure 8.1. Velocity profiles at cycle 2 ($t = 50 \mu\text{sec}$) for 1D planar, cylindrical and spherical incompressible flow.

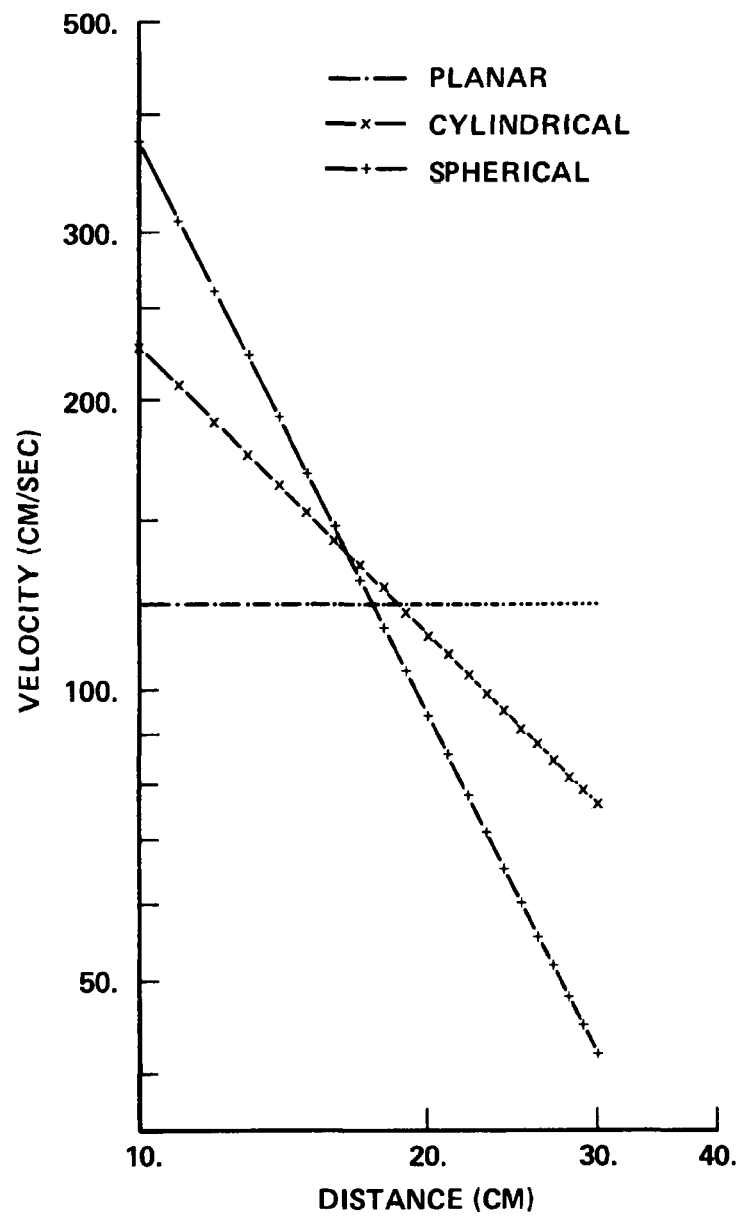


Figure 8.2. Velocity profiles at cycle 10 ($t = 250 \mu\text{sec}$) for 1D planar, cylindrical and spherical incompressible flow.

Figure 8.3 shows the pressure as a function of distance at cycle 2 for all three symmetries. These profiles remained essentially unchanged throughout the remainder of the calculation. This is because very little motion takes place during the short duration of the calculation. In the planar case, the pressure profile should remain unchanged, but for the two divergent geometries the pressure profile will gradually become more linear as the shell moves outward and divergence effects become less important.

8.2.1.4 Input Decks. The STEALTH input deck for the 1D planar calculation is provided in Table 8.1. The input decks for the other two calculations are identical with the exception of the title card (TTL) and the card which specifies the symmetry (SYM). These modifications are provided following the 1D planar input deck in Tables 8.2 and 8.3.

8.2.2 Calculation of the Generation of an Undular Bore

8.2.2.1 Problem Description. A calculation of the generation and propagation of an undular bore was performed to demonstrate the capabilities of the 2D incompressible flow version of STEALTH for problems involving free surface waves. This calculation was also intended as a sample problem to be run by new users of the codes.

The undular bore is generated when a fluid, which initially has a uniform velocity to the right, runs into a rigid wall on the right. As the fluid is stopped by the wall, a surface wave is generated which moves to the left.

This problem was also performed as a test problem for the SOLA-SURF code and is documented in the report on that code (Reference 3). This provides a basis for comparison for the STEALTH solution.

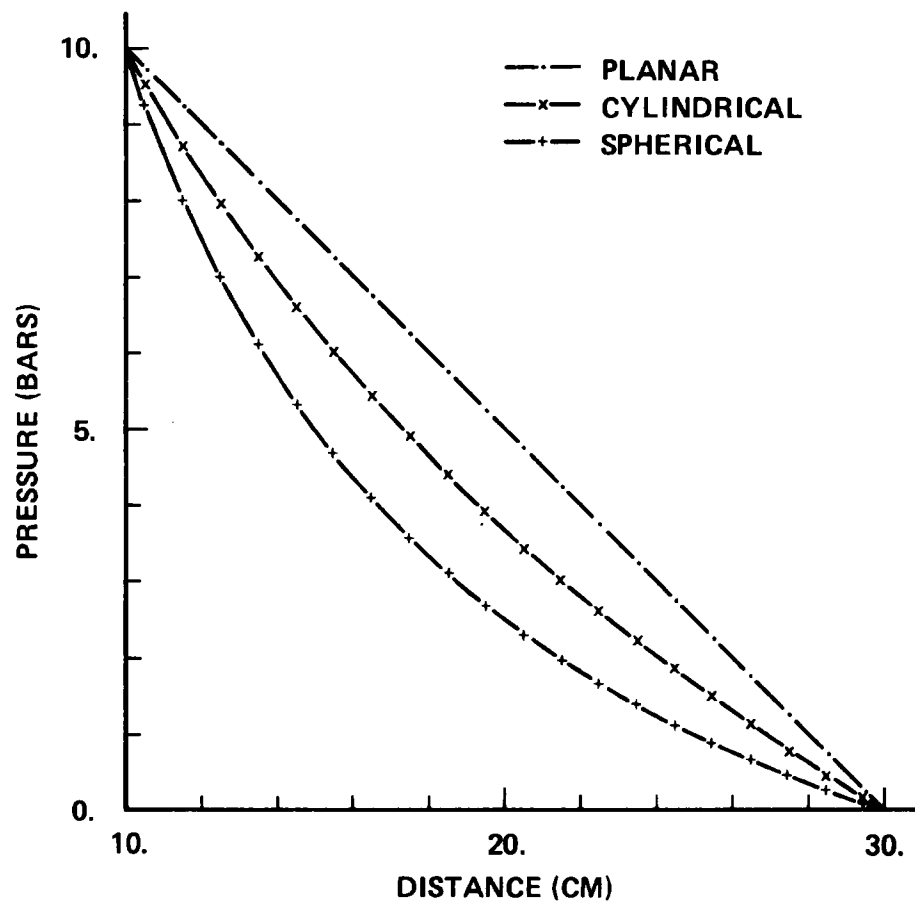


Figure 8.3. Pressure profiles at cycle 2 ($t = 50 \mu\text{sec}$) for 1D planar, cylindrical and spherical incompressible flow.

TABLE 8.1

INPUT DECK FOR 1D PLANAR INCOMPRESSIBLE FLOW

TTL	1D PLANAR INCOMPRESSIBLE FLOW					
PRB						2.0
SYM	1.0					
ITR	500.	.00000001	1.8			
GRD	1.0	1.0	21.			
END						
MAT						2.0
121	1.0	1.0				
END						
CPT						2.0
211	1.0	1.0	10.			
221	1.0	1.0	21.			
241	1.0	20.	10.	30.		
END						
ZON						2.0
311	1.0	1.0	21.			
321	1.0	1.0				
322	1.0	1.0				
END						
BDY						2.0
421	1.0	2.0	5.0	1.0		
421	21.	3.0	5.0			
422	1.0	1.0				
431	1.0	1.0	0.0	1000000.		
432	1.0	.00001				
END						
TIM						2.0
511	25.					
512	.001	25.				
521	250.	50.				
END						
EDT						2.0
621	1.0	0.0	250.	50.		
622	1.0	21.				
623	1.0	11.				
623	2.0	12.				
623	3.0	13.				
623	4.0	64.				
623	5.0	47.				
623	6.0	43.				
623	7.0	45.				
623	8.0	42.				
631	1.0	0.0	250.	50.		
632	1.0	1.0	21.			
672	1.0	2.0	64.	11.		50.
672	2.0	2.0	64.	11.		250.
672	3.0	2.0	12.	11.		50.
672	4.0	2.0	12.	11.		250.
END						
END						

TABLE 8.2

MODIFICATIONS TO 1D INCOMPRESSIBLE FLOW DATA DECK
FOR CYLINDRICAL SYMMETRY

TTL	1D CYLINDRICAL INCOMPRESSIBLE FLOW
SYM	2.0

TABLE 8.3

MODIFICATIONS TO 1D INCOMPRESSIBLE FLOW DATA DECK
FOR SPHERICAL SYMMETRY

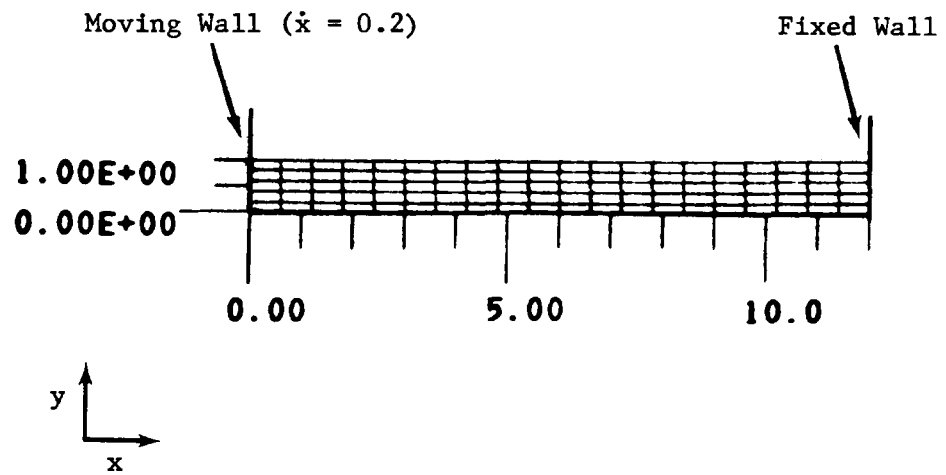
TTL	1D SPHERICAL INCOMPRESSIBLE FLOW
SYM	3.0

8.2.2.2 Problem Set-Up. The initial configuration for this calculation is shown in Figure 8.4, along with some of the input parameters. The initial fluid height is 1.0 in dimensionless units and the length is 12.0 units. The grid, which was made to correspond to the grid used in the SOLA-SURF calculation of this problem, is uniform and consists of 21 x 6 grid points or 20 x 5 zones. This results in a zone size of 0.6 units in the x-direction and 0.2 units in the y-direction. This grid is fairly coarse and the zones have a relatively high aspect ratio. It is adequate for our purposes here, however, since we are not trying to achieve a high degree of accuracy.

The boundaries on the left, bottom, and right are free-slip walls. The walls on the bottom and right are rigid, while the wall on the left moves with a velocity of 0.2 which is also the initial velocity of the fluid throughout the mesh. The top boundary is a free surface.

The time step and convergence criteria were chosen to be 0.2 and 10^{-3} , respectively, to correspond to values used in the SOLA-SURF calculation. The value of the relaxation factor ($\omega = 1.5$) was chosen to optimize the rate of convergence of the iteration. If a substantially larger value is used, the iteration will not converge on the first cycle, primarily because the initial conditions do not satisfy the incompressibility condition (see Section 6.3.4). A value smaller than 1.5 results in a slower rate of convergence on subsequent cycles.

The calculation was run using the ALE rezoner. The specific rezone option used (NSALE = 3.0) allows the points on the top surface to remain as Lagrangian points, while the remainder of the mesh is rezoned to maintain uniform spacing as closely as possible. It was necessary to use the ALE method for this problem because a purely Lagrangian mesh becomes tangled in the lower right hand corner as the fluid flow attempts to turn the corner.



Grid Spacing	$\Delta x = 0.6$ $\Delta y = 0.2$	Time Step	$\Delta t = 0.2$
Initial Velocity	$\dot{x}_0 = 0.2$	Convergence Criterion	$\epsilon = 10^{-3}$
Density	$\rho_0 = 1.0$	Relaxation Factor	$\omega = 1.5$
Gravity	$g_y = -1.0$		

Figure 8.4. Initial configuration for undular bore problem.

The problem was run to a time of 11.0 or for just over 50 cycles. This is sufficient time for the reflected surface wave to propagate nearly to the left boundary.

8.2.2.3 Results. The mesh configuration at five different times is shown in Figure 8.5. These mesh plots show a small amplitude surface wave forming at the right boundary and propagating to the left. Velocity vector plots at these same times are provided in Figure 8.6. This figure clearly shows the nature of the flow in the region behind (to the right of) the front of the wave. At the front, the flow is nearly stagnated so that all that remains is a low amplitude oscillatory motion of the fluid that manifests itself as oscillations of the free surface behind the initial wave front.

Details of the free surface can be seen more clearly in Figure 8.7, which shows the free surface configuration with an amplified vertical scale. It is clear from this figure that by the end of the calculation, the wave has strongly interacted with the moving wall at the left boundary.

The calculated wave form and speed compare very well with the results of the SOLA-SURF calculation of this problem. The calculated fluid depth behind the bore (i.e., the average depth at the righthand wall) is approximately 1.2 and the bore velocity, defined as the velocity of the mid-point of the bore front, is 1.13. These are to be compared with a height of 1.211 and a velocity of 1.121 calculated by SOLA-SURF. The theoretical values for height and velocity, quoted in Reference 3, are 1.209 and 1.156, respectively.

8.2.2.4 Input Deck. The STEALTH input deck for the undular bore problem is provided in Table 8.4.

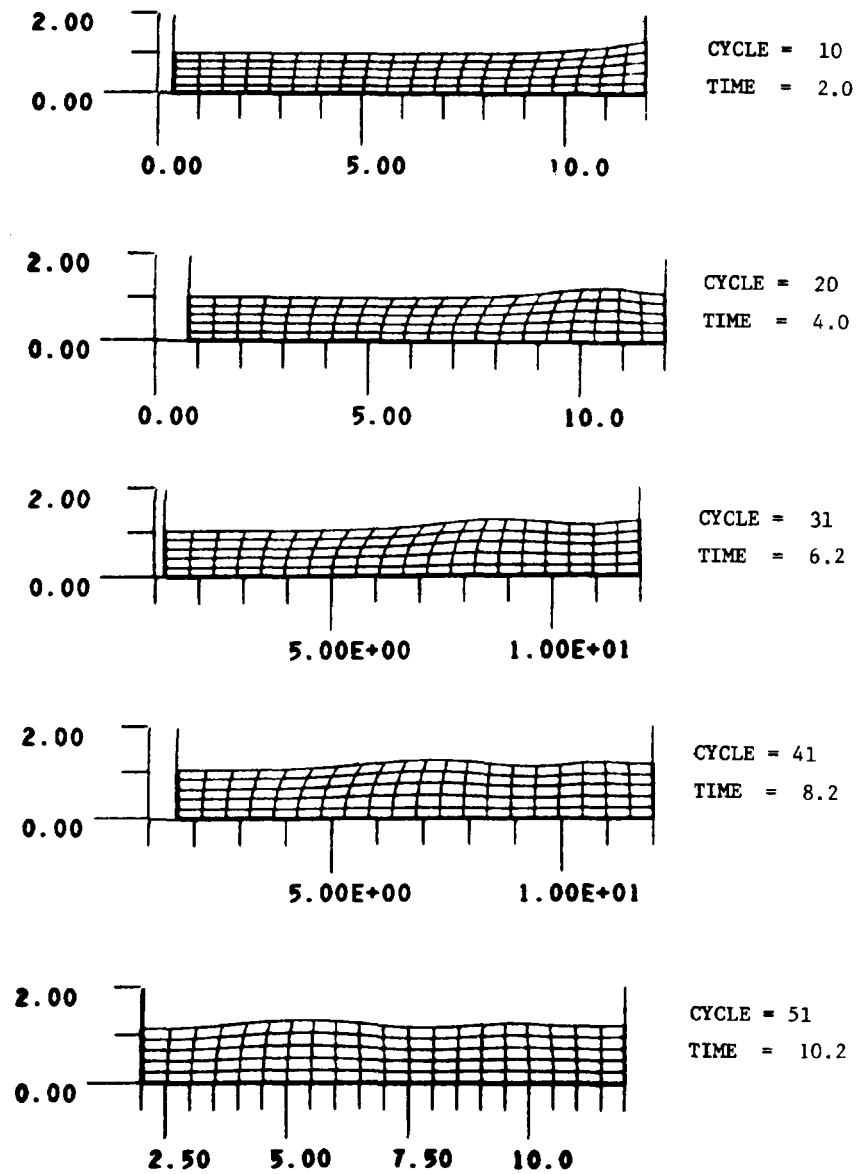


Figure 8.5. Mesh configuration at several times for the undular bore problem.

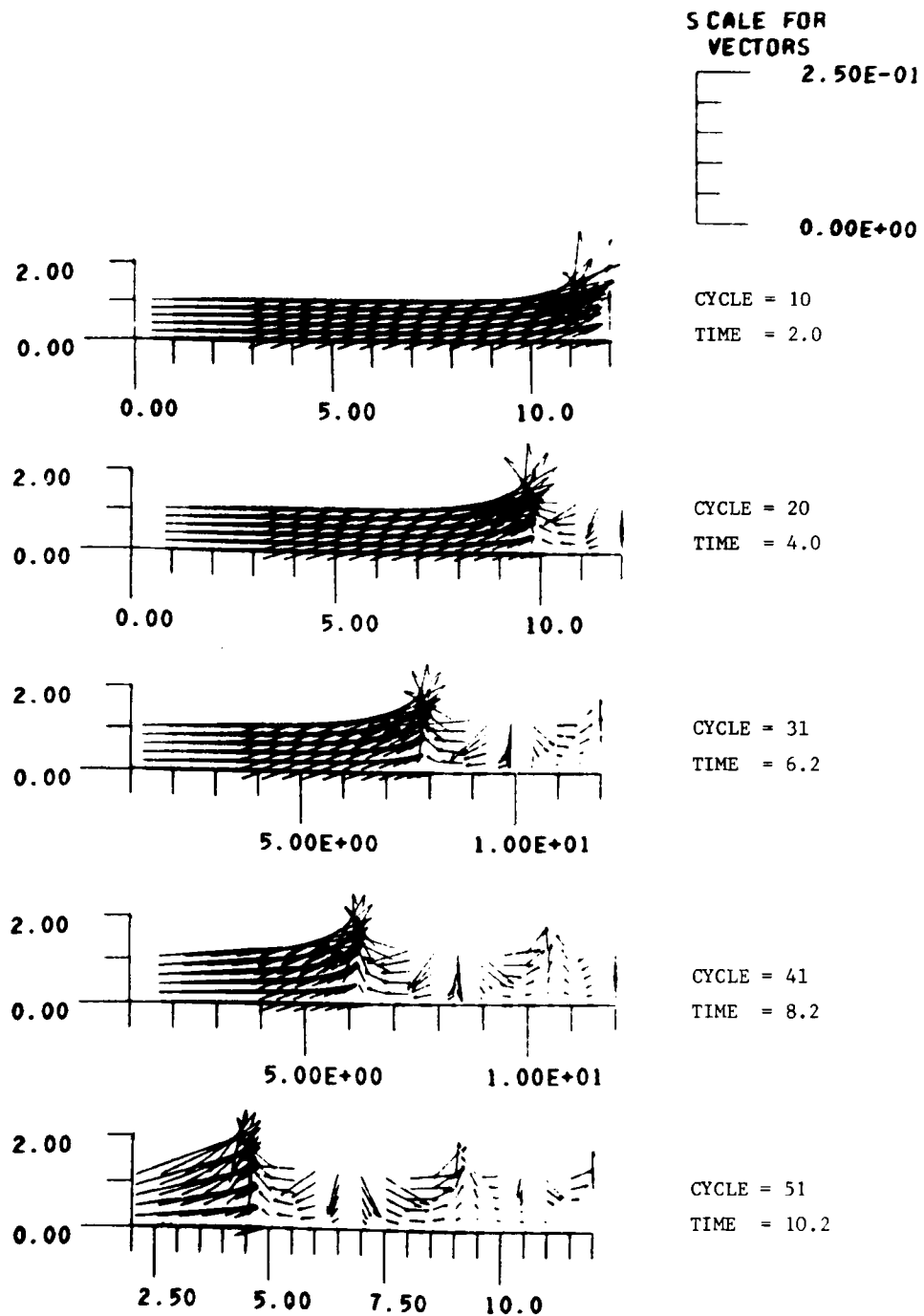


Figure 8.6. Velocity vector plots at several times for the undular bore problem.

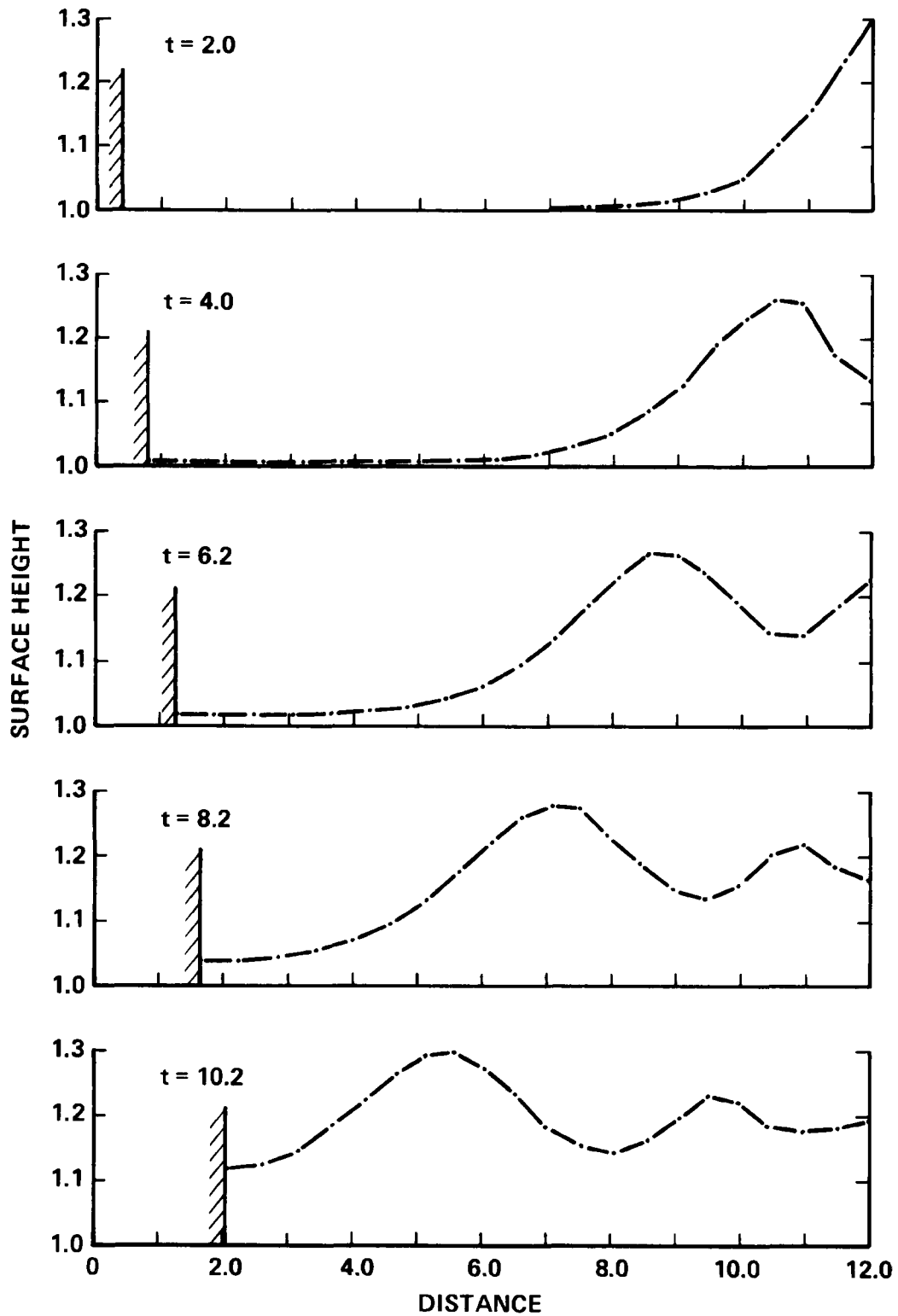


Figure 8.7. Free surface configuration at several times for the undular bore problem.

TABLE 8.4

DATA DECK FOR UNDULAR BORE CALCULATION

CALCULATION OF AN UNDULAR BORE						
TTL						
PRB						2.0
PRO	2.0					
SYM	1.0					
MIN						0.05
GRV		-1.		2.0		
GRD	1.0	1.0	21.	6.0		
ITR	200.	.001	1.5			
ALE	3.0	1.0	1.0			
CPL	.25					
END						
MAT						2.0
121 RDN	1.0	1.0				
END						
GPT				2.0		2.0
211 ORIG	1.0	1.0	1.0	0.0		0.0
212 WPT	1.0	0.0	2.0	2.0		
212 WPT	2.0	0.0	0.0	1.0		
212 WPT	3.0	12.	0.0	1.0		
212 WPT	4.0	12.	2.0	3.0		
221 GPBLK	1.0	1.0	21.	1.0		6.0
246 ZNING	1.0	0.0	0.6	0.0		0.2
END						
ZON						2.0
311 ZBLK	1.0	1.0	21.	1.0		2.0
311 ZBLK	2.0	1.0	21.	2.0		3.0
311 ZBLK	3.0	1.0	21.	3.0		4.0
311 ZBLK	4.0	1.0	21.	4.0		5.0
311 ZBLK	5.0	1.0	21.	5.0		6.0
321 MPN	1.0	1.0				
321 MPN	2.0	1.0				
321 MPN	3.0	1.0				
321 MPN	4.0	1.0				
321 MPN	5.0	1.0				
322 SCLR	1.0	1.0				
322 SCLR	2.0	1.0				
322 SCLR	3.0	1.0				
322 SCLR	4.0	1.0				
322 SCLR	5.0	1.0				
331 VCTR	1.0	0.2				
331 VCTR	2.0	0.2				
331 VCTR	3.0	0.2				
331 VCTR	4.0	0.2				
331 VCTR	5.0	0.2				
END						
BDY						2.0
411 TLC	1.0	2.0	6.0	1.0		6.0
411 LFT	2.0	1.0	6.0	1.0		1.0
411 BOT	3.0	1.0	1.0	21.		1.0
411 RHT	4.0	21.	1.0	21.		6.0
412 TLC	1.0	1.0	6.0			2.0
412 LFT	2.0	1.0	6.0			2.0
412 BOT	3.0	1.0	6.0			3.0
412 RHT	4.0	1.0	6.0			4.0
422 MMBD	1.0	1.0				
441 XVFNC	1.0	1.0	0.0	100000.		
442 XVEL	1.0	0.2				
443 YVFNC	1.0	1.0	0.0	100000.		
444 YVEL	1.0					
481 LFT	1.0	1.0	2.0			
481 BT/RT	2.0	3.0	4.0			
482 LFT	1.0	1.0	4.0	5.0		1.0
482 BT/RT	2.0	1.0	5.0	5.0		1.0
END						

(Continued on next page)

TABLE 8.4 (continued)

TIM					2.0	
511	DTSOR	.2				
512	DTLIM	.000010	.2			
521	MXT/C	11.	100.			
END						
EDT					2.0	
621	PREDT	1.0	0.0	10.	2.0	
622	PRLIM	1.0	21.	1.0	6.0	
623	XPN	1.0	11.			
623	YPN	2.0	14.			
623	XVL	3.0	12.			
623	YVL	4.0	15.			
623	PRH	5.0	64.			
623	VSR	6.0	45.			
623	DNS	7.0	46.			
623	ZMS	8.0	47.			
631	RSEDIT	1.0	0.0	10.	2.0	
632	RGLIM	1.0	1.0	21.	1.0	6.0
675	PLTS	1.0	3.0			2.0
675		2.0	4.0	64.		2.0
675		3.0	5.0			2.0
675		4.0	3.0			4.0
675		5.0	4.0	64.		4.0
675		6.0	5.0			4.0
675		7.0	3.0			6.0
675		8.0	4.0	64.		6.0
675		9.0	5.0			6.0
675		10.	3.0			8.0
675		11.	4.0	64.		8.0
675		12.	5.0			8.0
675		13.	3.0			10.
675		14.	4.0	64.		10.
675		15.	5.0			10.
674		16.	2.0	14.	11.	2.0
674		17.	2.0	14.	11.	4.0
674		18.	2.0	14.	11.	6.0
674		19.	2.0	14.	11.	8.0
674		20.	2.0	14.	11.	10.
END						6.0
END						

8.2.3 Flow Over an Obstacle with a Rectangular Cross Section

8.2.3.1 Problem Description. Two similar calculations were performed to test the two symmetries of the 2D incompressible flow code. The principal objective of these calculations is to demonstrate the capabilities of the 2D incompressible flow version of STEALTH in the Eulerian mode.

The problems consist of a fluid with $\rho = 1.0$ flowing through a channel in which is located an obstacle with a rectangular cross section. For the problem with planar symmetry, the obstacle is a slab 5 units long (y-direction) and 10 units wide (x-direction) which extends to infinity in the z-direction (perpendicular to the plane of the calculation). The channel is 50 units wide in the x-direction and extends to infinity in the y- and z-directions. For the equivalent cylindrically symmetric problem, the obstacle is a cylinder 5 units long with a diameter of 10 units. The channel is cylindrical with a diameter of 50 units. The axis of symmetry is in the y-direction. In both cases, the flow is in the y-direction.

8.2.3.2 Problem Set-Up. A schematic of the configuration for the two calculations is shown in Figure 8.8. In both cases, only half of the space domain is calculated because of symmetry considerations. In the case of planar symmetry, the left boundary is a plane of symmetry; for the cylindrical case, the left boundary is an axis of symmetry. In both cases, the boundary condition at the symmetry boundary is a free-slip wall.

The flow in the problem is upward. The initial velocity is uniform throughout the channel, with a magnitude of $\dot{y} = 1.0$, except at the grid points within the obstacle, where it is zero. The boundary condition at the bottom is an inflow condition with the velocity specified to be $\dot{y} = 1.0$; the boundary at the top is a continuative outflow boundary. On the right, a free-slip wall boundary condition is used.

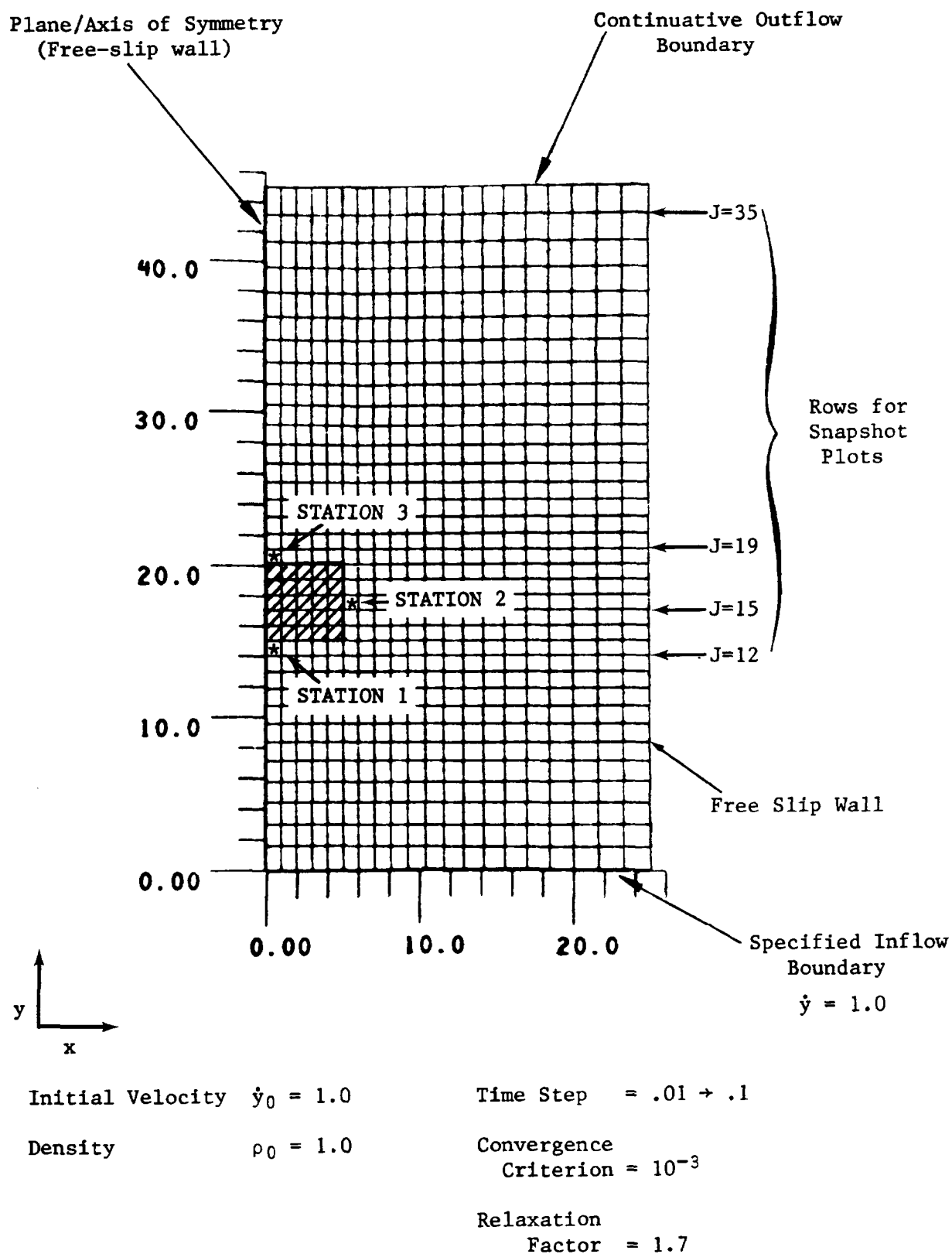


Figure 8.8. Configuration for calculations of incompressible flow over an obstacle with a rectangular cross section.

The obstacle is shown shaded at the left side of the figure. It is defined by specifying the grid points along the outside of the obstacle to have zero velocity. This can be done through standard input by defining those surfaces to be boundary surfaces.

The overall grid consists of 20 x 35 zones or 21 x 36 grid points. The bottom of the grid is three obstacle radii (or half-widths in the case of planar symmetry) from the upstream edge of the obstacle, and the top of the grid is five radii from the downstream edge. These distances were selected to try to minimize perturbations from the boundaries in the region near the obstacle. The right boundary (channel wall) is four obstacle radii from the outer edge of the obstacle. The zone size within the obstacle is 1 x 1. Outside the obstacle, Δx and Δy increase geometrically as the distance from the obstacle increases. The dimensions of the largest zone in the the upper right-hand corner are about 1.73 x 1.86.

The time step for these problems was chosen to be 0.1, which allows the fluid to move 1/10 of a zone width per cycle. However, because the initial conditions do not satisfy the incompressibility condition, it was necessary to use a smaller time step initially, as explained in Section 7.5. An initial value of 0.01 was used. This was allowed to increase by 20% per cycle until the final value of 0.1 was reached by cycle 14.*

The problems were run to a final time of 2.0. This allowed sufficient time for the transient effects of the initial conditions to die out, and for the steady-state solution to be obtained. In fact, the initial transients appeared to be dissipated by a time of 1.0.

*This problem was run before the automatic time step calculation was incorporated into these codes. With the automatic time step calculation approximately the same time step would be achieved with a safety factor of 0.1.

The convergence criterion was selected to be $\epsilon = 10^{-3}$. This was chosen using Eq.(6.4) and estimating $\frac{\partial v}{\partial x}$ as follows. The free stream flow, which has a magnitude of $\dot{y} = 1.0$, stagnates in front of the obstacle near the axis of symmetry. We expect this stagnation to take place over some characteristic distance, Δy , which is comparable to the obstacle diameter. Thus, we estimated a typical $\frac{\partial v}{\partial x}$ to be on the order of

$$\frac{\partial v}{\partial x} = \frac{\text{free stream velocity } (=1.0)}{\text{obstacle diameter } (=10.0)} = 0.1$$

Using Eq.(6.4), this gives $\epsilon = 10^{-3}$. For better accuracy, $\epsilon = 10^{-4}$ should be used.

The relaxation parameter was selected to be $\omega = 1.7$, which seemed to work well for these problems. However, no extensive study was made to determine the optimum ω , since the problems were run for only a few cycles.

The problem was run using the Eulerian option in the ALE rezoner. This was done primarily as a demonstration of this option. A Lagrangian grid could have been used for these problems since they were not run long enough for mesh distortion to be a problem. For similar problems that are run for longer times, however, the Eulerian option is the most effective approach.

8.2.3.3 Results. In these calculations, the objective was to obtain the steady-state solution. The initial conditions, obviously do not satisfy the incompressibility condition in the vicinity of the obstacle. Therefore a fairly severe pressure environment is generated around the obstacle which gradually decays, and eventually a steady-state solution is reached. Although the problem was run to a final time of 2.0, examining pressure as a function of time at several stations adjacent to the obstacle (indicated by asterisks in Figure 8.8) shows that steady-state is reached by $t \sim 1.0$ in both calculations.

To demonstrate the magnitude of the initial transient effects, the initial transient pressure, as well as the final steady-state pressure at each station, are given in Table 8.5. Table 8.5 shows that the initial environment was much less severe for the cylindrical case because of divergence effects; on the other hand, these initial perturbations appeared to die out more slowly in the cylindrical case.

TABLE 8.5 INITIAL TRANSIENT PRESSURE AND FINAL STEADY-STATE PRESSURE AT SEVERAL STATIONS

	<u>Planar Symmetry</u>		<u>Cylindrical Symmetry</u>	
	<u>Initial Pressure</u>	<u>Final Pressure</u>	<u>Initial Pressure</u>	<u>Final Pressure</u>
Station 1	955	9.51	421	1.53
Station 2	204	5.40	13	1.08
Station 3	-537	2.78	-404	0.689

The steady-state velocity field and pressure contours for the problem involving planar symmetry are shown in Figures 8.9 and 8.10, respectively. The same plots for the problem involving cylindrical symmetry are provided in Figures 8.11 and 8.12. The velocity fields for the two symmetries look qualitatively the same, although the magnitude of the radial flow is smaller in the cylindrical case. The pressure contours are also qualitatively similar, but the pressures are lower in magnitude for the cylindrical case. Also, in the cylindrical case, there appear to be some oscillations in the solution near the front of the obstacle. These are small oscillations left from the initial transients that have not completely decayed. They are partly due to the coarseness of the mesh (10 x 10 zones in the obstacle would have provided much better accuracy). These oscillations decay slowly as the problem runs to later times.

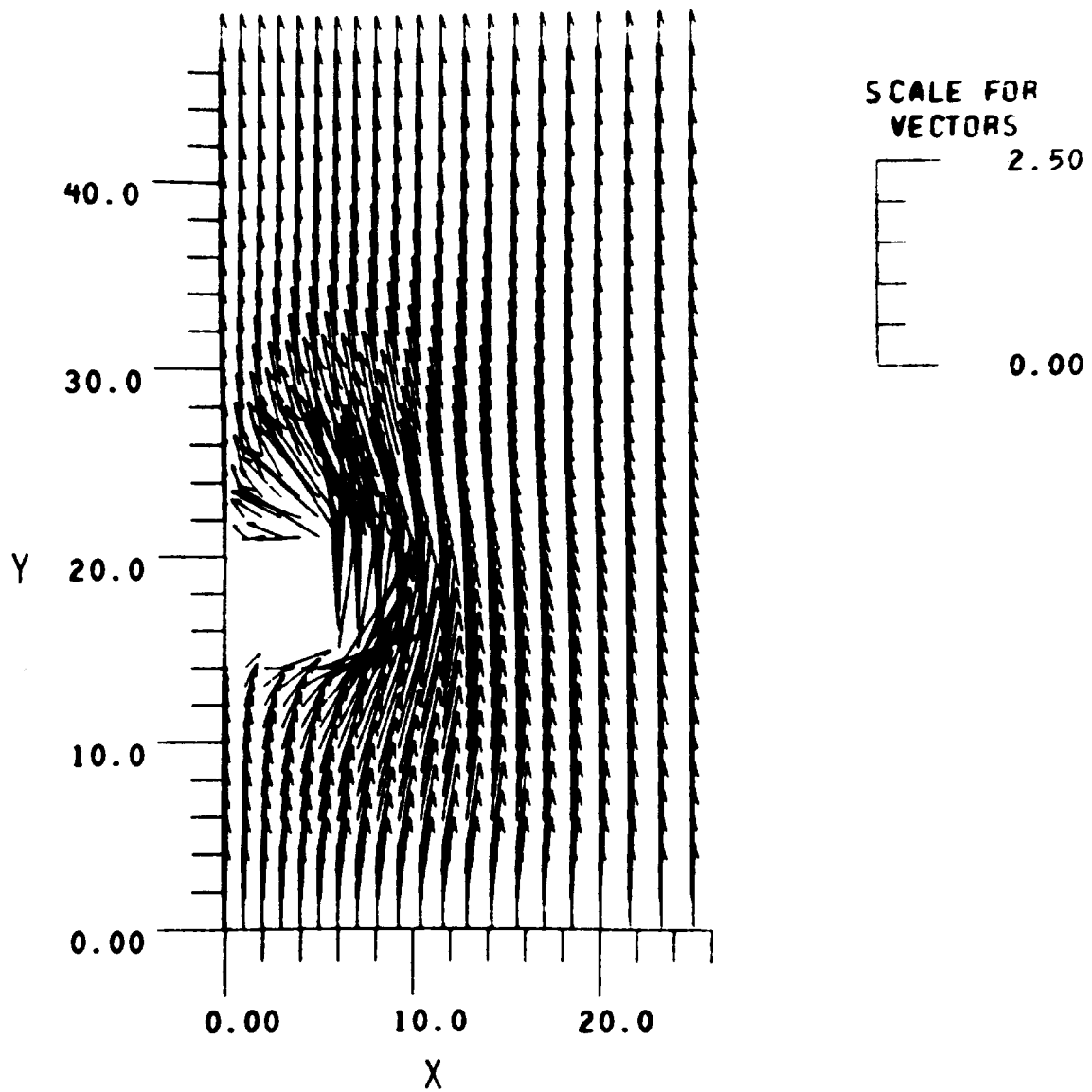


Figure 8.9. Velocity vector plot at cycle 19, time = 1.0850 for the calculation of flow over a planar obstacle with rectangular cross section.

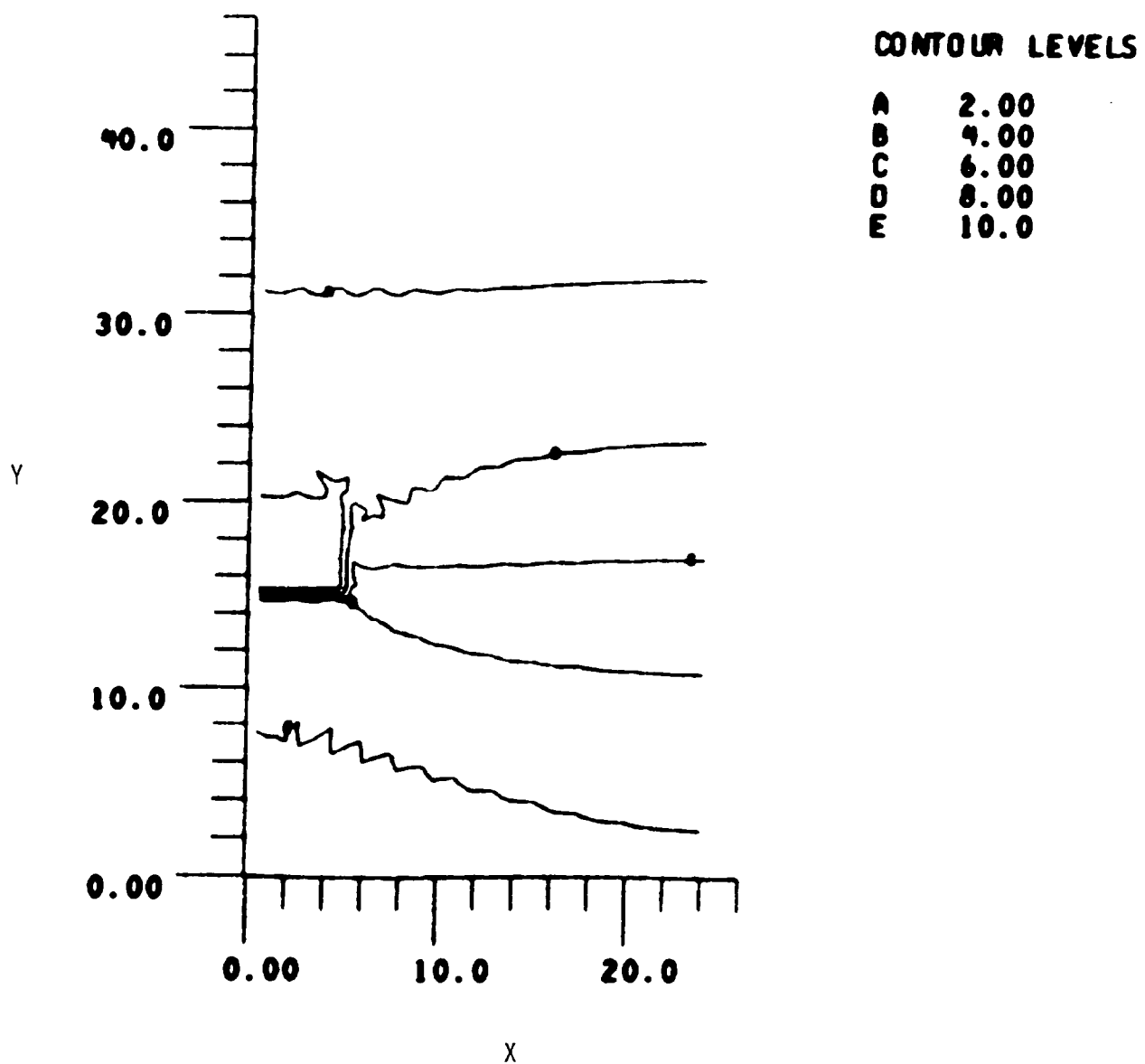


Figure 8.10. Pressure contour plot at cycle 19, time = 1.0850 for the calculation of flow over a planar obstacle with rectangular cross section.

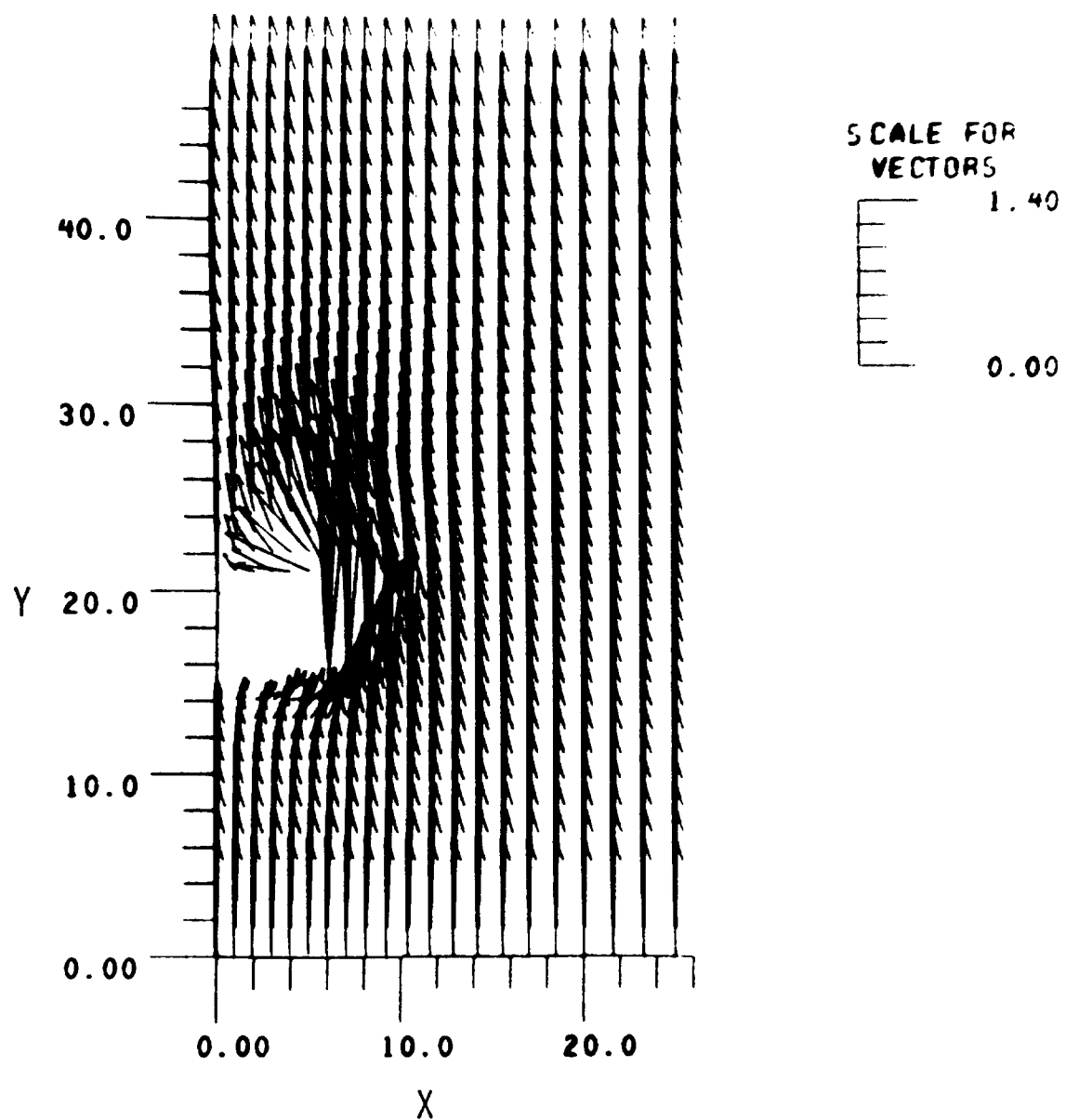


Figure 8.11. Velocity vector plot at cycle 19, time = 1.0850 for the calculation of flow over a cylindrical obstacle with rectangular cross section.

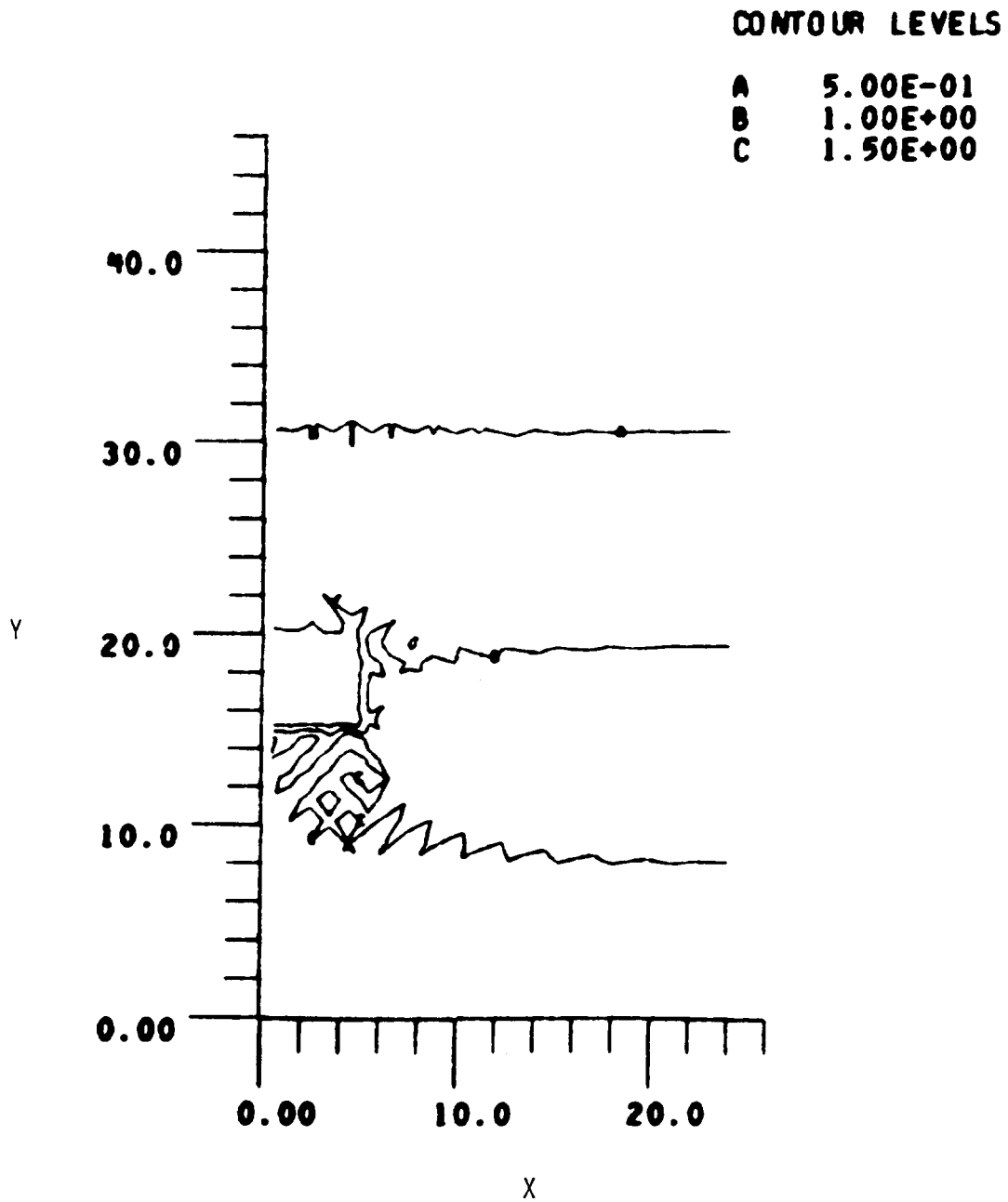


Figure 8.12. Pressure contour plot at cycle 19, time = 1.0850 for the calculation of flow over a cylindrical obstacle with rectangular cross section.

Figures 8.13 - 8.16 provide snapshots of the y-component of velocity along the rows indicated in Figure 8.8 for the calculation involving planar symmetry. Figures 8.17 - 8.20 provide similar snapshots for the cylindrical case. These plots show the same oscillations in front of the obstacle that appeared in pressure contour plots. They also show similar oscillations at the rear of the obstacle. The snapshots along row 35 also show that the flow has not returned to its free stream condition by the time it reaches the downstream boundary. This means that this boundary could have some effect on the solution since the continuative outflow boundary condition is only approximate. Although no plots were obtained near the upstream boundary, a similar condition exists at that location. For a calculation in which a high degree of accuracy is desired, both boundaries should be placed approximately twice as far from the obstacle.

8.2.3.4 Input Deck. The STEALTH input deck for the 2D planar calculation is provided in Table 8.6. The input deck for the 2D cylindrical calculation is identical with the exception of the title card (TTL) and the card which specifies symmetry (SYM). These modifications are provided following the 2D planar input deck in Table 8.7.

8.2.4 Calculation of the Growth of a Rayleigh-Taylor Instability

8.2.4.1 Problem Description. When a heavy fluid lies above a light one, the interface between the two fluids is unstable. Any perturbation to that interface will grow, producing what is known as a Rayleigh-Taylor instability (References 10, 11). To demonstrate the capabilities of the 2D incompressible flow version of STEALTH, calculations of the growth of a Rayleigh-Taylor instability were performed for density ratios of 2:1 and 10:1.

In these calculations, the two fluids are initially at rest with the heavier fluid on top. A velocity perturbation of the form

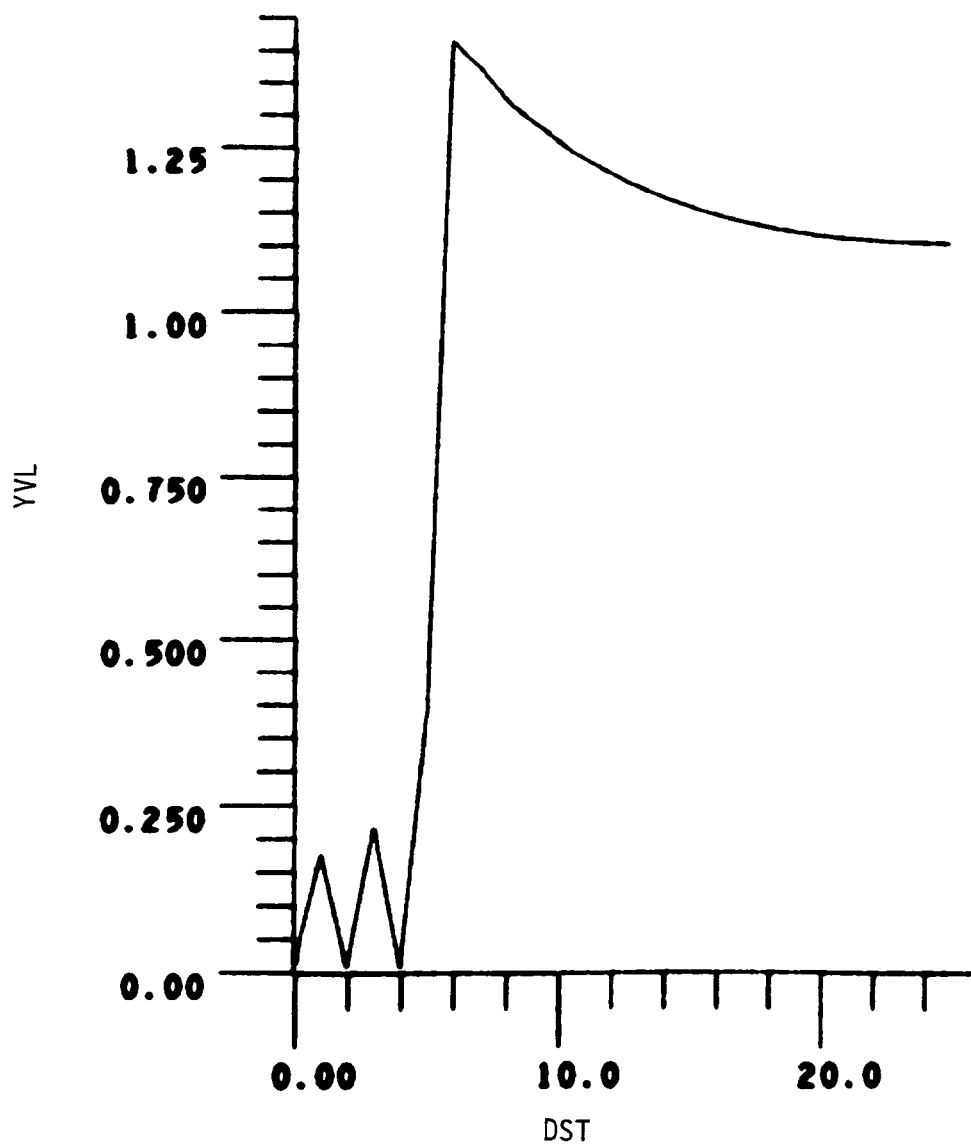


Figure 8.13. Snapshot of row 12 at cycle 19, time = 1.0850 for the calculation of flow over a planar obstacle with rectangular cross section.

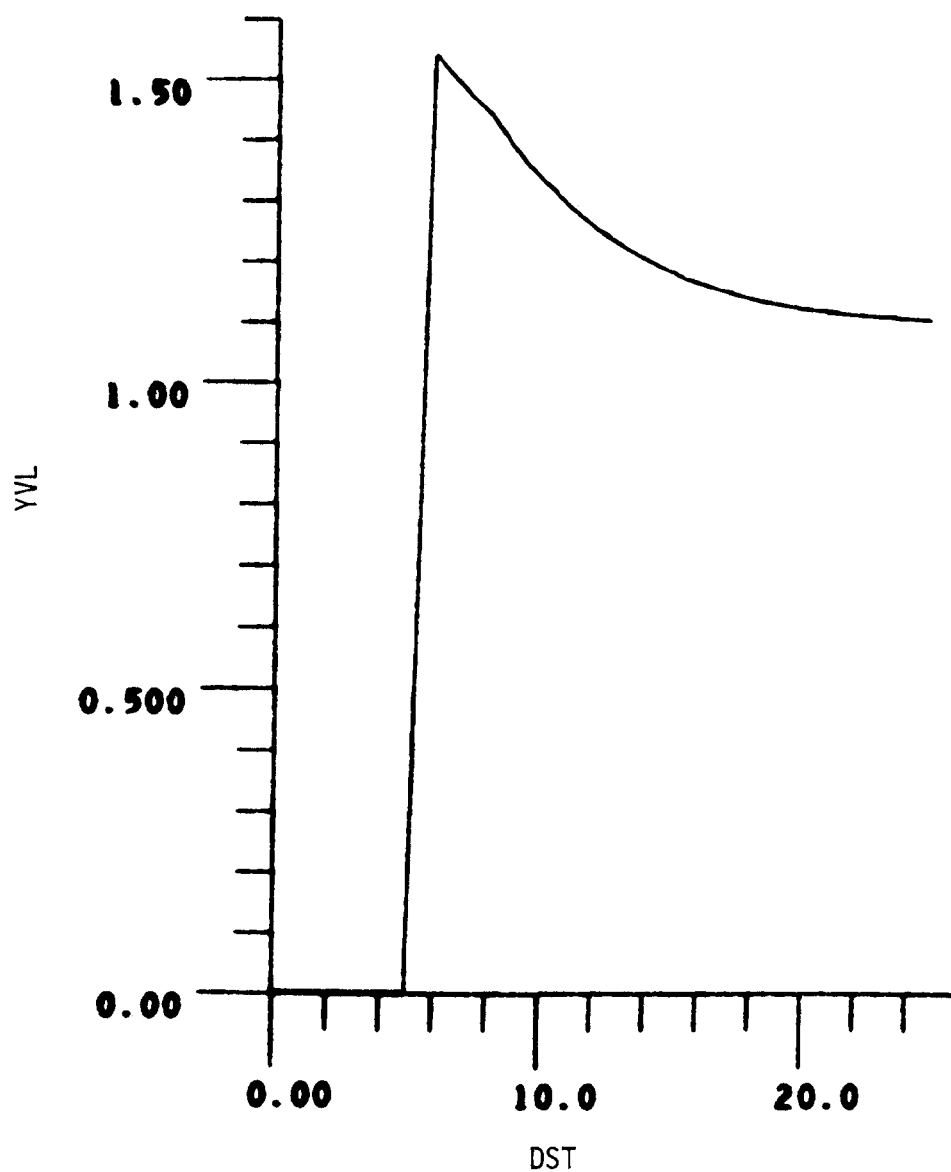


Figure 8.14. Snapshot of row 15 at cycle 19, time = 1.0850 for the calculation of flow over a planar obstacle with rectangular cross section.

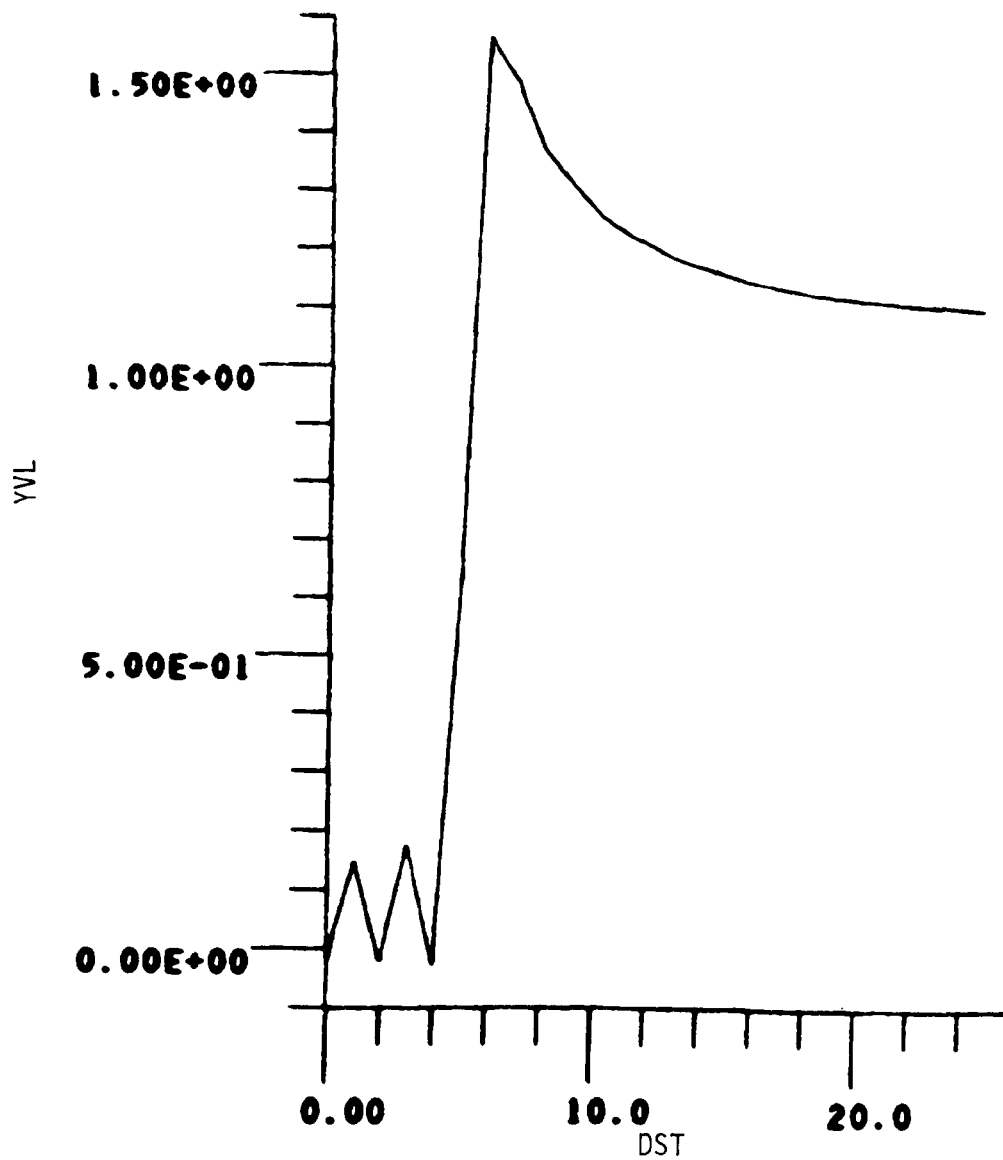


Figure 8.15. Snapshot of row 19 at cycle 19, time = 1.0850 for the calculation of flow over a planar obstacle with rectangular cross section.

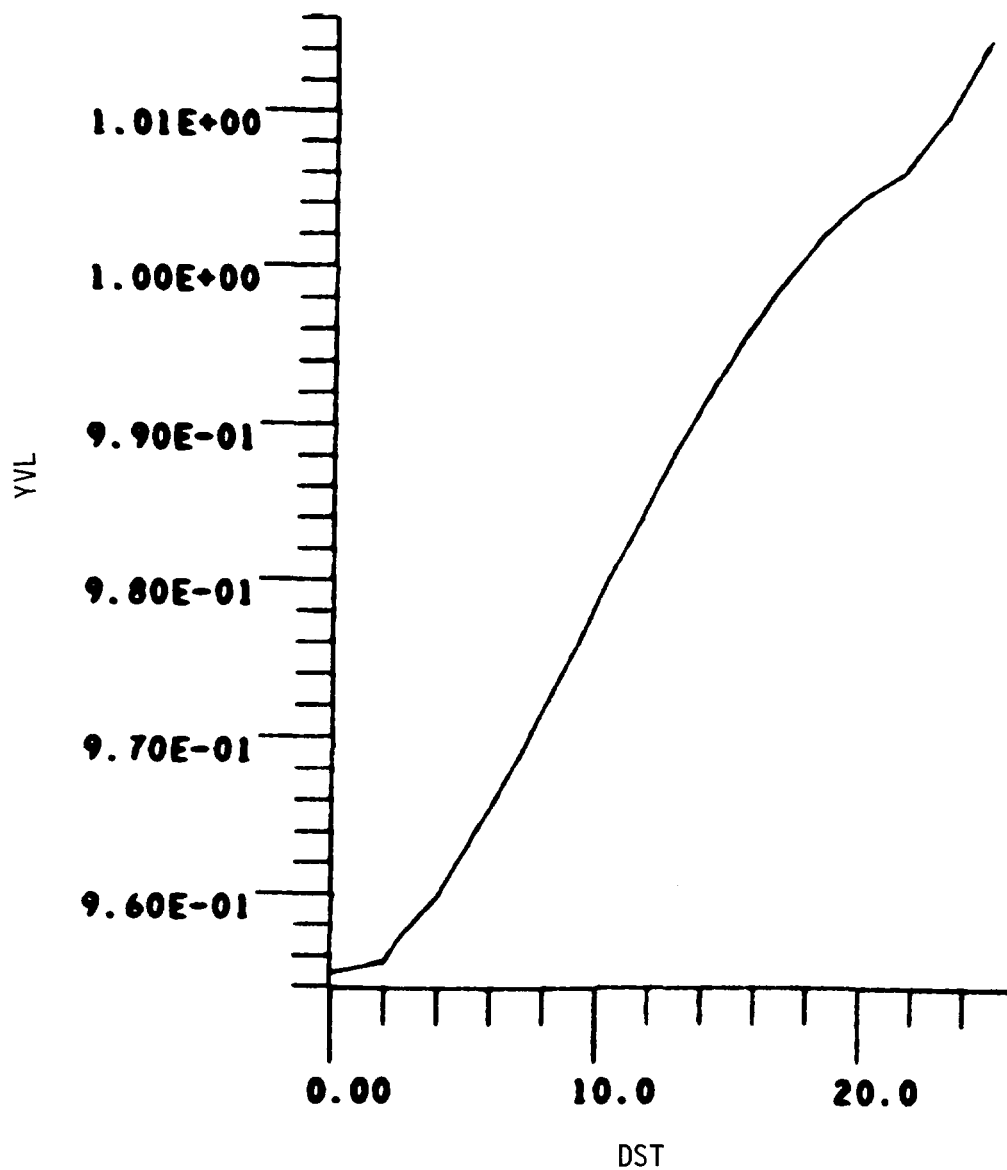


Figure 8.16. Snapshot of row 35 at cycle 19, time = 1.0850 for the calculation of flow over a planar obstacle with rectangular cross section.

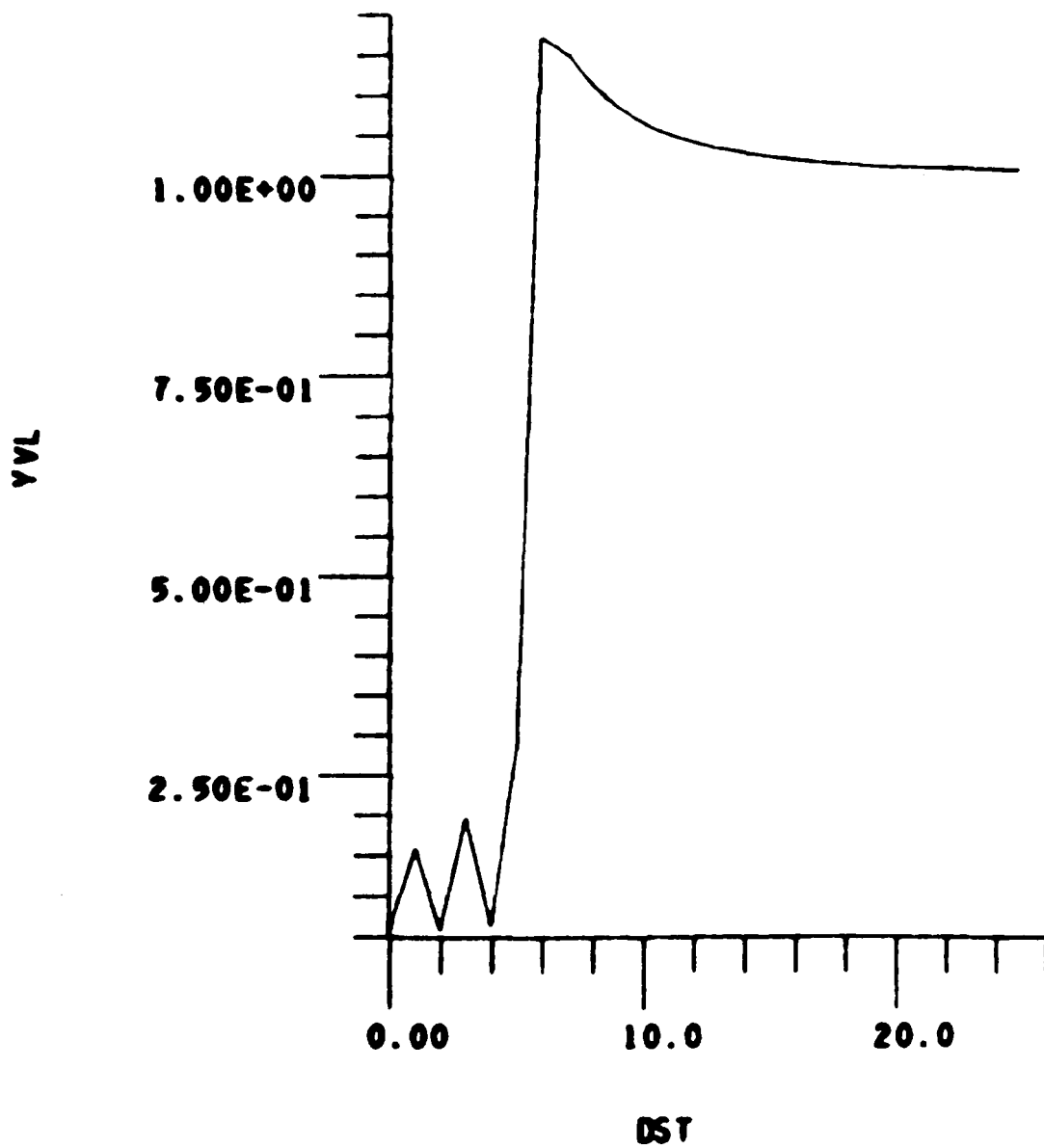


Figure 8.17. Snapshot of row 12 at cycle 19, time = 1.0850 for the calculation of flow over a cylindrical obstacle with rectangular cross section.

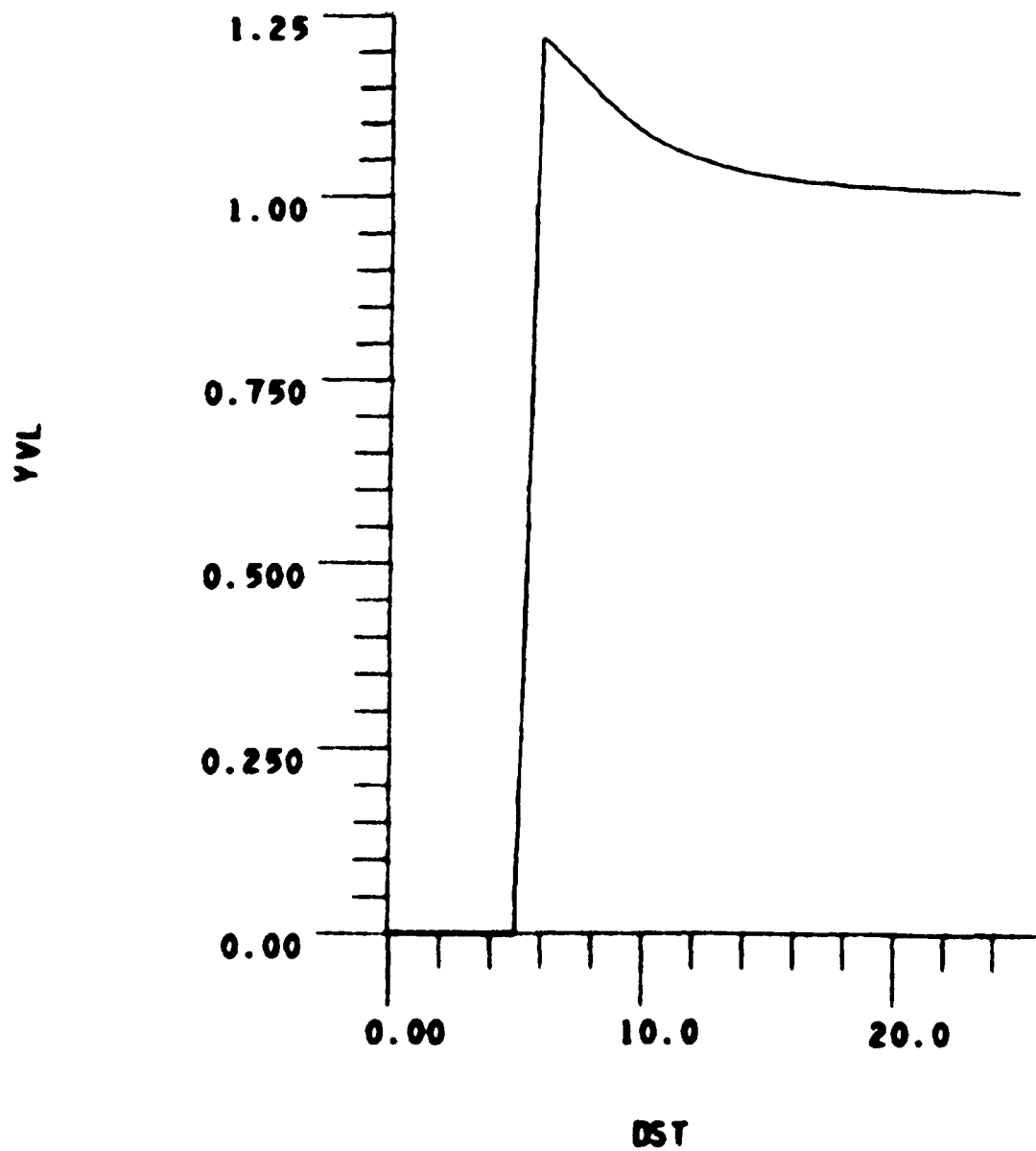


Figure 8.18. Snapshot of row 15 at cycle 19, time = 1.0850 for the calculation of flow over a cylindrical obstacle with rectangular cross section.

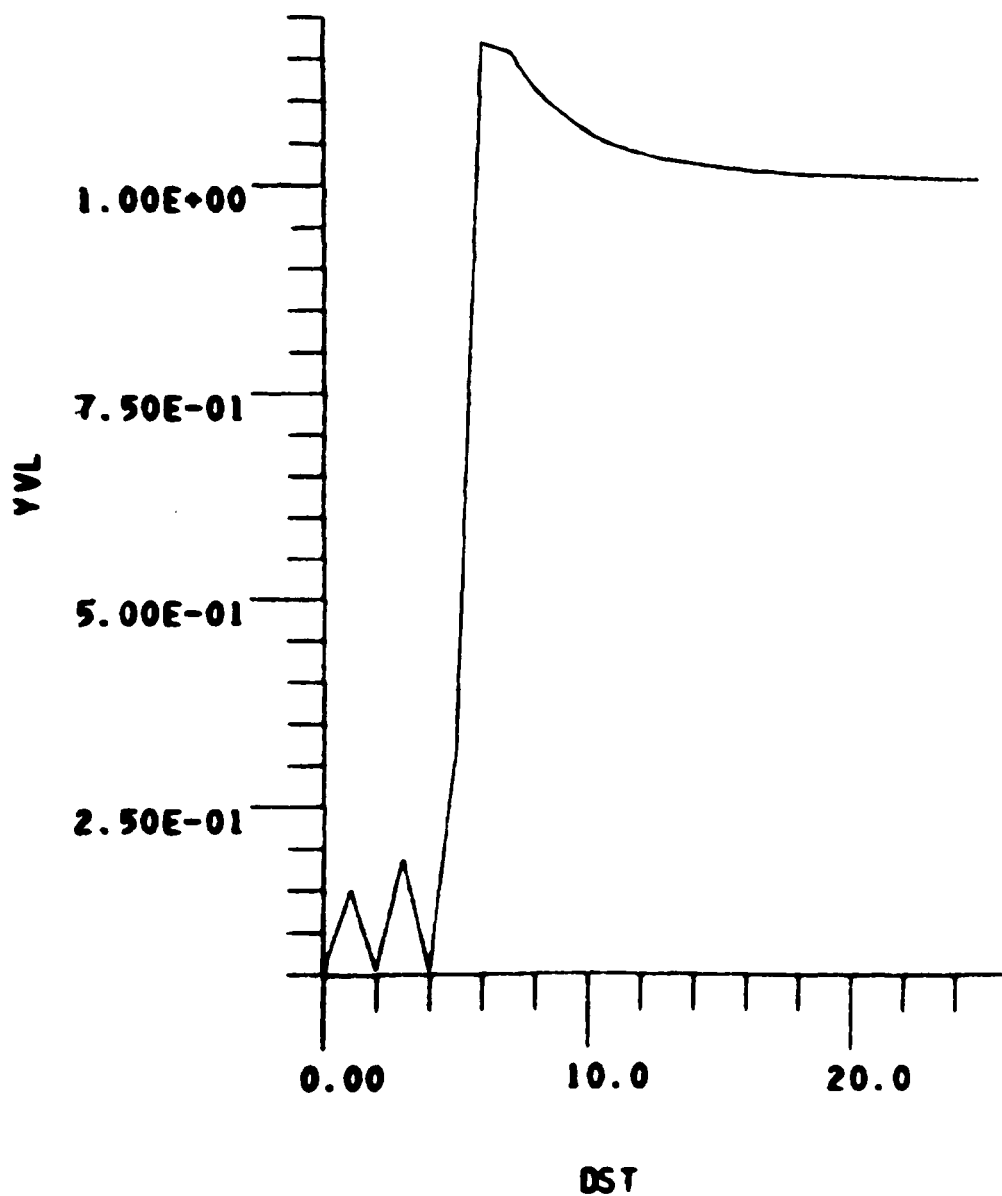


Figure 8.19. Snapshot of row 19 at cycle 19, time = 1.0850 for the calculation of flow over a cylindrical obstacle with rectangular cross section.

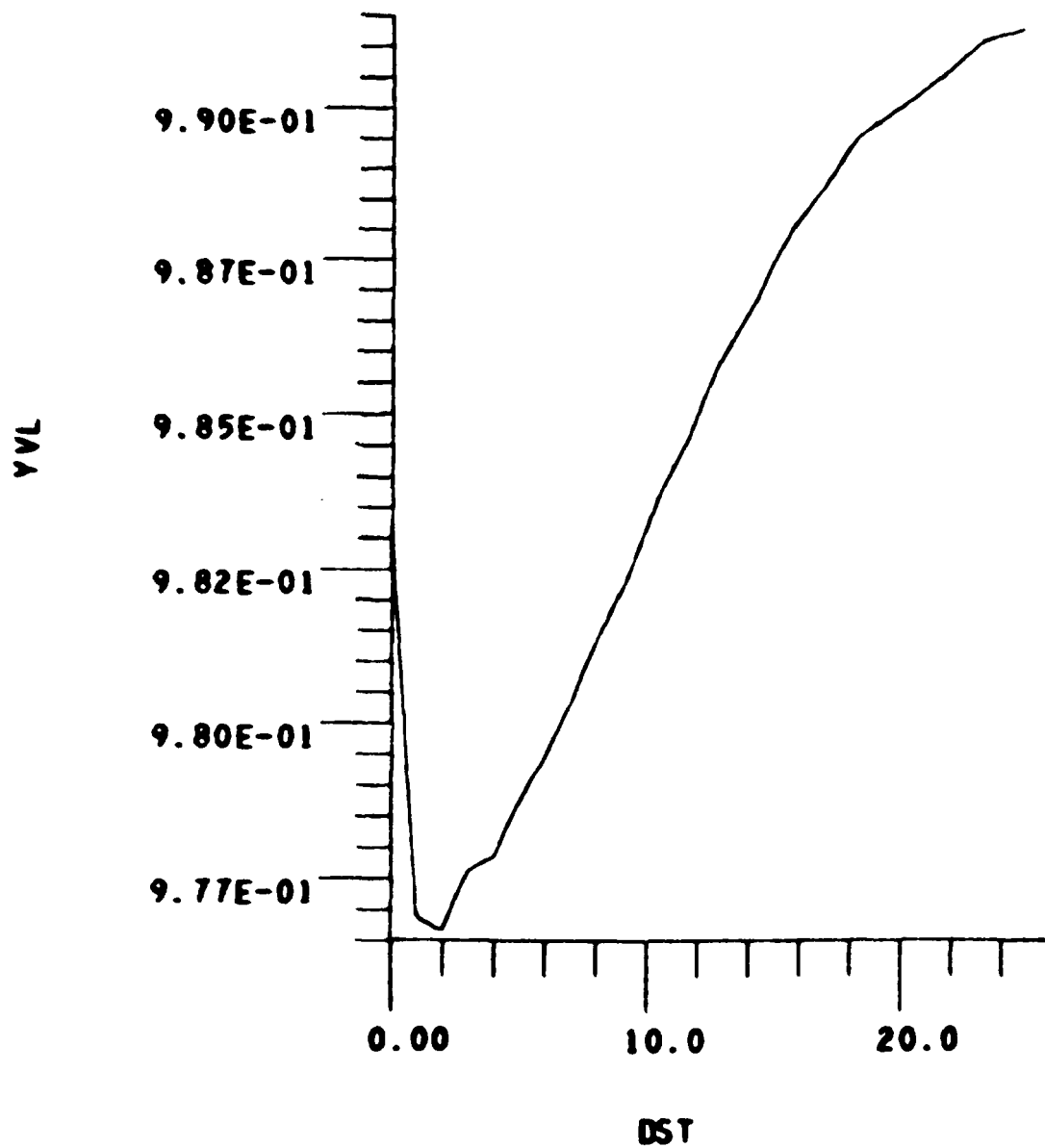


Figure 8.20. Snapshot of row 35 at cycle 19, time = 1.0850 for the calculation of flow over a cylindrical obstacle with rectangular cross section.

TABLE 8.6

DATA DECK FOR CALCULATION OF FLOW OVER A PLANAR OBSTACLE
WITH A RECTANGULAR CROSS SECTION

FLOW OVER A PLANAR OBSTACLE WITH RECTANGULAR CROSS SECTION									
TTL									
PRB									
PRO	2.0								
SYM	1.0								
MIN						0.25			
GRD	1.0	1.0	21.	36.					
ITR	500.	.001	1.7						
ALE	2.0	1.0	1.0						
CPL	.25								
END									
NAT						2.0			
121 RDN	1.0	1.0							
END									
GPT					2.0		2.0		
211 ORIG	1.0	1.0	1.0	0.0			0.0		
212 WPT1	1.0	25.	-1.	2.0					
212 WPT2	2.0	25.	46.	3.0					
212 WPT3	3.0	0.0	46.	2.0					
212 WPT4	4.0	0.0	-1.	3.0					
221 BLK1	1.0	1.0	6.0	1.0			13.		
221 BLK2	2.0	6.0	21.	1.0			13.		
221 BLK3	3.0	1.0	6.0	13.			18.		
221 BLK4	4.0	6.0	21.	13.			18.		
221 BLK5	5.0	1.0	6.0	18.			36.		
221 BLK6	6.0	6.0	21.	18.			36.		
247 BLK1	1.0	0.0	5.0	0.0		1.0	.9618		
247 BLK2	2.0	5.0	20.	0.0		1.039846	.9618		
247 BLK3	3.0	0.0	5.0	15.		1.0	1.0		
247 BLK4	4.0	5.0	20.	15.		1.039846	1.0		
247 BLK5	5.0	0.0	5.0	20.		1.0	1.0372907		
247 BLK6	6.0	5.0	20.	20.		1.039846	1.0372907		
END									
ZON									2.0
311 BLK1	1.0	1.0	21.	1.0			12.		
311 BLK2	2.0	1.0	6.0	12.			18.		
311 BLK3	3.0	6.0	21.	12.			18.		
311 BLK4	4.0	1.0	21.	18.			36.		
321 MPN	1.0	1.0							
321 MPN	2.0	1.0							
321 MPN	3.0	1.0							
321 MPN	4.0	1.0							
322 RLV	1.0	1.0							
322 RLV	2.0	1.0							
322 RLV	3.0	1.0							
322 RLV	4.0	1.0							
331 YVL	1.0	0.0	1.0						
331 YVL	3.0	0.0	1.0						
331 YVL	4.0	0.0	1.0						
END									

(Continued on next page)

TABLE 8.6 (continued)

BDY					2.0
411 BLC	1.0	1.0	2.0	1.0	1.0
411 BOT	2.0	1.0	1.0	21.	1.0
411 RHT	3.0	21.	1.0	21.	35.
411 TRC	4.0	21.	35.	21.	36.
411 TOP	5.0	21.	36.	1.0	36.
411 LFTT	6.0	1.0	36.	1.0	19.
411 LFTC	7.0	1.0	19.	1.0	13.
411 LFTB	8.0	1.0	13.	1.0	2.0
411 OBS	9.0	1.0	13.	6.0	13.
411 OBS	10.	6.0	13.	6.0	18.
411 OBS	11.	6.0	18.	1.0	18.
412 BLC	1.0	1.0	4.0	5.0	1.0
412 BOT	2.0	1.0	4.0	5.0	1.0
412 RHT	3.0	1.0	6.0	5.0	2.0
412 TRC	4.0	1.0	9.0	5.0	
412 TOP	5.0	1.0	9.0	5.0	
412 LFTT	6.0	1.0	6.0	5.0	4.0
412 LFTC	7.0	1.0	5.0	5.0	
412 LFTB	8.0	1.0	6.0	5.0	4.0
412 OBS	9.0	1.0	5.0	5.0	
412 OBS	10.	1.0	5.0	5.0	
412 OBS	11.	1.0	5.0	5.0	
422 MM8D	1.0	1.0			
441 XVFNC	1.0	1.0		10000.	
442 XVB	1.0	0.0			
443 YVFNC	1.0	1.0		10000.	
444 YVB	1.0	1.0			
481 WLRHT	1.0	1.0	2.0		
481 WLLFT	2.0	3.0	4.0		
482 WLRHT	1.0	1.0	5.0	5.0	
482 WLLFT	2.0	1.0	5.0	5.0	
END					
TIM					2.0
511 DTSOR	.01				
512 DTLIM	.001	0.1			
521 MXT/C	2.0	100.			
END					
EDT					2.0
616 PLTCY	2.0				
621 PRTEd	1.0	0.0	0.5	.25	
621 PRTEd	2.0	0.5	5.0	0.5	
622 PRTLH	1.0	21.	1.0	36.	
623 XPN	1.0	11.			
623 YPN	2.0	14.			
623 XVL	3.0	12.			
623 YVL	4.0	15.			
623 PRH	5.0	64.			
623 RLV	6.0	42.			
623 VSR	7.0	45.			
623 ZMS	8.0	47.			
624 NDMF	2.0				
631 RSEDt	1.0	0.0	0.5	.25	
631 RSEDt	2.0	0.5	5.0	0.5	
632 RGLIM	1.0	1.0	21.	1.0	36.

(Continued on next page)

TABLE 8.6 (continued)

671	PLTHS	1.0	0.0	100.	2.0			
674	HIST	1.0	1.0	64.	1.0	2013.		
674	HIST	2.0	1.0	64.	1.0	7016.		
674	HIST	3.0	1.0	64.	1.0	2019.		
674	SNAP	4.0	2.0	15.	11.		0.5	12.
674	SNAP	5.0	2.0	15.	11.		0.5	15.
674	SNAP	6.0	2.0	15.	11.		0.5	19.
674	SNAP	7.0	2.0	15.	11.		0.5	35.
674	SNAP	8.0	2.0	15.	11.		1.0	12.
674	SNAP	9.0	2.0	15.	11.		1.0	15.
674	SNAP	10.	2.0	15.	11.		1.0	19.
674	SNAP	11.	2.0	15.	11.		1.0	35.
675	CNTR	12.	4.0	64.			0.5	
675	VCTR	13.	5.0				0.5	
675	CNTR	14.	4.0	64.			1.0	
675	VCTR	15.	5.0				1.0	
675	CNTR	16.	4.0	64.			2.0	
675	VCTR	17.	5.0				2.0	
END								
END								

TABLE 8.7

MODIFICATIONS FOR CYLINDRICAL SYMMETRY

TTL	FLOW OVER A CYLINDRICAL OBSTACLE WITH RECTANGULAR CROSS SECTION
SYM	2.0

$$\dot{y} = A \cos \pi x/L \quad (8.4)$$

is initially applied at the interface; this causes an instability with wavelength $2L$ to grow. The heavier fluid moves downward into the lighter fluid in one region, forming what is known as the "spike", while in another region the lighter fluid moves upward, forming what is called the "bubble". Similar problems have been computed using an Eulerian particle-in-cell technique (Reference 12). Although differences in the way the problems were calculated (primarily zone size differences) prevent a direct comparison of the results, these other calculations do provide a good qualitative check on the results obtained here.

8.2.4.2 Problem Set-Up. The initial configuration for these calculations is shown in Figure 8.21. The width of the computational domain is 0.02 units, which is half the wavelength of the initial velocity perturbation (i.e., $L = 0.02$). This means the tip of the spike will move downward along the right boundary, while the center of the bubble will move upward on the left. The height of each fluid region is 0.03 units or $1.5L$; this is to keep these boundaries sufficiently far from the interface to minimize interference with the growth of the instability. All boundaries in the problem are free-slip walls. The symmetry is planar. The acceleration of gravity has a value $g_y = -1.0$ so that it acts downward.

The zones are geometrically graded in the y -direction to minimize the number of zones required while still maintaining accuracy near the interface. The zones immediately adjacent to the interface have dimensions 0.00133×0.00133 . In moving away from the interface, the zone width in the x -direction is kept constant while each subsequent Δy increases by about 5.5%. The total mesh consists of 16×31 grid points or 15×30 zones; the interface is at $J = 16$.

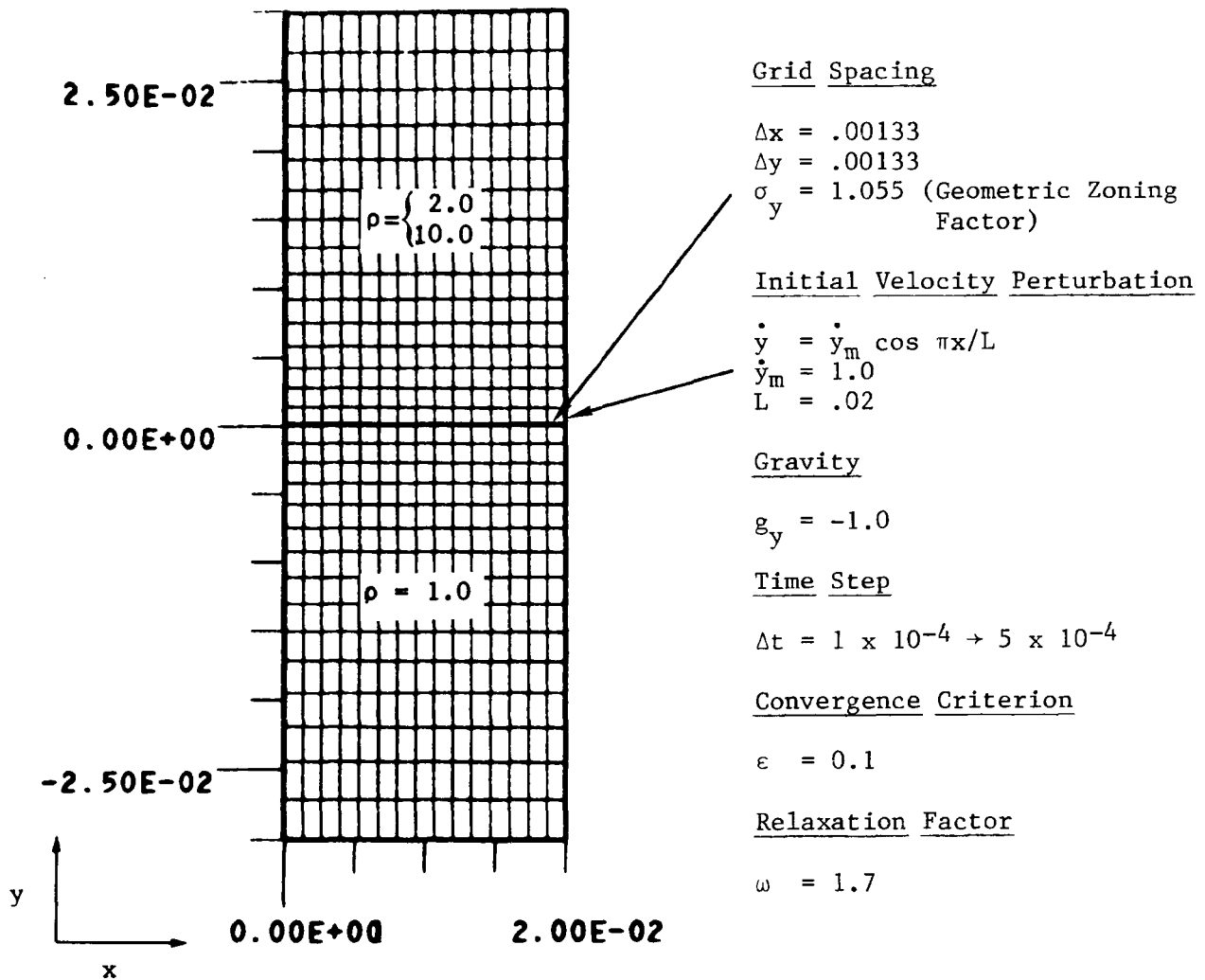


Figure 8.21. Initial configuration for Rayleigh-Taylor instability problem.

A Lagrangian mesh is used for these calculations in order to provide good resolution of the interface. Although an Eulerian mesh would be better able to handle the severe distortions that occur, the interface would become diffuse because of the numerical mass and momentum diffusion that is inherent in Eulerian methods. To handle the severe distortions while maintaining good resolution of the interface, the ALE method could be used. However, at the time these calculations were done, the mesh rezone options required for these calculations were not yet available.

The fluids in these problems are initially at rest with a hydrostatic pressure gradient in equilibrium with the force of gravity. An initial velocity perturbation with the form given by Eq.(8.4) is applied at the interface; the constants are given by

$$A = 1.0, \quad L = 0.2.$$

Since this initial velocity field does not satisfy the incompressibility condition, on the first cycle the code must calculate a modified velocity field such that $\nabla \cdot \underline{v} = 0$. According to Reference 12, it can be shown that this new velocity field is

$$\dot{x} = \frac{\pi A \Delta y}{2L} \sin\left(\frac{\pi x}{L}\right) \left[2H(y) - 1\right] \exp\left(\frac{-\pi|y|}{L}\right) \quad (8.5)$$

$$\dot{y} = \frac{\pi A \Delta y}{2L} \cos\left(\frac{\pi x}{L}\right) \exp\left(\frac{-\pi|y|}{L}\right) \quad (8.5)$$

where Δy is the mesh spacing in the y-direction, and $H(y)$ is the Heaviside function,

$$H(y) = \begin{cases} 1 & y > 0, \\ 0 & y < 0. \end{cases}$$

This motion is a rotation, as opposed to the shearing motion produced by the original initial conditions. Momentum and vorticity are conserved in the transformation, however. Figure 8.22 shows the velocity field obtained by the code on the first cycle. This calculated initial velocity field seems to agree well with the above equations taken from Reference 12. was based on numerical stability considerations.*

The time step for these calculations was chosen to be 5×10^{-4} . The maximum initial velocity is given by the coefficient of the sine and cosine in Eq.(8.5), i.e.,

$$\dot{y}_{\max} = \frac{\pi A \Delta y}{2L} = 0.1$$

As the Rayleigh-Taylor instability grows, the velocity of the spike tip is expected to increase somewhat, but probably by not more than a factor of 2.** The initial zone width is 0.00133. Since this is a Lagrangian calculation, we expect the zone width to decrease as the mesh distorts. The compression of the zone width is expected to be the greatest near the spike tip where we estimated it might be as much as a factor of 10. With these assumptions, which we hoped were conservative, the stable time step is calculated to be 5×10^{-4} . This is based on the criterion that the fluid cannot move more than a zone width in a time step. As it turns out, these assumptions were not quite conservative enough for the 10:1 density ratio case. This will be discussed in the next section.

*This problem was run before the automatic time step calculation was incorporated into these codes. With that feature only a stable initial time step needs to be calculated. Therefore the considerations of the evolution of the maximum fluid velocity and minimum zone size that needed to be made here are no longer relevant since they are accounted for automatically.

**Based on results reported in Reference 12.

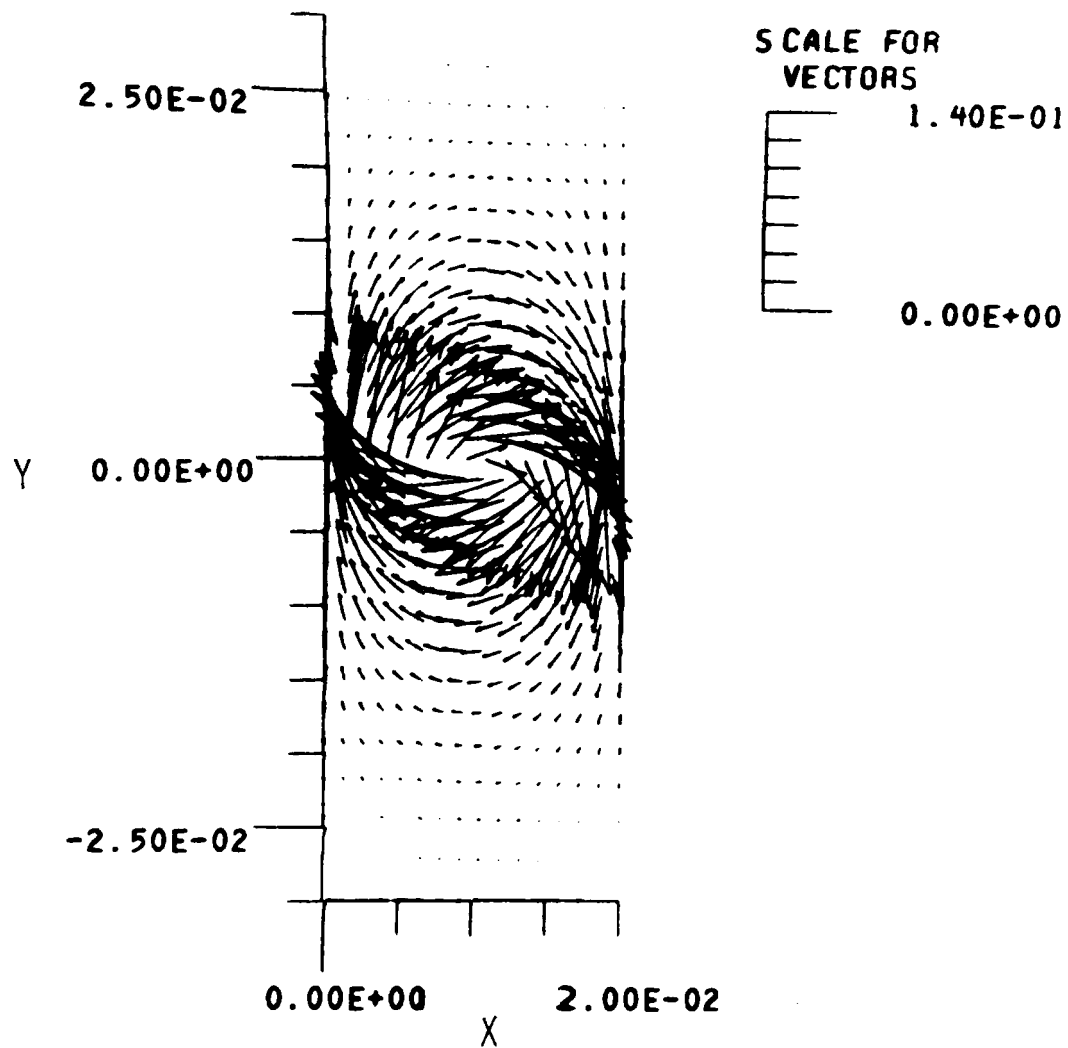


Figure 8.22. Velocity vector plot at cycle 1, time = 0.000100 for the Rayleigh-Taylor instability calculation.

As we said earlier, the initial conditions do not satisfy $\nabla \cdot \underline{y} = 0$. This means that these initial conditions do not provide a good first guess for the solution to be obtained in the first cycle. Therefore, a small time step is required initially for the iteration to converge to the proper solution. The initial time step was chosen to be 1×10^{-4} ; this was allowed to grow by 20% per cycle until the final time step of 5×10^{-4} was reached at cycle 10.

The convergence criterion was selected to be 0.1. This was obtained from Eq.(6.4) by estimating a typical velocity gradient, $\frac{\partial v}{\partial x}$, for the problem. An approximate value of $\frac{\partial v}{\partial x}$ can be obtained from the solution reached in the first cycle and expressed in Eqs.(8.5). The y-velocity in this solution has a maximum ($\dot{y}_m = 0.105$) at the side boundaries and is zero in the middle of the grid. Conversely, the x-velocity has a maximum with the same magnitude in the middle of the mesh and is zero at the sides. In both cases, a typical gradient is

$$\frac{\partial v}{\partial x} \sim \frac{V_{\max} (=0.1)}{\frac{1}{2} L (=0.01)} = 10.$$

Using this value, Eq.(6.4) gives $\epsilon = 0.1$.

The relaxation parameter was chosen to be $\omega = 1.7$. Although this results in a large number of iterations initially, it seems to provide a good rate of convergence throughout most of the calculation.

8.2.4.3 Results. Figures 8.23 - 8.28 show the calculated mesh configuration at various times for the 2:1 density ratio. The arrows indicate the location of the spike and bubble tips. The Lagrangian mesh has become severely distorted by the end of the calculation at $t = 0.15$. Although the zone width in several regions, particularly near the spike tip, appears to be smaller than 1/10 of the initial width (the value assumed in the last section in selecting the time step), zones have not started turning inside out and the calculation appears to be stable.

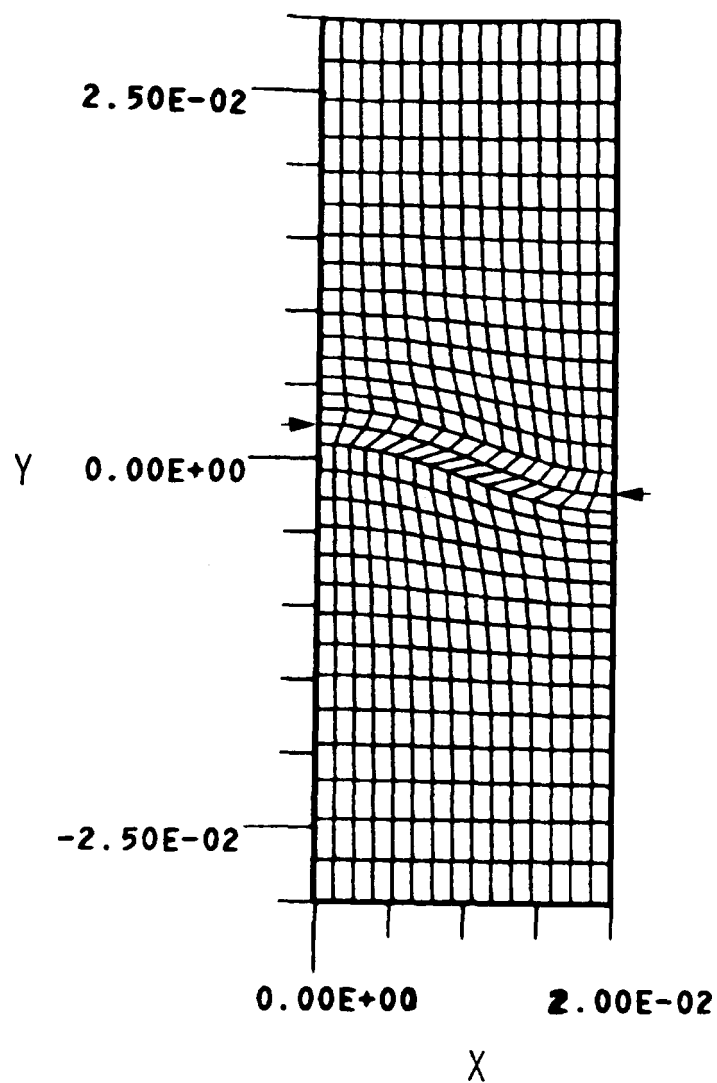


Figure 8.23. Mesh configuration at cycle 55, time = 0.025079 for the Rayleigh-Taylor instability calculation with a density ratio of 2:1.

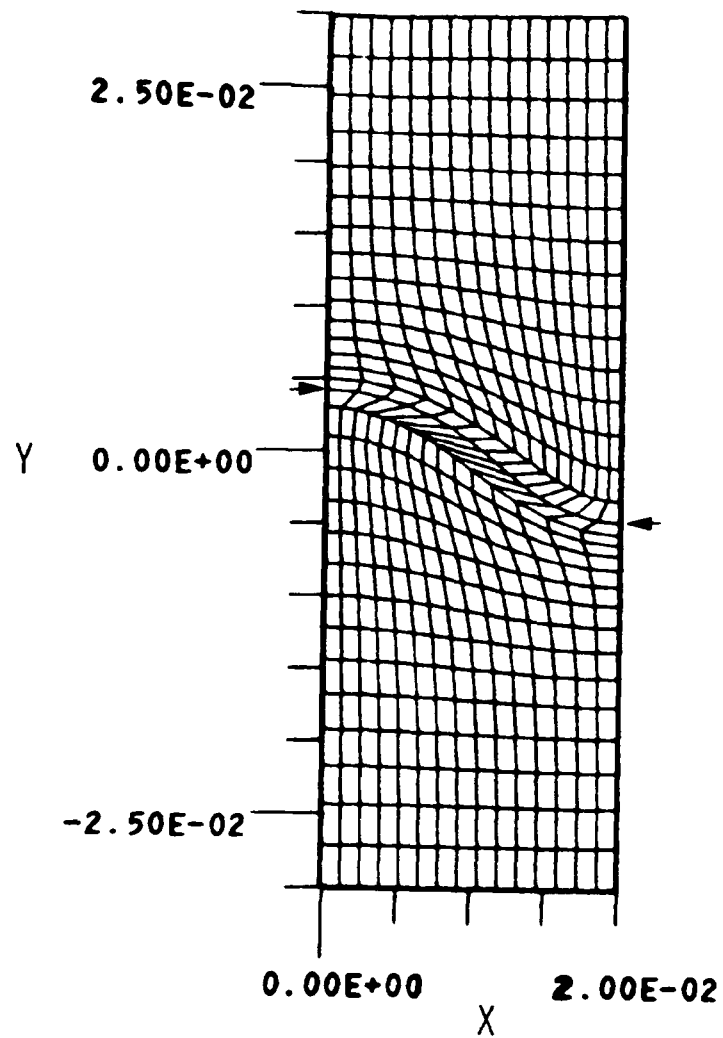


Figure 8.24. Mesh configuration at cycle 105, time = 0.050079 for the Rayleigh-Taylor instability calculation with a density ratio of 2:1.

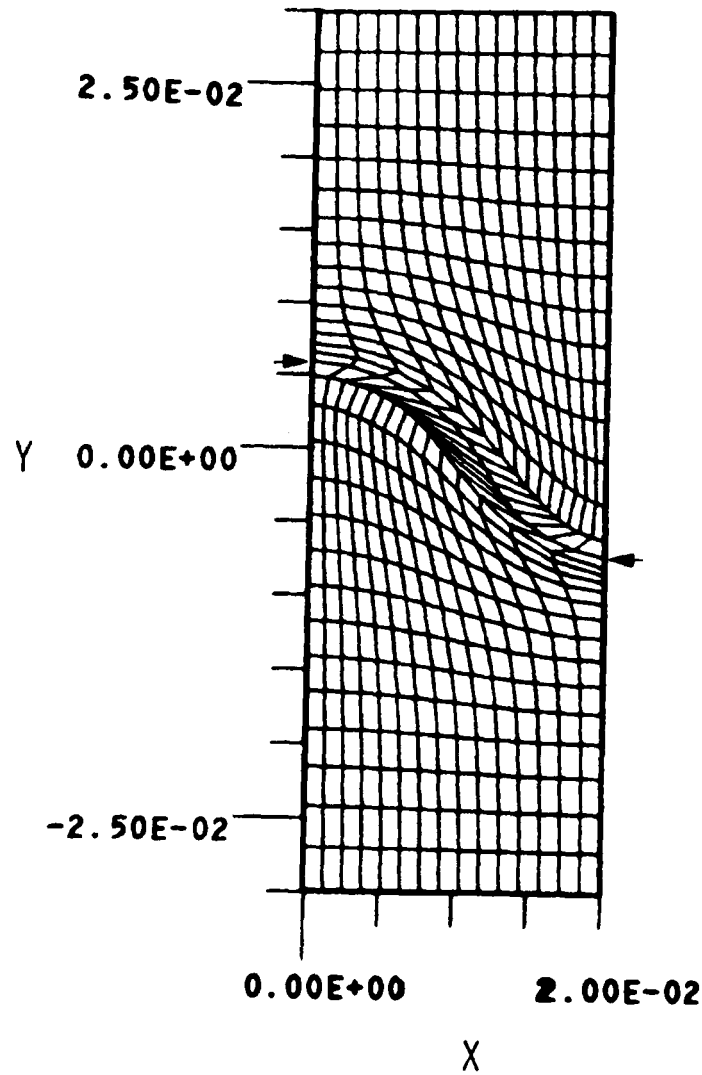


Figure 8.25. Mesh configuration at cycle 155, time = 0.075079 for the Rayleigh-Taylor instability calculation with a density ratio of 2:1.

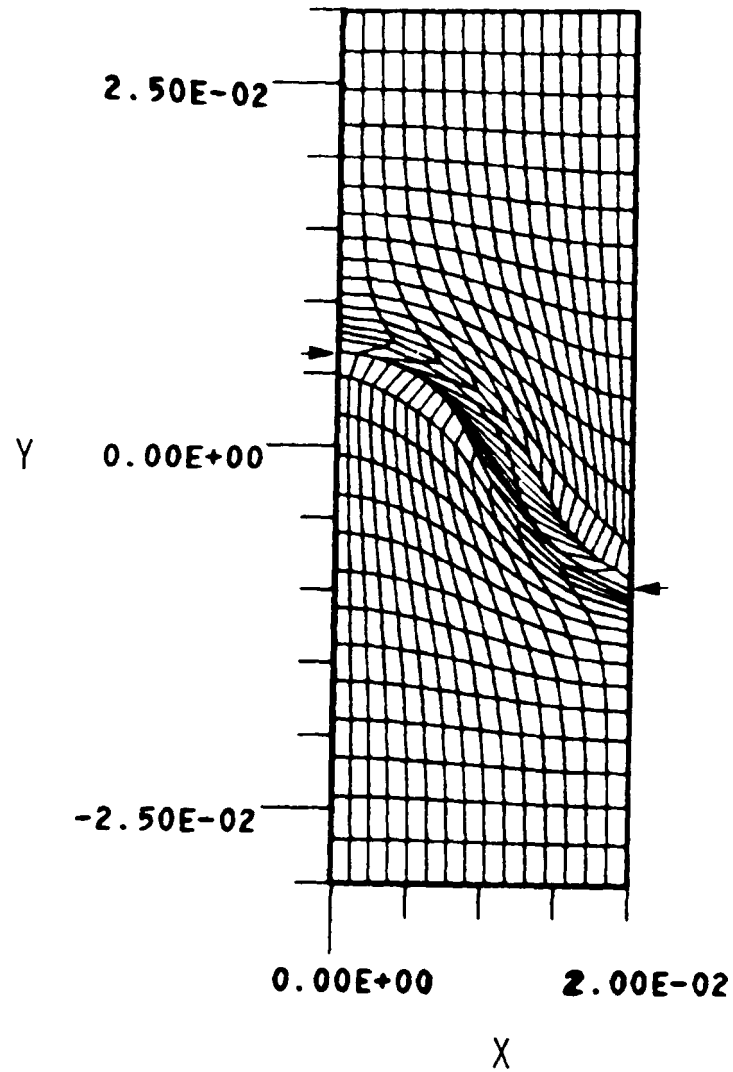


Figure 8.26. Mesh configuration at cycle 205, time = 0.10008 for the Rayleigh-Taylor instability calculation with a density ratio of 2:1.

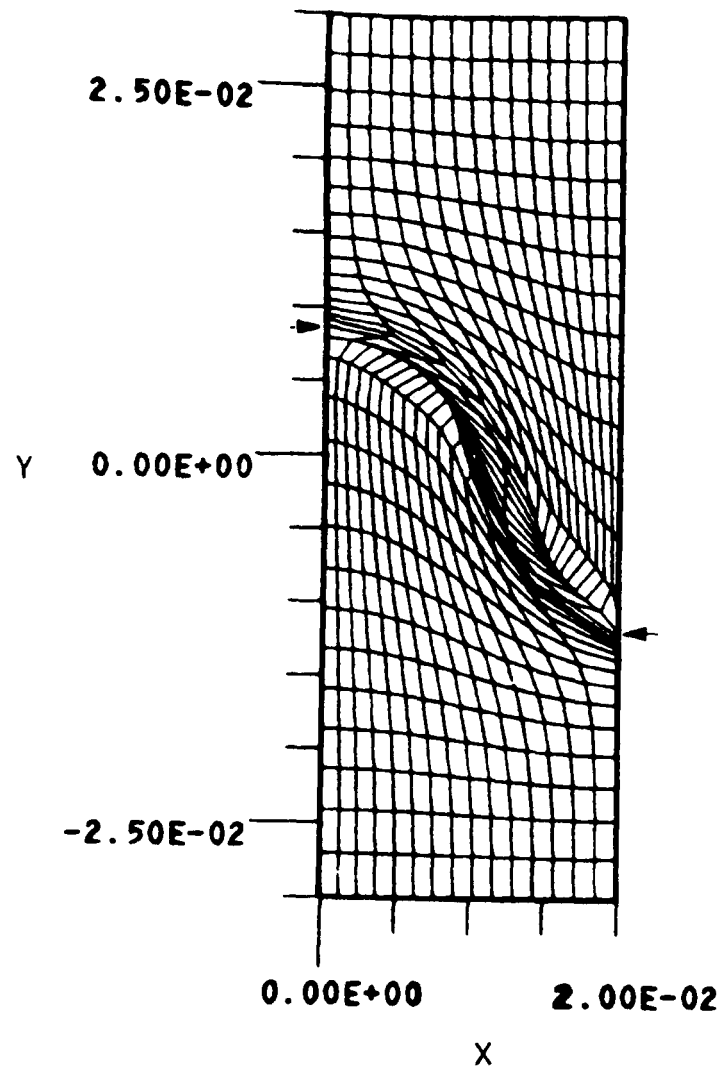


Figure 8.27. Mesh configuration at cycle 255, time ≈ 0.12508 for the Rayleigh-Taylor instability calculation with a density ratio of 2:1.

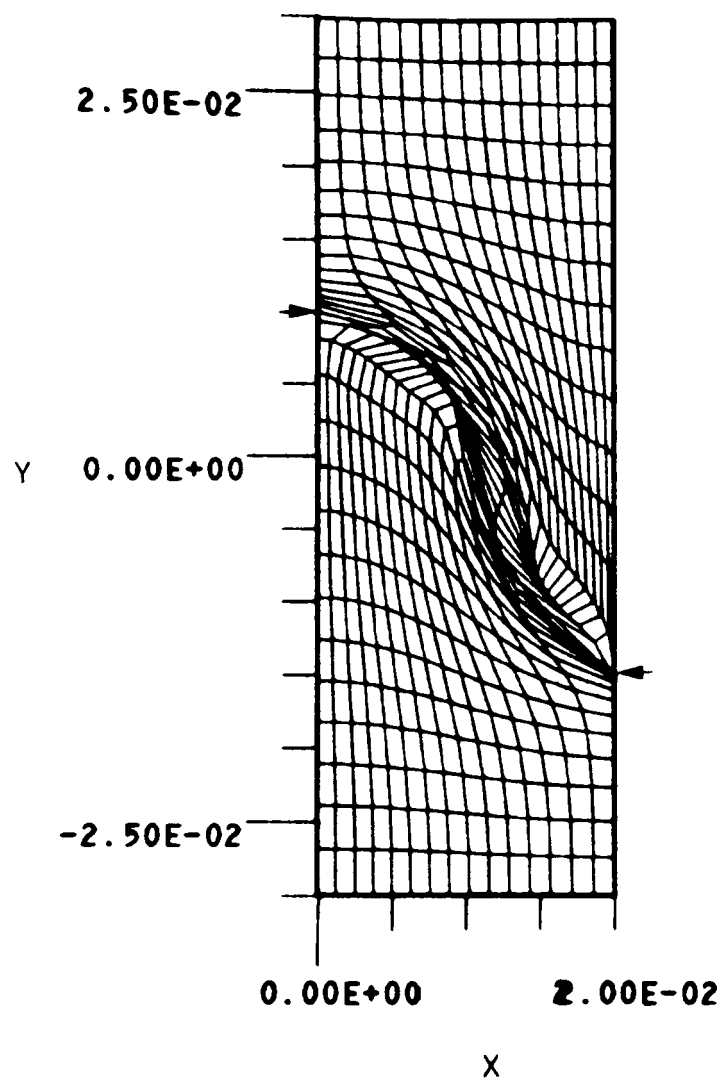


Figure 8.28. Mesh configuration at cycle 305, time = 1.15008 for the Rayleigh-Taylor instability calculation with a density ratio of 2:1.

Because it is difficult to identify the shape of the interface from the mesh plots, a separate plot of the interface configuration at several times is provided in Figure 8.29.

Figures 8.30 - 8.33 show the calculated mesh configuration for the 10:1 density ratio. In this case, the mesh has become distorted enough near the spike tip that several zones on the right boundary have started to turn inside out.* This is evident at the spike tip at $t = 0.75$ and shows more clearly at $t = 0.100$. This instability seems to be localized and, i.e., no anomalous velocities or zone deformations appear in the rest of the mesh. Fortunately, it does not appear that the instability has grown enough to affect the rest of the solution up to the time at which the problem was terminated. Therefore, although the instability affects the calculation of that point on the interface that lies on the right boundary, the spike tip location can be estimated from the location of the rest of the interface. This is what was done in locating the arrow on the right side of Figures 8.32 and 8.33.

Figure 8.34 shows the configuration of the interface at several times for the 10:1 density ratio. Again, the location of the point on the right boundary was estimated for the last two times shown. We feel this introduces only a small error.

The velocity field at several times for the 2:1 density ratio and the 10:1 density ratio are provided in Figures 8.35 - 8.37 and Figures 8.38 - 8.40, respectively. Figure 8.41 shows the amplitude as a function of time of the spike and the bubble for both calculations.

*The automatic time step calculation, which was not available when this calculation was done, probably would have prevented this instability.

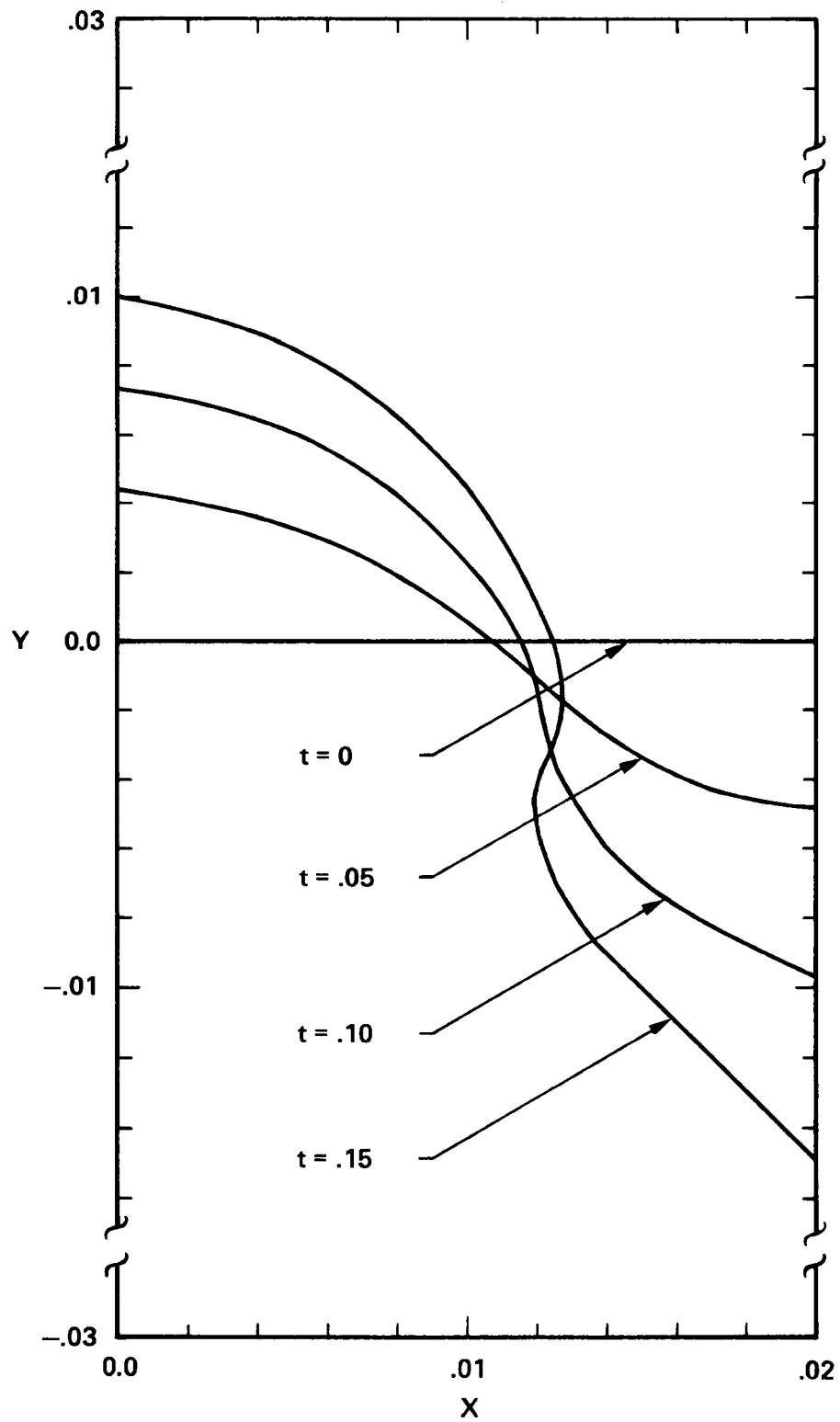


Figure 8.29. Interface configuration for the Rayleigh-Taylor instability calculation with a density ratio of 2:1.

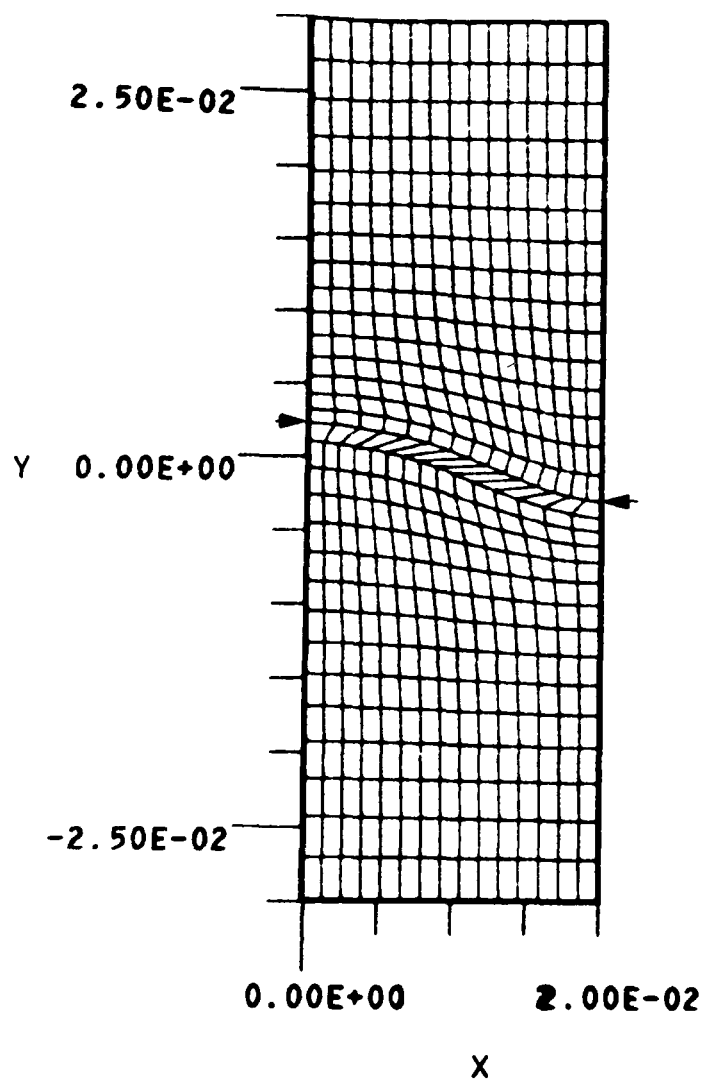


Figure 8.30. Mesh configuration at cycle 55, time = 0.025079 for the Rayleigh-Taylor instability calculation with a density ratio of 10:1.

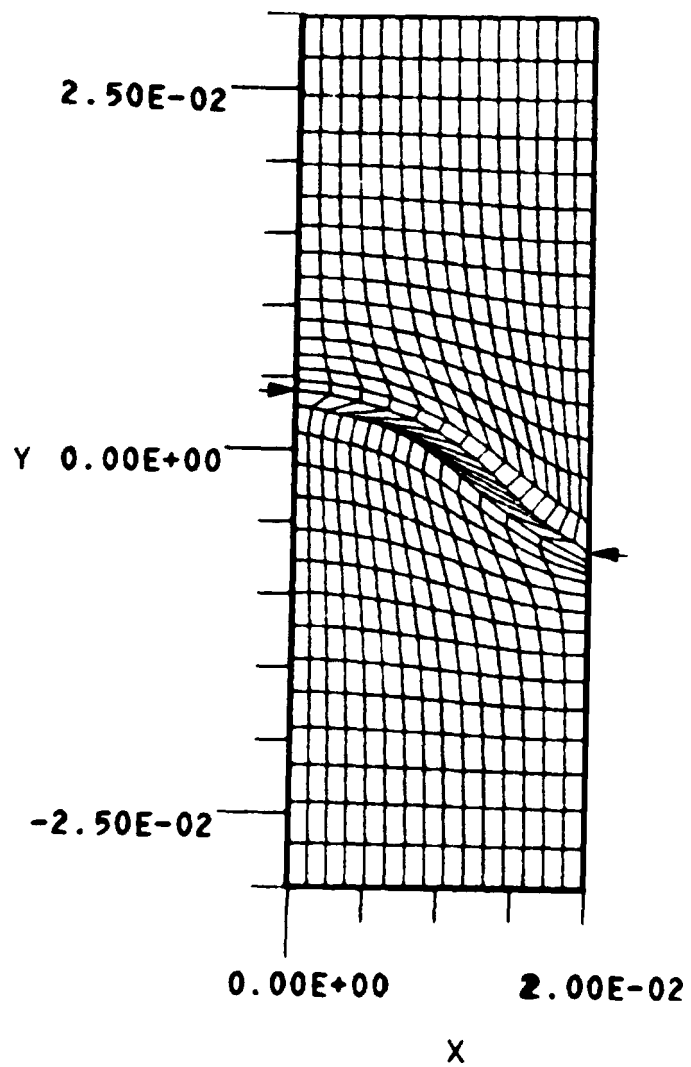


Figure 8.31. Mesh configuration at cycle 105, time = 0.050079 for the Rayleigh-Taylor instability calculation with a density ratio of 10:1.

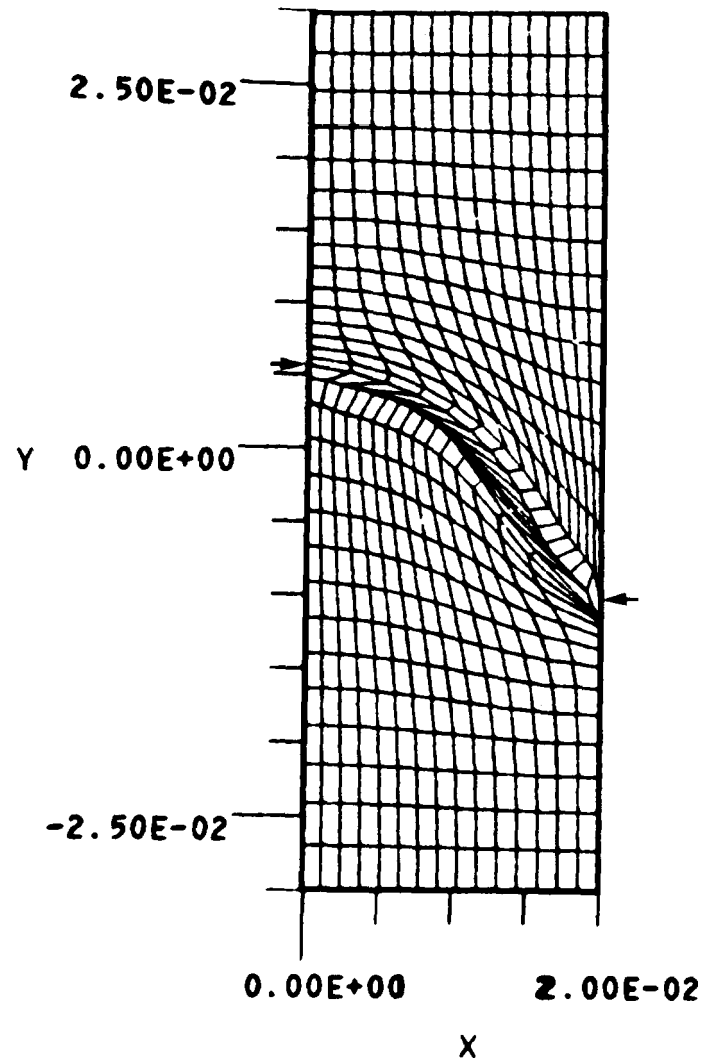


Figure 8.32. Mesh configuration at cycle 155, time = 0.075079 for the Rayleigh-Taylor instability calculation with a density ratio of 10:1.

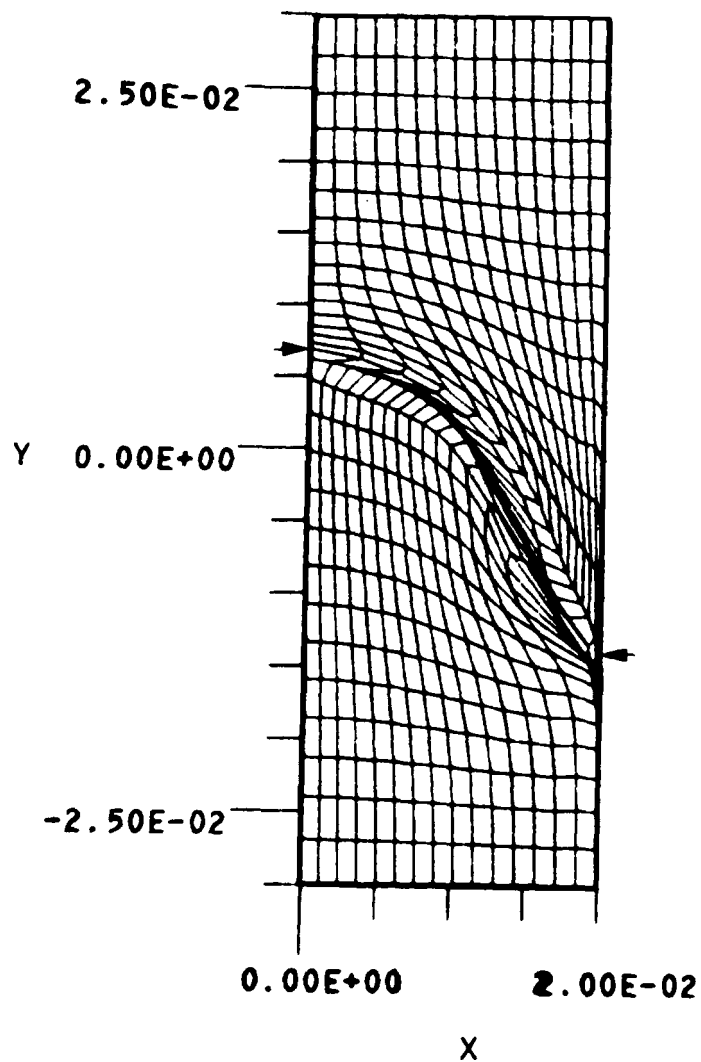


Figure 8.33. Mesh configuration at cycle 205, time = 0.10008 for the Rayleigh-Taylor instability calculation with a density ratio of 10:1.

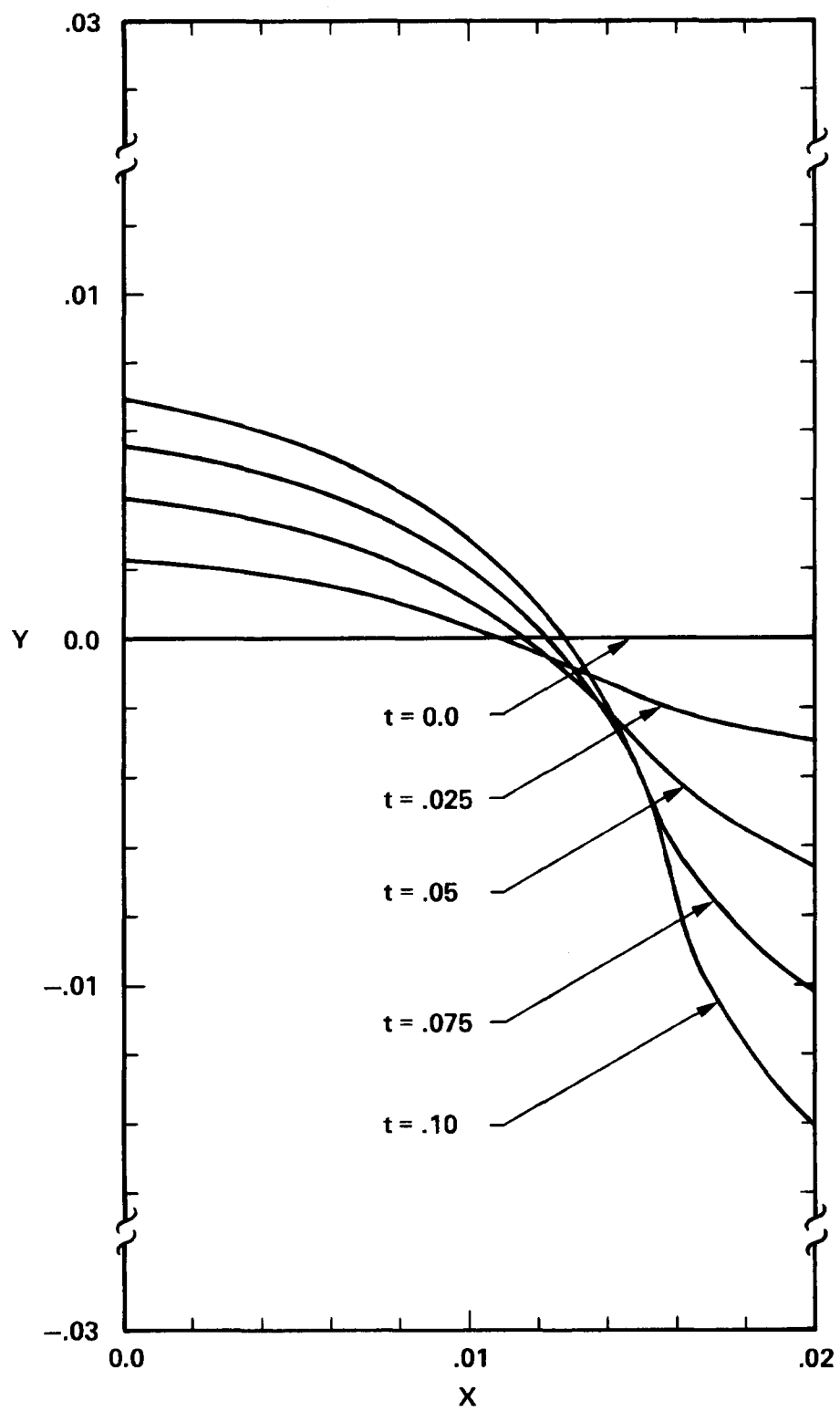


Figure 8.34. Interface configuration for 10:1 density ratio.

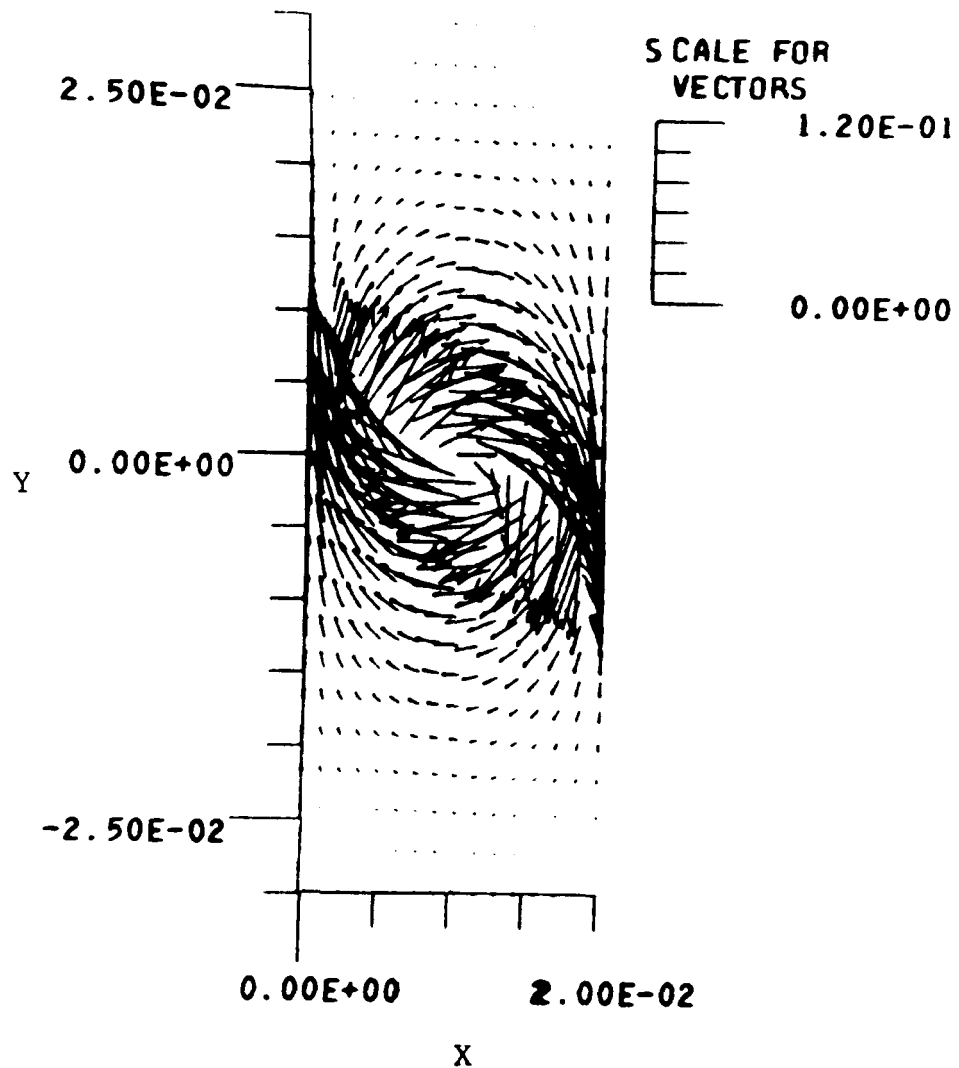


Figure 8.35. Velocity vector plot at cycle 55, time = 0.025079 for the Rayleigh-Taylor instability calculation with a density ratio of 2:1.

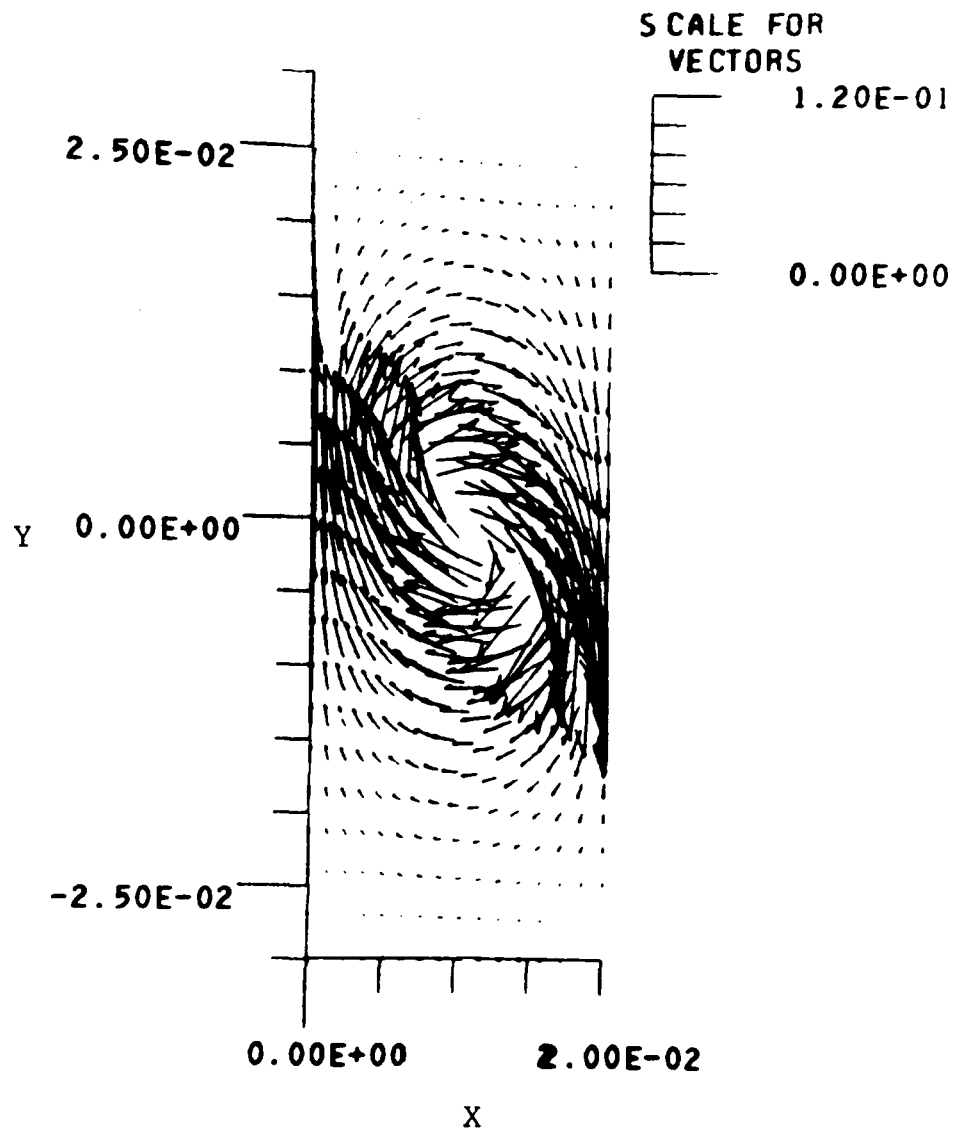


Figure 8.36. Velocity vector plot at cycle 155, time = 0.075079 for the Rayleigh-Taylor instability calculation with a density ratio of 2:1.

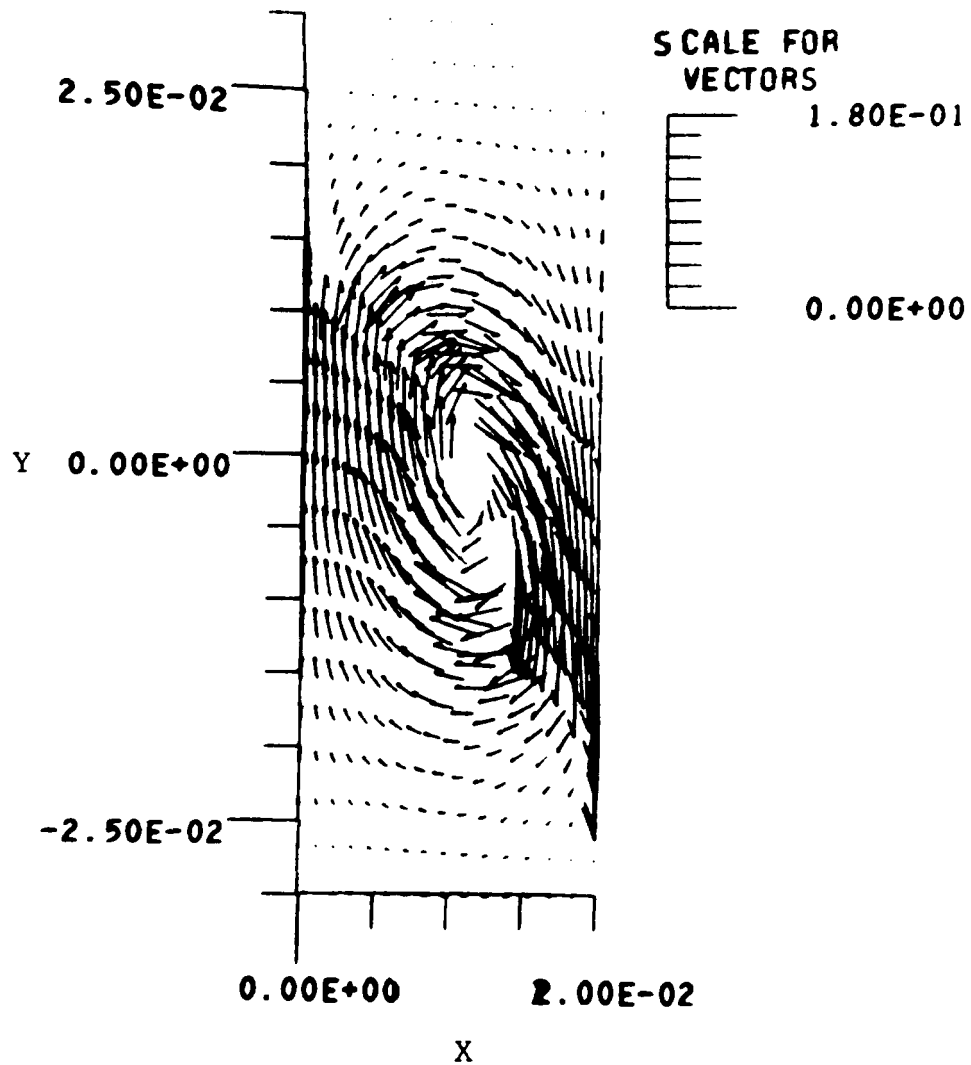


Figure 8.37. Velocity vector plot at cycle 305, time = 0.15008 for the Rayleigh-Taylor instability calculation with a density ratio of 2:1.

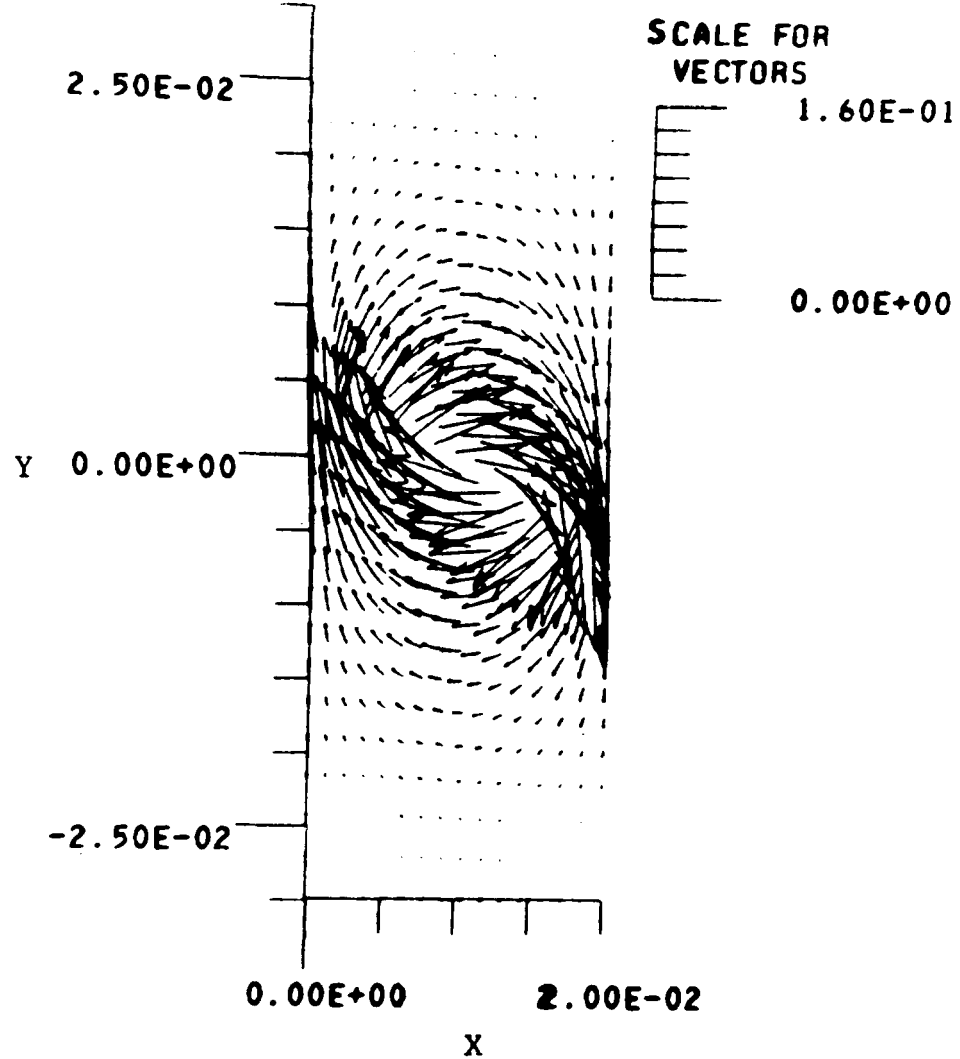


Figure 8.38. Velocity vector plot at cycle 55, time = 0.025079 for the Rayleigh-Taylor instability calculation with a density ratio of 10:1.

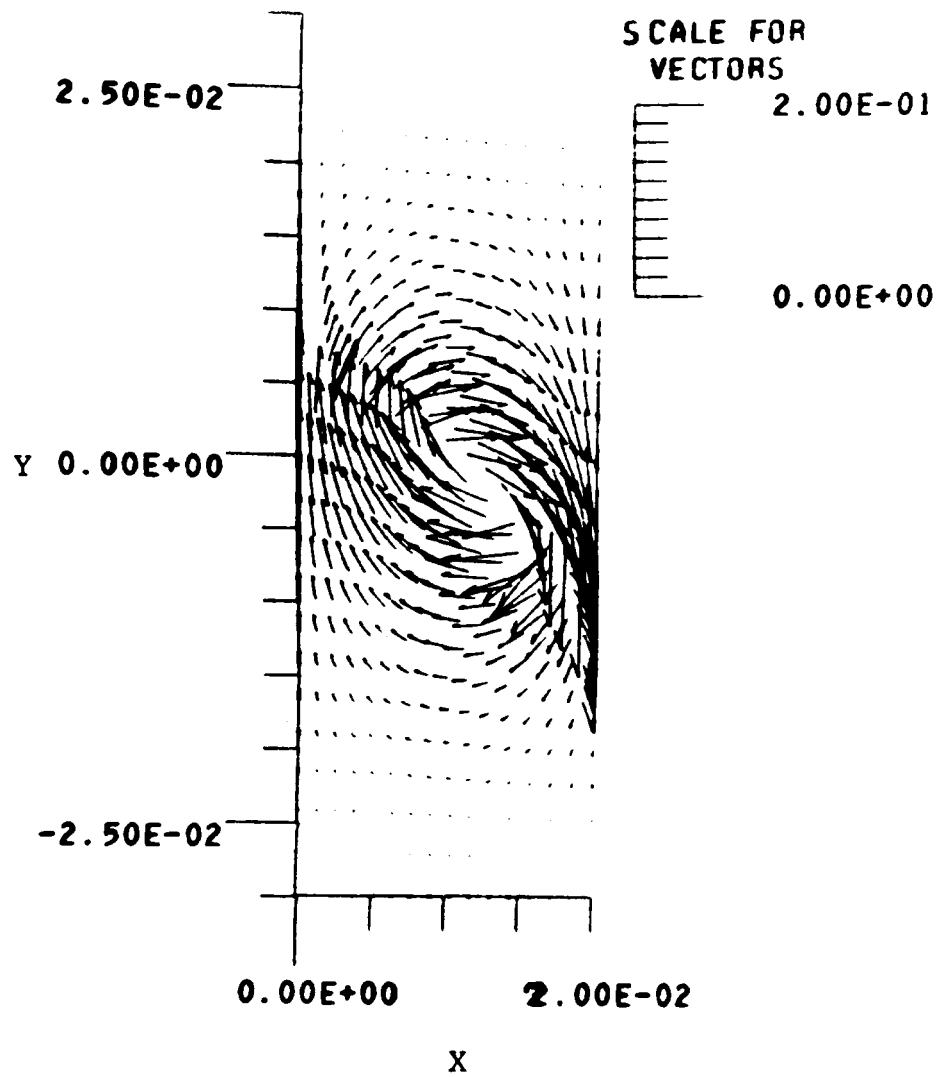


Figure 8.39. Velocity vector plot at cycle 105, time = 0.050079 for the Rayleigh-Taylor instability calculation with a density ratio of 10:1.

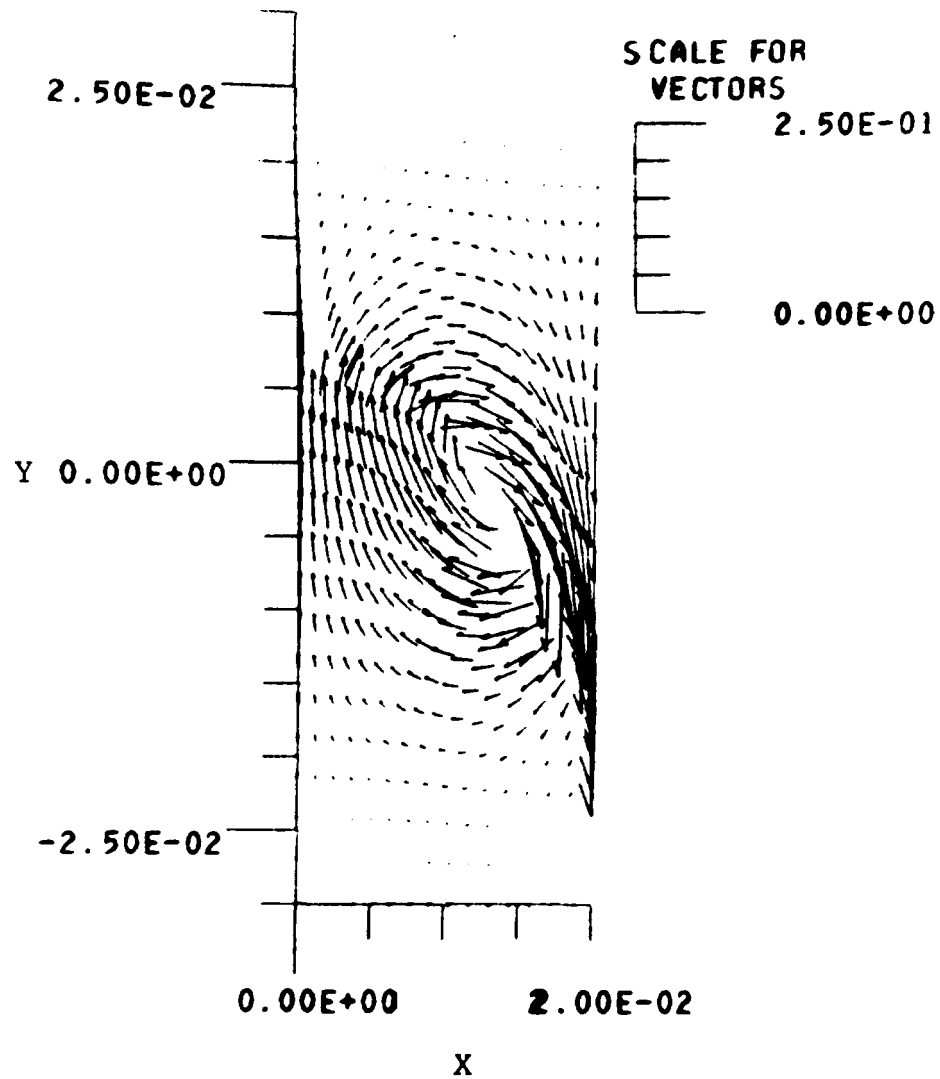


Figure 8.40. Velocity vector plot at cycle 155, time = 0.075079 for the Rayleigh-Taylor instability calculation with a density ratio of 10:1.

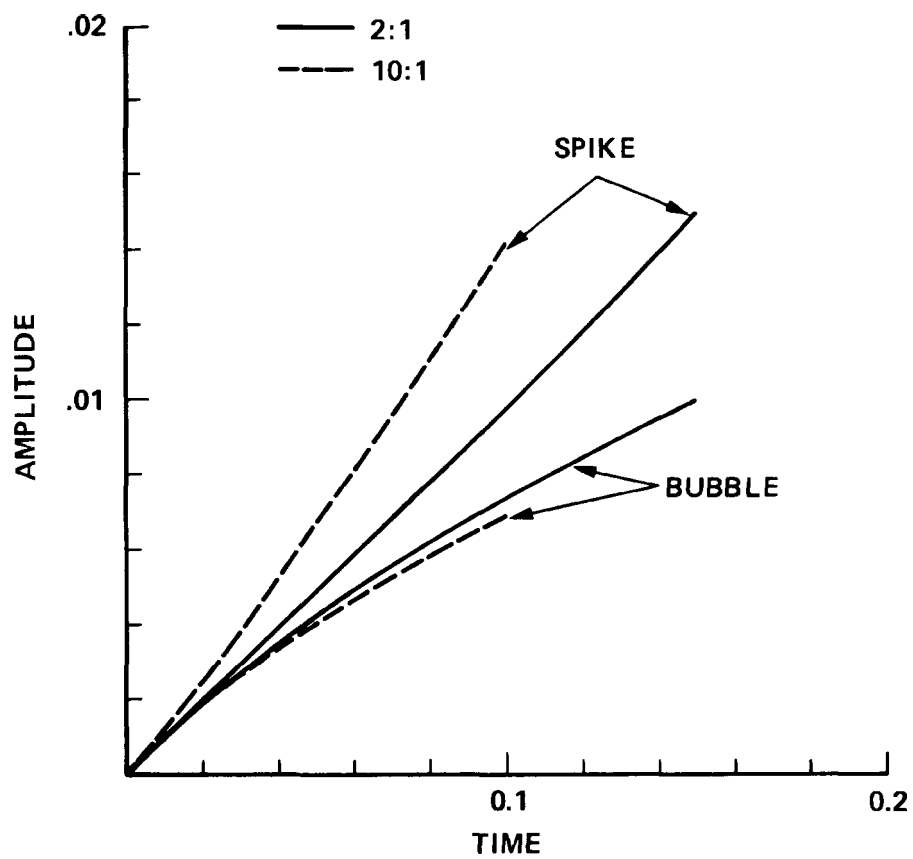


Figure 8.41. Spike and bubble amplitude as a function of time for the Rayleigh-Taylor instability calculation.

The results of these calculations show several features in common with the results reported in Reference 12 and with predictions of the Rayleigh-Taylor theory (Reference 10 and 11). First of all, the asymmetry between the spike and bubble shapes increases with increasing density ratio as expected. The shapes calculated here agree well with those reported in Reference 12. For the 10:1 density ratio, a narrow spike forms, whereas for the 2:1 case, the spike is considerably broader.

Secondly, the rate of growth of the spike tip increases with density as predicted by theory. This is evident from Figure 8.41. However, the growth rate does not agree with the predictions of linear theory because of the presence of nonlinear effects in the calculations. The same thing was found for the calculations reported in Reference 12. The linear theory is only expected to be applicable during the early stages of growth.

Finally, Figures 8.28 and 8.29 indicate that a Kelvin-Helmholtz instability is starting to grow at the interface for the 2:1 density ratio calculation. This is a shear instability that causes the interface to form a spiral. It was predicted by Rayleigh (Reference 10) and was also observed in the calculations reported in Reference 12. Rayleigh predicts that the growth rate decreases with increasing density ratio, which explains why it is not observed in the 10:1 case.

8.2.4.4 Input Decks. The STEALTH input for the 2:1 density ratio calculation is provided in Table 8.8. The input deck for the 10:1 density ratio calculation is identical with the exception of the title card (TTL), the card which specifies the density of the upper region (Type 121 for region 2), and the card which specifies the problem time limit (Type 521). These modifications are provided in Table 8.9.

TABLE 8.8

DATA DECK FOR TAYLOR INSTABILITY CALCULATION
WITH 2:1 DENSITY RATIO

TTL	TAYLOR INSTABILITY - 2 TO 1 DENSITY RATIO						
PRB	2.0						
PRO	2.0						
SYM	1.0						
MIN	3.00E-04						
GRV		-1.		2.0			
GRD	1.0	1.0	16.	31.			
ITR	300.	.1	1.7				
CPL	.25						
END							
MAT	2.0						
121 RDN1	1.0	1.0					
121 RDN2	2.0	2.0					
END							
GPT	2.0						
211 ORIG	1.0	1.0	1.0	0.0	2.0	-0.03	
212 WPT	1.0	0.0	0.03	2.0			
212	2.0	0.0	-0.03	1.0			
212	3.0	0.02	-0.03	1.0			
212	4.0	0.02	0.03	3.0			
212	5.0	0.02	-0.03	2.0			
212	6.0	0.02	0.03	1.0			
212	7.0	0.	0.03	1.0			
212	8.0	0.	-0.03	3.0			
221 BLK	1.0	1.0	16.	1.0	16.		
221	2.0	1.0	16.	16.	31.		
247 ZNC	1.0	0.0	0.02	-0.03	0.03	1.0	0.94731425
247	2.0	0.0	0.02	0.0	0.03	1.0	1.0556159
END							
ZOM	2.0						
311 BLK	1.0	1.0	16.	1.0	15.		
311	2.0	1.0	1.0	15.	16.		
311	3.0	1.0	2.0	15.	16.		
311	4.0	2.0	3.0	15.	16.		
311	5.0	3.0	4.0	15.	16.		
311	6.0	4.0	5.0	15.	16.		
311	7.0	5.0	6.0	15.	16.		
311	8.0	6.0	7.0	15.	16.		
311	9.0	7.0	8.0	15.	16.		
311	10.0	8.0	9.0	15.	16.		
311	11.0	9.0	10.0	15.	16.		
311	12.0	10.0	11.0	15.	16.		
311	13.0	11.0	12.0	15.	16.		
311	14.0	12.0	13.0	15.	16.		
311	15.0	13.0	14.0	15.	16.		
311	16.0	14.0	15.0	15.	16.		
311	17.0	15.0	16.0	15.	16.		
311	18.	1.0	16.	16.	31.		

(Continued on next page)

TABLE 8.8 (continued)

321	MPN	1.0	1.0			
321		2.0	1.0			
321		3.0	1.0			
321		4.0	1.0			
321		5.0	1.0			
321		6.0	1.0			
321		7.0	1.0			
321		8.0	1.0			
321		9.0	1.0			
321		10.0	1.0			
321		11.0	1.0			
321		12.0	1.0			
321		13.0	1.0			
321		14.0	1.0			
321		15.0	1.0			
321		16.0	1.0			
321		17.0	1.0			
321		18.0	2.0			
322	RLV	1.0	1.0			
322		2.0	1.0			
322		3.0	1.0			
322		4.0	1.0			
322		5.0	1.0			
322		6.0	1.0			
322		7.0	1.0			
322		8.0	1.0			
322		9.0	1.0			
322		10.0	1.0			
322		11.0	1.0			
322		12.0	1.0			
322		13.0	1.0			
322		14.0	1.0			
322		15.0	1.0			
322		16.0	1.0			
322		17.0	1.0			
322		18.0	1.0			
331	YVL	1.0				
331		2.0		1.0		
331		3.0		.97815		
331		4.0		.913545		
331		5.0		.809015		
331		6.0		.66913		
331		7.0		.5		
331		8.0		.309015		
331		9.0		.10453		
331		10.		-.10453		
331		11.		-.309015		
331		12.		-.5		
331		13.		-.66913		
331		14.		-.809015		
331		15.		-.913545		
331		16.		-.97815		
331		17.		-1.0		
331		18.				
END						
BDY						2.0
411	BLFT	1.0	1.0	17.	1.0	1.0
411	BOT	2.0	1.0	1.0	16.	1.0
411	BRHT	3.0	16.	1.0	16.	16.
411	TRHT	4.0	16.	16.	16.	31.
411	TOP	5.0	16.	31.	1.0	31.
411	TLFT	6.0	1.0	31.	1.0	17.
412		1.0	1.0	6.0		2.0
412		2.0	1.0	6.0		3.0
412		3.0	1.0	6.0		4.0
412		4.0	2.0	6.0		6.0
412		5.0	2.0	6.0		7.0
412		6.0	2.0	6.0		8.0

(Continued on next page)

TABLE 8.8 (continued)

481	1.0	1.0	4.0			
481	2.0	5.0	8.0			
482	1.0	1.0	5.0	5.0		
482	2.0	2.0	5.0	5.0		
END						
TIM					2.0	
511	DTSOR	0.0001				
512	DTLIM	0.000001	0.0005			
521	MXT/C	.15	500.			
END						
EDT					2.0	
621	EDTM	1.0	0.0	0.2	0.025	
622	EDLM	1.0	16.	1.0	31.	
623	XPN	1.0	11.0			
623	YPN	2.0	14.0			
623	XVL	3.0	12.0			
623	YVL	4.0	15.0			
623	PPH	5.0	64.0			
623	VSR	6.0	45.0			
623	DNS	7.0	46.0			
623	ZMS	8.0	47.0			
624	NOMF	2.0				
631	REDTM	1.0	0.0	0.2	0.025	
632	REG1	1.0	1.0	16.	1.0	16.
632	REG2	2.0	1.0	16.	16.	31.
674	XV(X)	1.0	2.0	12.	11.	1.0
674	YV(X)	2.0	2.0	15.	11.	1.0
675	MESH	3.0	3.0			1.0
675	MESH	4.0	3.0			
675	MESH	5.0	3.0			.025
675	MESH	6.0	3.0			.050
675	MESH	7.0	3.0			.075
675	MESH	8.0	3.0			.100
675	MESH	9.0	3.0			.125
675	MESH	10.	3.0			.15
675	VCTR	10.	5.0		1.0	
675	VCTR	11.	5.0			.025
675	VCTR	12.	5.0			.050
675	VCTR	13.	5.0			.075
675	VCTR	14.	5.0			.100
675	VCTR	15.	5.0			.125
675	VCTR	16.	5.0			.15
END						
END						

TABLE 8.9

MODIFICATIONS TO THE TAYLOR INSTABILITY DATA DECK
FOR 10:1 DENSITY RATIO

TTL	TAYLOR INSTABILITY - 10 TO 1 DENSITY RATIO		
121	RDN2	2.0	10.
521	MXT/C	0.1	500.

8.2.5 Calculation of Sloshing in a Large Fluid-Filled Tank Subjected to Horizontal Accelerations

8.2.5.1 Problem Description. When a large fluid storage tank is accelerated by strong ground motions such as would be produced by an earthquake, potentially damaging loads on the tank structure are produced directly by the ground motions and also by the resultant fluid motions within the tank. The STEALTH test calculations discussed in this section address the second of these phenomena, the sloshing motion of a fluid within a horizontally accelerated storage tank.

The calculations discussed here involve a rigid rectangular tank filled with an incompressible fluid (water) which is accelerated by a horizontal velocity waveform. Two different waveforms were used. The first was a simple, half-period sine wave with an amplitude of 2.23 ft/sec and a period of 4.35 second. The second was a more complicated waveform meant to be somewhat more representative of earthquake-generated ground motions in frequency content, amplitude, and duration. In fact, ground motion data from the 1964 Alaska earthquake were used in developing the waveform.

The mathematical expression for the second velocity waveform is

$$\dot{x} = -0.7235 \sin (2.125 \pi t) + 0.82 \sin (1.875 \pi t), 0 < t \leq 8 \text{ sec.},$$

which corresponds to the following acceleration waveform:

$$\ddot{x} = 9.66 \sin (2\pi t) \sin (0.125 \pi t).$$

The acceleration waveform is shown in Figure 8.42. The period of the oscillations is 1 second while the period of the envelope is 16 seconds. The waveform was applied for half of a period of the envelope.

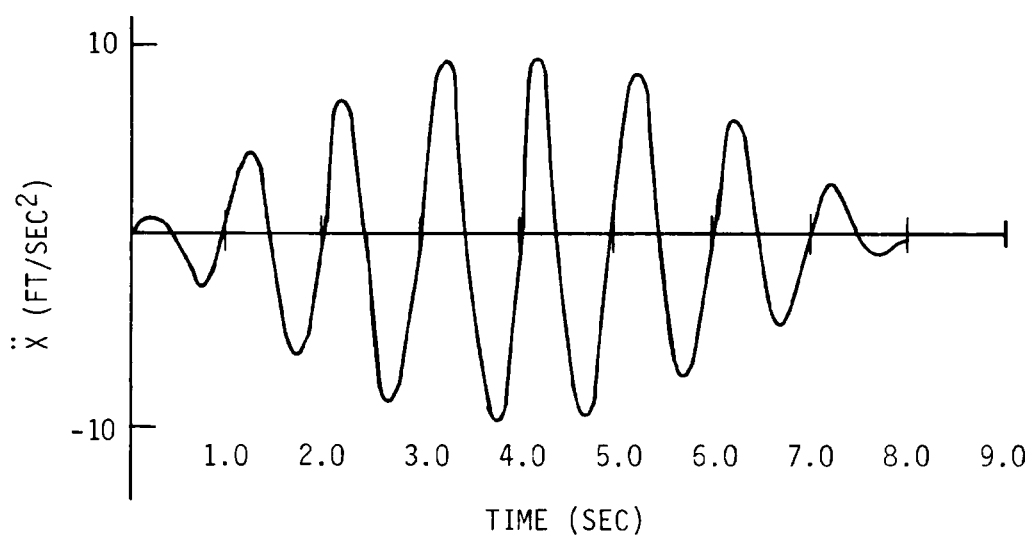


Figure 8.42. Horizontal acceleration waveform corresponding to the boundary condition used to simulate earthquake excitation of fluid motion in a storage tank.

The fundamental mode for free oscillation of a fluid in a rectangular tank is one in which the fluid surface moves alternately upward and downward on opposite sides of a line of zero displacement at the center of the tank. The angular frequency of this mode is related to the half-width of the tank ℓ , the still water height h , and the acceleration of gravity g by (Reference 19)

$$\omega^2 = \frac{1.58g}{\ell} \tanh \left(1.58 \frac{h}{\ell} \right) .$$

This provides a convenient check for the numerical solutions. The dimensions of the tank used for the STEALTH calculations were $\ell = 24$ feet and $h = 36$ feet which gives a fundamental frequency of .23 Hertz or a period of 4.35 seconds. This period was used for the input velocity waveform for the first calculation in order to excite predominantly the first mode of oscillation. Since the period of the input velocity for the second calculation is one second, higher modes are excited, although oscillations with the fundamental frequency should still be present.

8.2.5.2 Problem Set-Up. A schematic of the configuration used for both calculations is shown in Figure 8.43. The computational mesh defines the fluid (water) region which is bounded on the bottom and both sides by wall segments that represent the tank. The water, which is treated as an incompressible fluid with a density of 62.4 lb/ft^3 , (or 1.94 slugs/ft^3), has an original height of 36 feet. Since planar symmetry is used, this configuration represents a fluid filled rectangular tank with unit thickness.

The horizontal zone width, $\Delta x = 4$ feet, was chosen to provide good resolution of the fundamental mode of oscillation. The wavelength of this mode is twice the tank width so that each cell represents $1/24$ of a wavelength. The same mesh spacing was used in the y -direction.

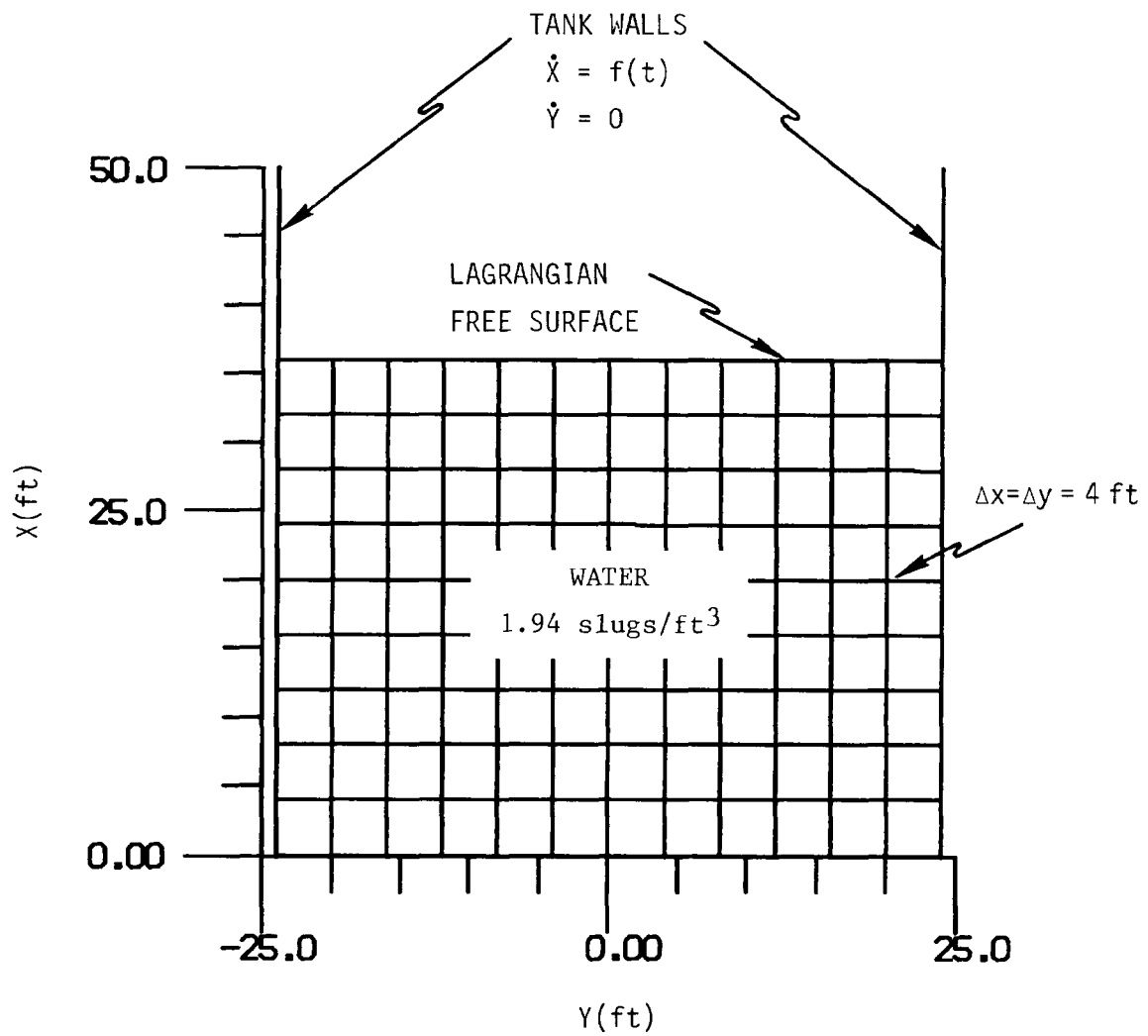


Figure 8.43. Configuration used for calculations of fluid sloshing in a rectangular tank.

The timestep for the first calculation was also chosen to give good resolution of the fundamental mode. A timestep representing 1/24 of a period ($\Delta t = 0.18$ sec) would provide resolution equivalent to the mesh spacing. However, $\Delta t = 0.1$ sec was chosen to give slightly better resolution. This gives slightly more than ten timesteps during the initial rise of the input velocity waveform.

For the second calculation, the timestep was reduced by half to $\Delta t = 0.05$ sec for the first eight seconds while the velocity boundary condition was being applied. This provided barely adequate resolution of this waveform, i.e., five timesteps per quarter cycle. After the velocity boundary condition was turned off, the timestep was permitted to increase gradually to 0.1 sec.

The convergence criterion was selected as follows. In order to estimate an average velocity gradient, we assume that the velocity changes from zero to the maximum amplitude of the velocity boundary condition in a quarter of a wavelength. For the first calculation this gives

$$\overline{\frac{\partial v}{\partial x}} \sim \frac{2.23 \text{ ft/sec}}{24 \text{ ft}} \sim 0.1$$

Thus, the maximum value for ϵ would be two orders of magnitude less than this or $\epsilon = 10^{-3}$. Similarly, for the second calculation

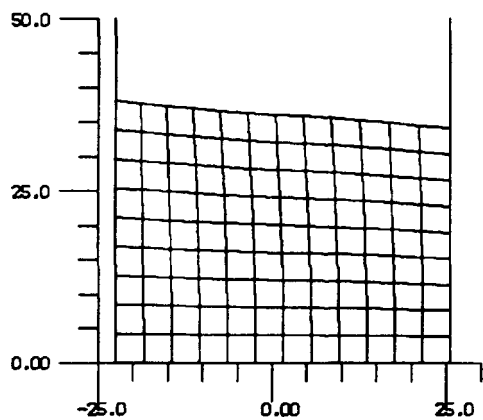
$$\overline{\frac{\partial v}{\partial x}} \lesssim \frac{(.72 + .82) \text{ ft/sec}}{24 \text{ ft}} = 0.06 \quad .$$

Thus, on this basis, the convergence criterion should be 6×10^{-4} . However, when the boundary condition is turned off we expect the magnitude of the velocities, and therefore, probably also $\overline{\partial v / \partial x}$, to decrease. Therefore we reduced the convergence criterion to $\epsilon = 10^{-4}$ for this calculation.

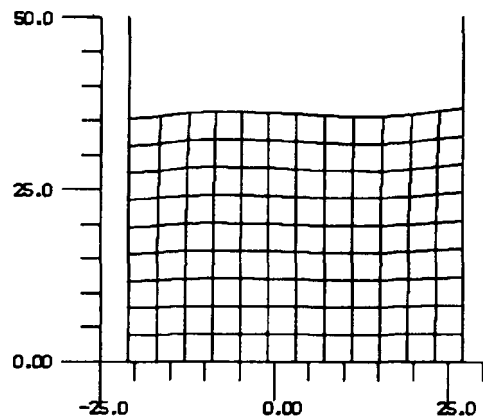
Both calculations were run using the ALE rezoner with the Lagrangian free surface option (NSALE = 3). This is the same option as was used for the undular bore calculation discussed previously in Section 8.2.2. Mass and momentum transport were both done using the full donor cell approximation.

8.2.5.3 Results. Figure 8.44 shows the mesh configuration for the first calculation approximately every 1.1 seconds ($\tau/4$) out to a time of twelve seconds. These show that, as expected, essentially only this first mode of oscillation was excited. Furthermore, the frequency appears to be approximately correct. Figures 8.45 and 8.46 show velocity fields and pressure contours at the same times. The pressure contour plots are actually plots of the excess pressure, $p - p_0$, where p_0 is the original hydrostatic pressure in each zone. Since the hydrostatic pressure is considerably larger than the pressure variations from the sloshing motions, the pressure variations would be masked by the hydrostatic pressure in contour plots of total pressure. Contour plots of $p - p_0$ show these variations much more clearly.

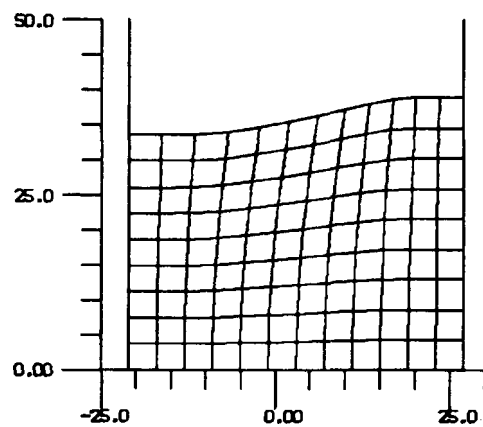
In order to determine quantitatively whether the calculation reproduces the correct fundamental frequency, we have plotted (in Figure 8.47) the y-position history of mesh point $I = 1, J = 10$ which is on the free surface adjacent to the left-hand wall. We see that the period of oscillation of this point is about 4.4 seconds which agrees well with the expected value. As another measure, we have plotted (in Figure 8.48) the kinetic energy history of the entire fluid. After an initial transient during which the boundary condition is active, a steady-state oscillation with a period of 2.2 seconds is established. Since we expect the frequency of the kinetic energy oscillations to be twice that of the surface oscillations, this again shows good agreement with the expected results.



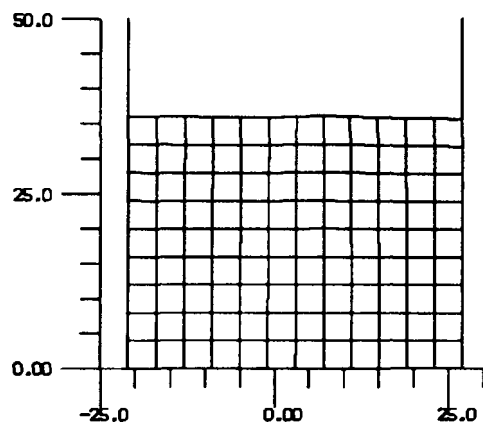
Time = 1.1



Time = 2.2

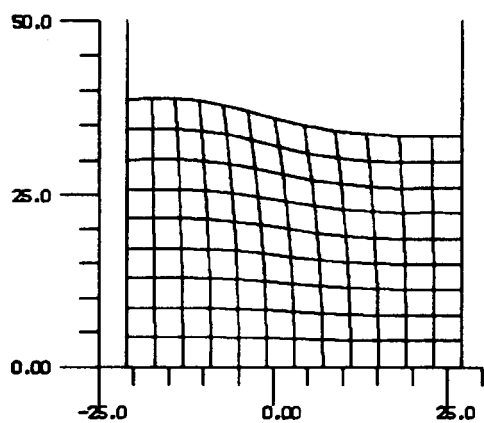


Time = 3.3

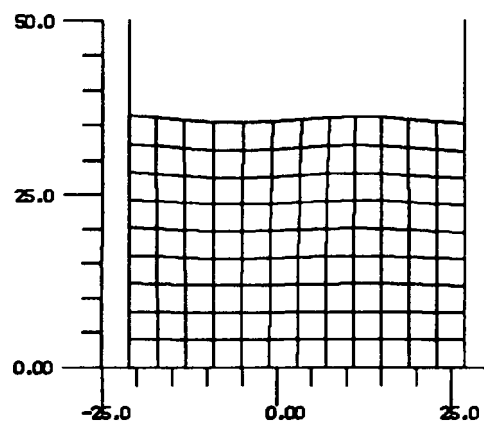


Time = 4.4

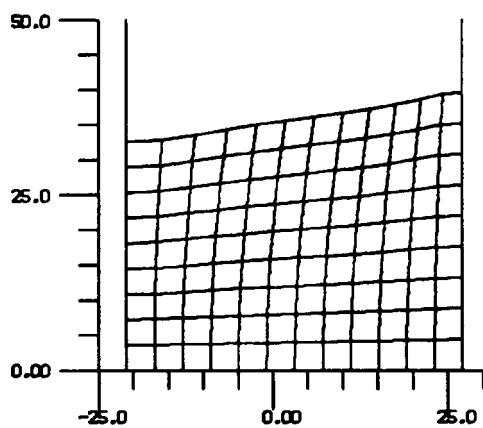
Figure 8.44. Mesh configuration at several times for the fluid sloshing calculation with a simple sine wave input.



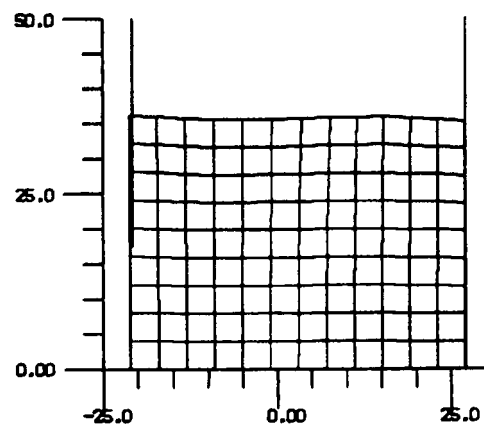
Time = 5.5



Time = 6.6

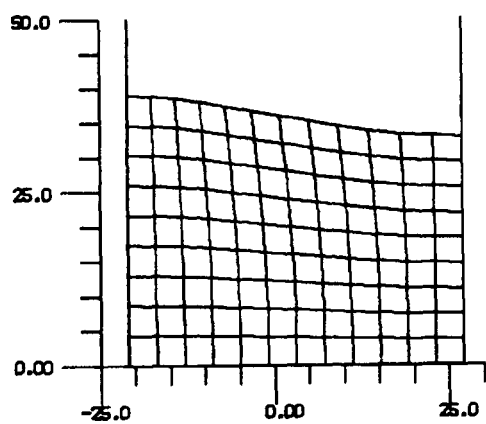


Time = 7.7

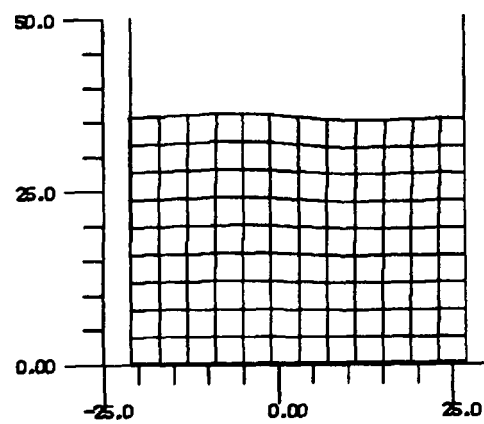


Time = 8.8

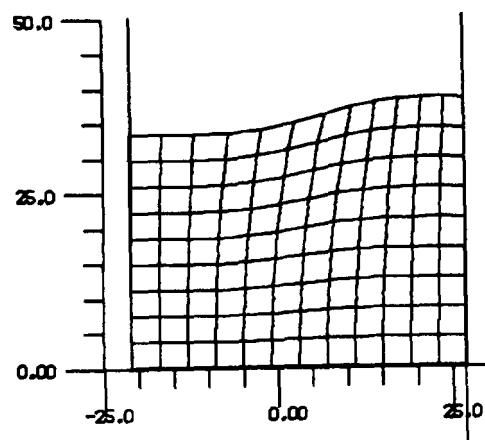
Figure 8.44 (continued)



Time = 9.9

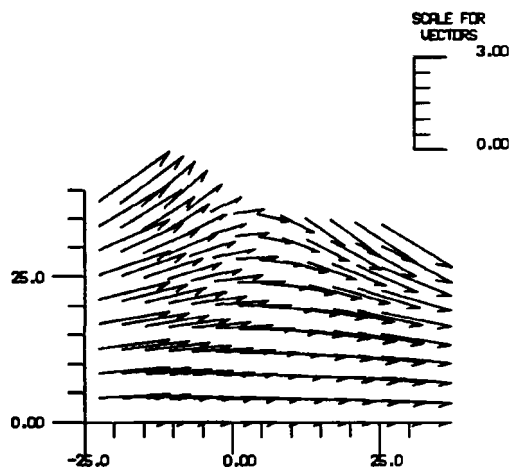


Time = 10.9

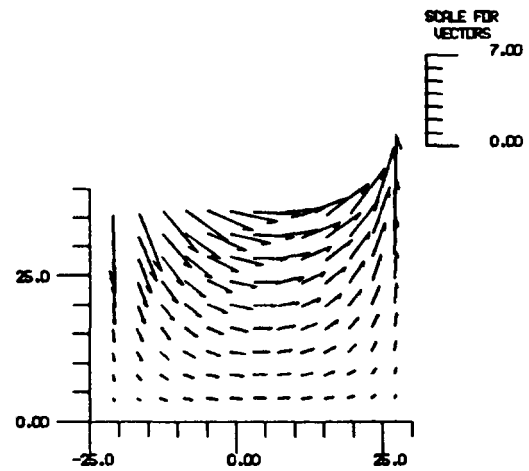


Time = 12.0

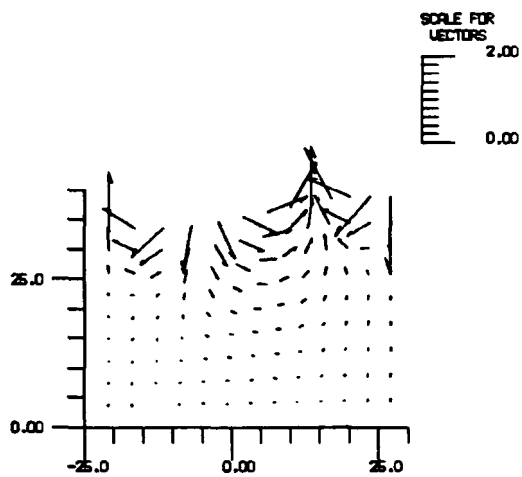
Figure 8.44 (continued)



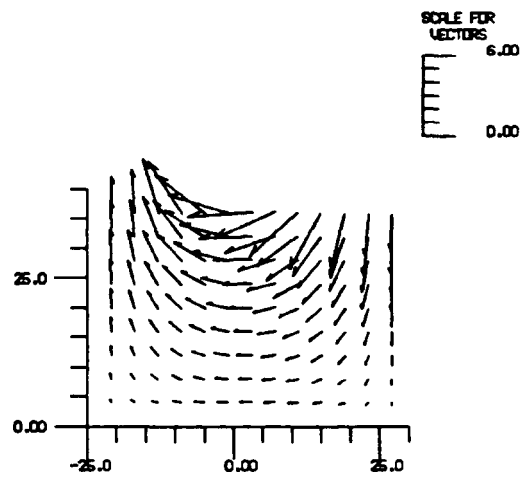
Time = 1.1



Time = 2.2

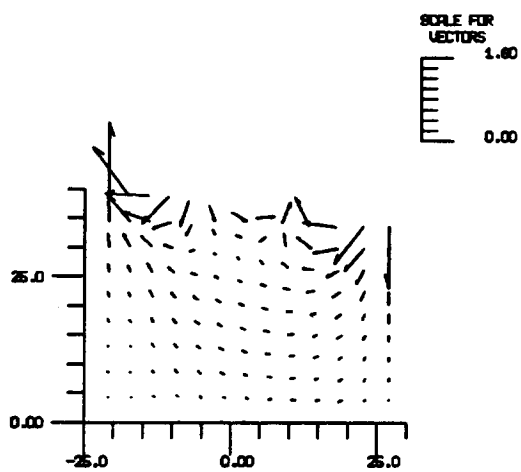


Time = 3.3

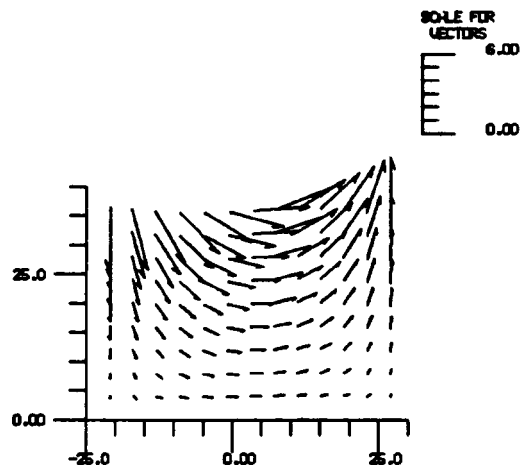


Time = 4.4

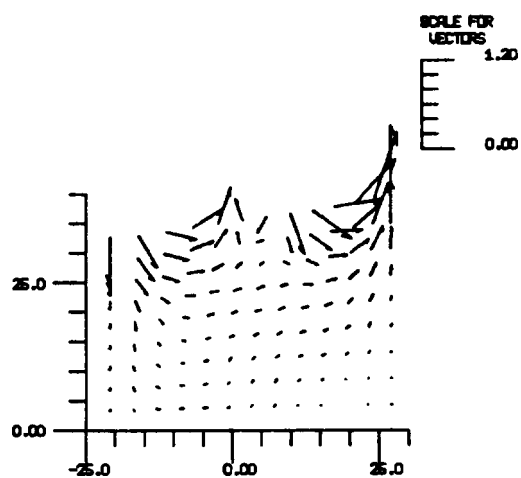
Figure 8.45. Velocity field at several times for the fluid sloshing calculation with a simple sine wave input. (Velocity units are ft/sec.)



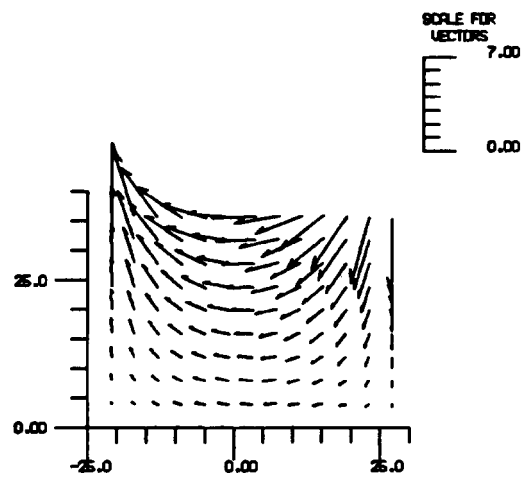
Time = 5.5



Time = 6.6

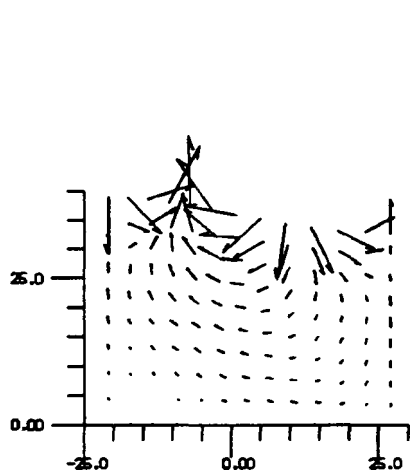


Time = 7.7

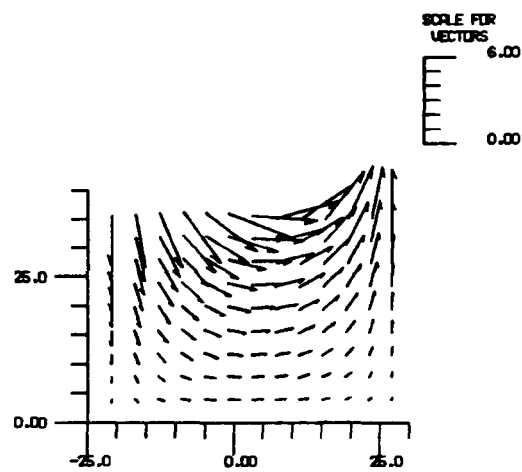


Time = 8.8

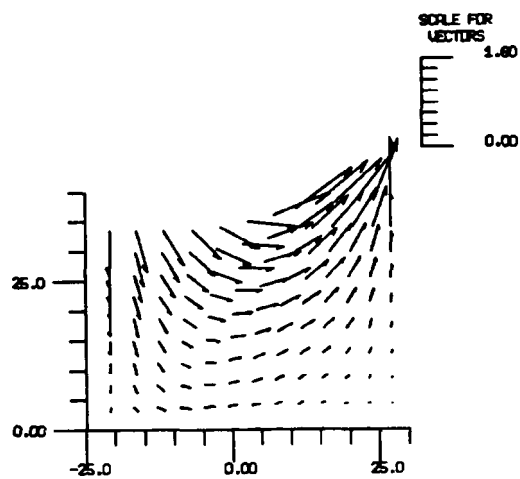
Figure 8.45 (continued)



Time = 9.9

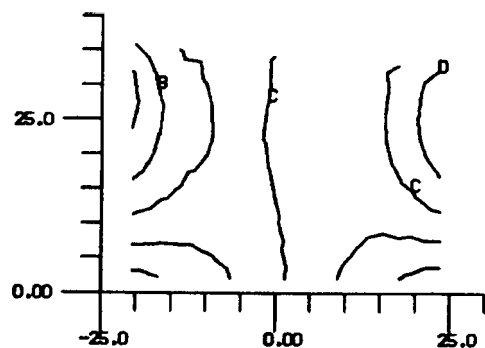


Time = 10.9

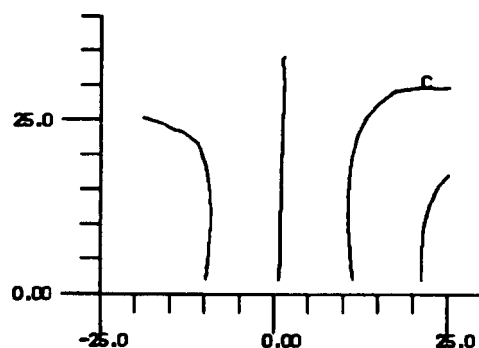


Time = 12.0

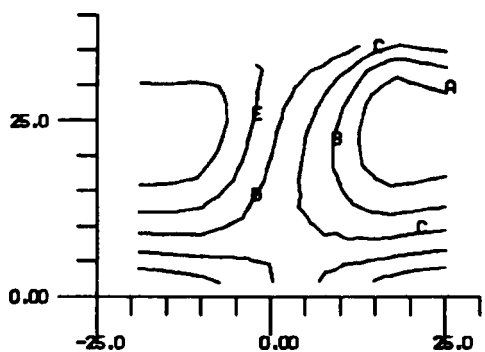
Figure 8.45 (continued)



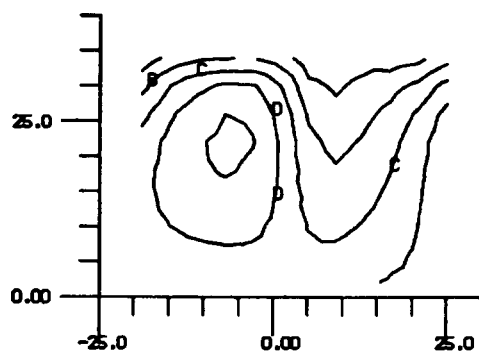
Time = 1.1



Time = 2.2



Time = 3.3



Time = 4.4

Figure 8.46. Contours of $p-p_0$ at several times for the fluid sloshing calculation with a simple sine wave input. (Pressure units are lbs/ft^2 .)



Time = 5.5



Time = 6.6

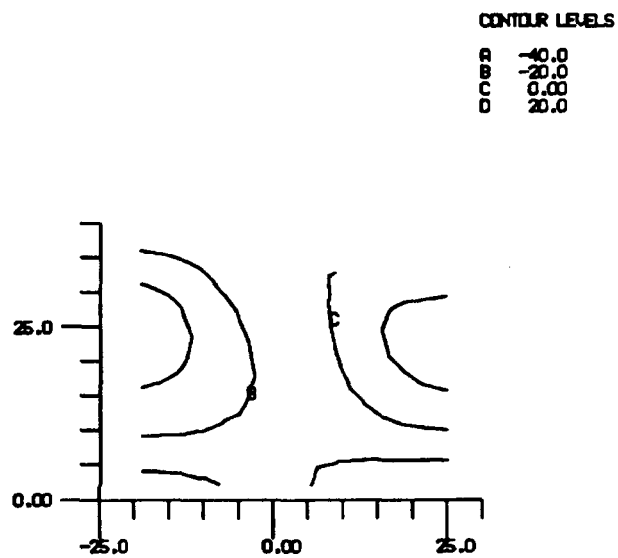


Time = 7.7

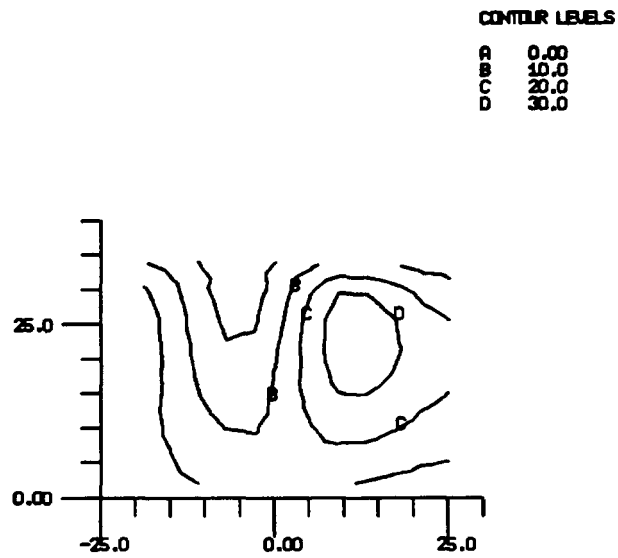


Time = 8.8

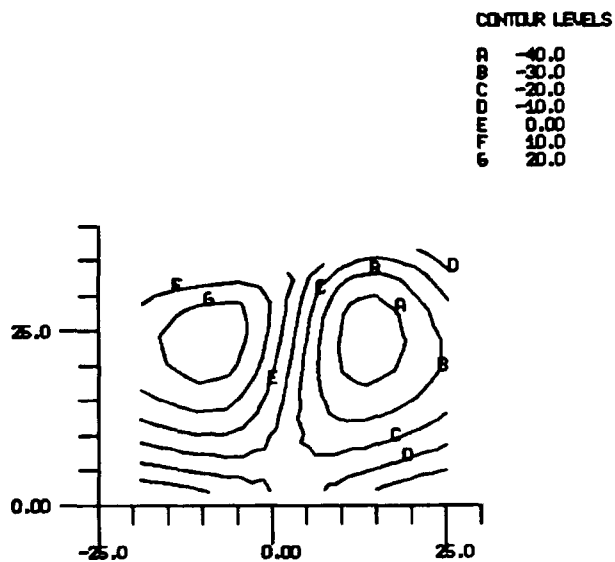
Figure 8.46 (continued)



Time = 9.9



Time = 10.9



Time = 12.0

Figure 8.46 (continued)

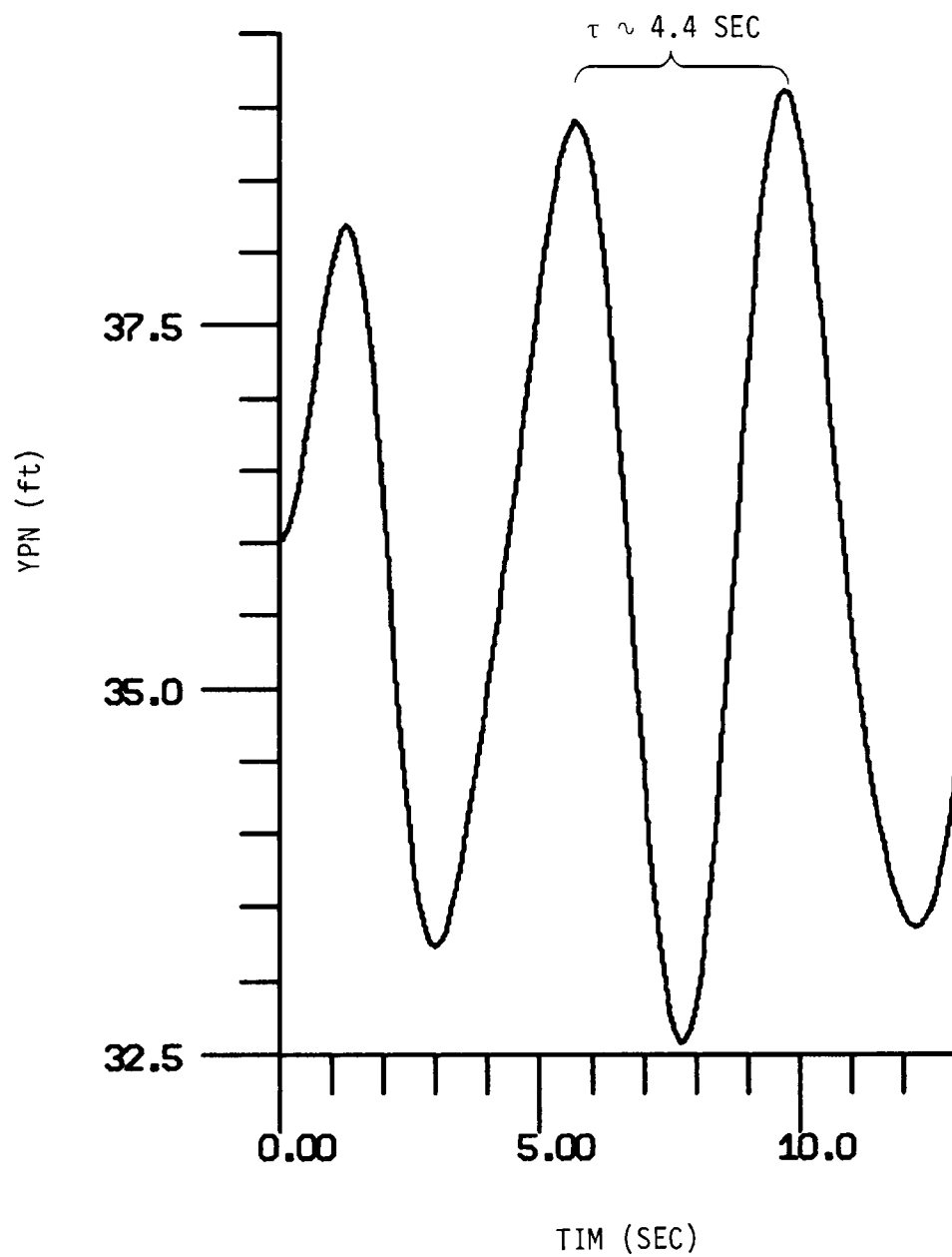


Figure 8.47. Surface height history adjacent to left-hand wall for fluid sloshing calculation with a simple sine wave input.

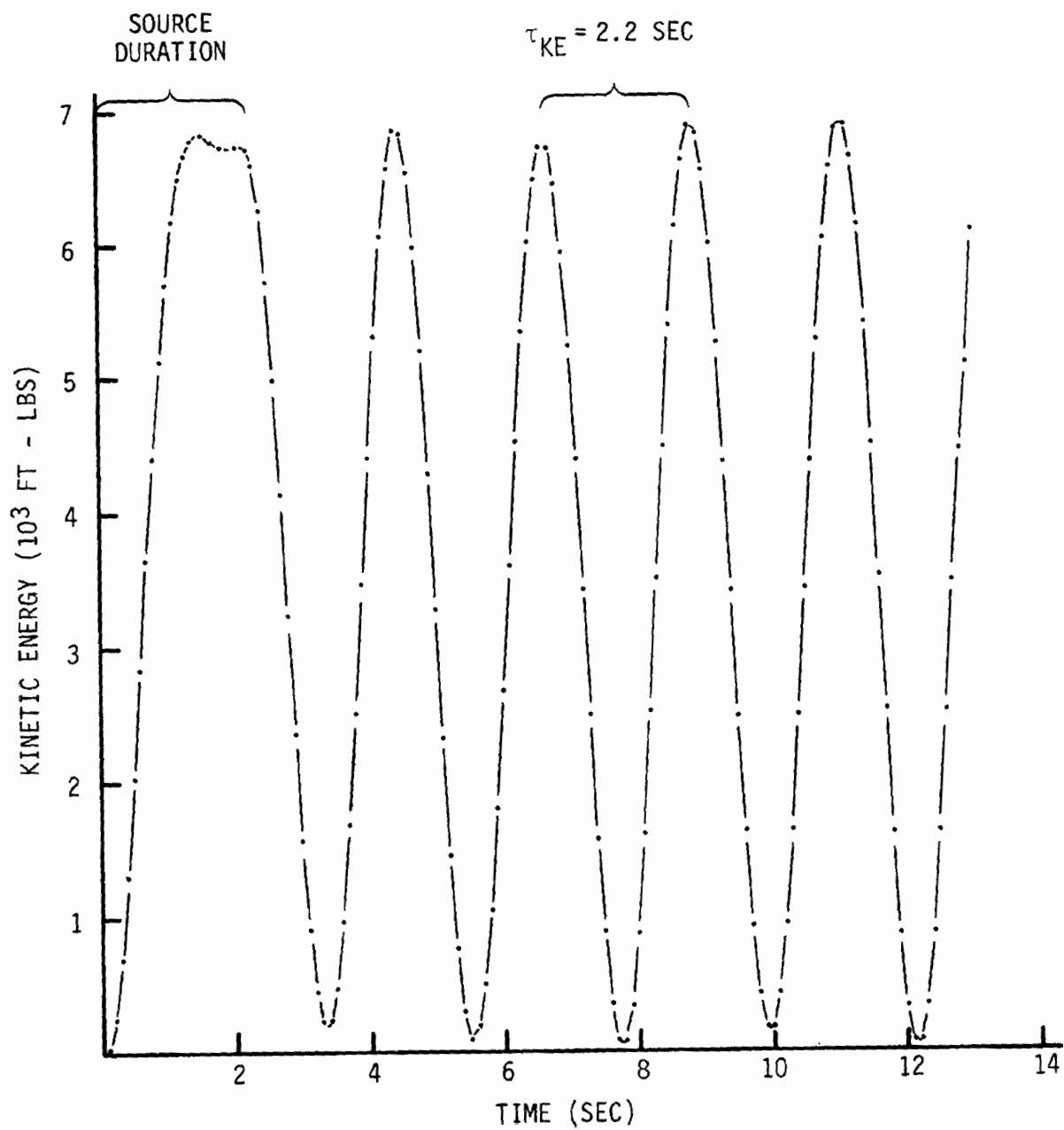


Figure 8.48. Kinetic energy history for the fluid sloshing calculation with a simple sine wave input.

Figure 8.49 shows pressure histories in several cells adjacent to both walls. The highest pressures are produced while the velocity boundary condition is turned on, but substantial pressures continue to be generated as the fluid sloshes from wall to wall. As one would expect, the frequency of the pressure oscillations is essentially the same as that of the free surface motions.

Figure 8.50 shows the position time history from the second calculation for the same mesh point as was plotted previously. In this case the point oscillates at the same frequency as the boundary condition until the boundary condition is turned off. After that the time oscillations slow down and appear to be approaching the frequency of the fundamental mode.

Pressure histories for this calculation are shown in Figure 8.51. In contrast to the first calculation, these pressure oscillations are completely dominated by the boundary condition. Because this boundary condition produces a much smaller displacement and therefore much less sloshing motion than the one used for the first calculation, the pressure oscillations essentially stop after the boundary condition is turned off.

Pressure contours and velocity fields for this calculation are shown in Figures 8.52 and 8.53, respectively. Comparison of these with similar plots from the first calculation shows that higher modes of oscillation have been excited. This is particularly evident in the velocity field plots at times after the boundary condition has been turned off. Note also that the magnitude of the fluid velocity decreases by about an order of magnitude when the boundary condition is turned off.

8.2.5.4 Input Decks. The STEALTH input for the calculation with the simple sine wave input is provided in Table 8.10. The input deck for the calculation with a simulated earthquake boundary condition is provided in

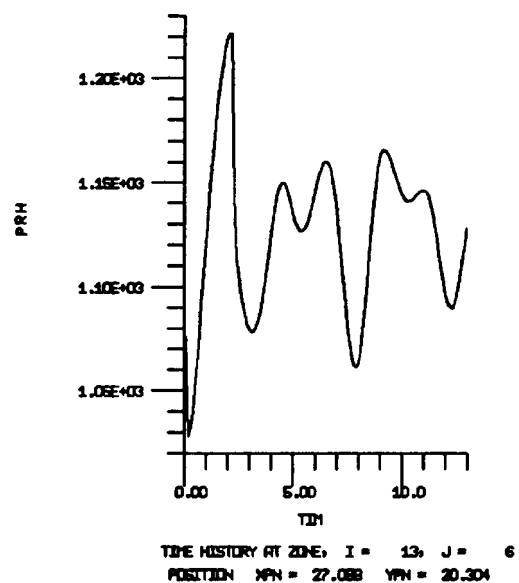
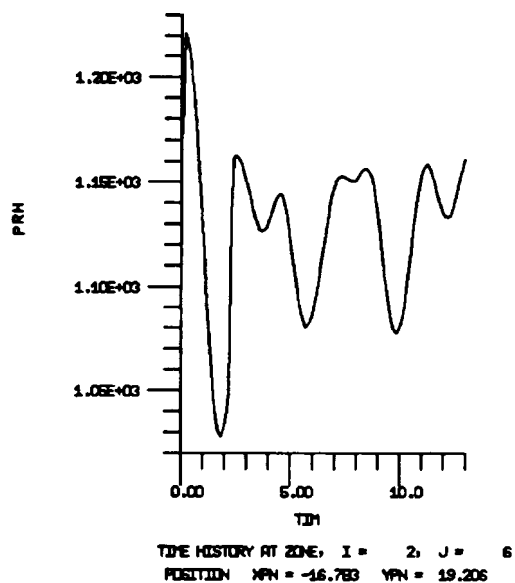
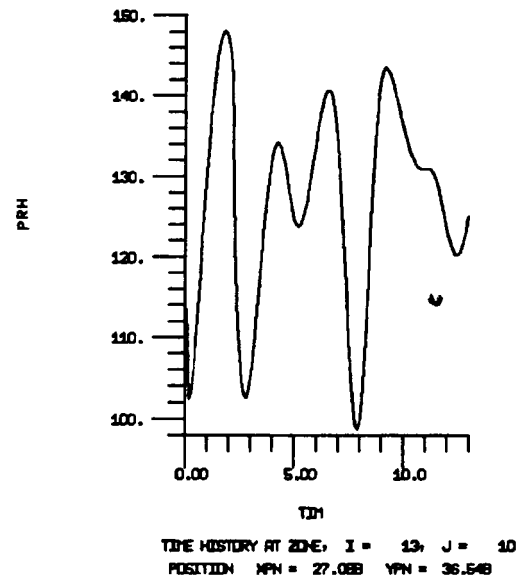
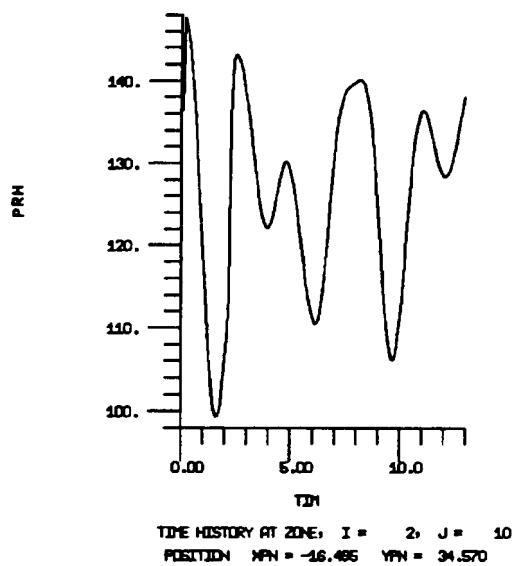


Figure 8.49. Pressure histories at several points adjacent to the walls for the fluid sloshing calculation with a simple sine wave input. (Units are lbs/ft² and seconds.)

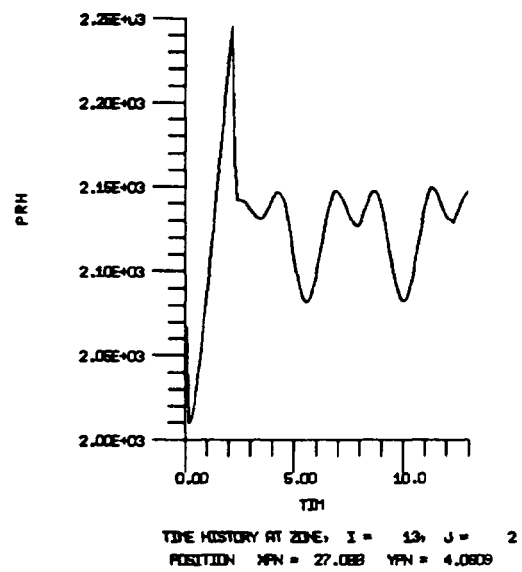
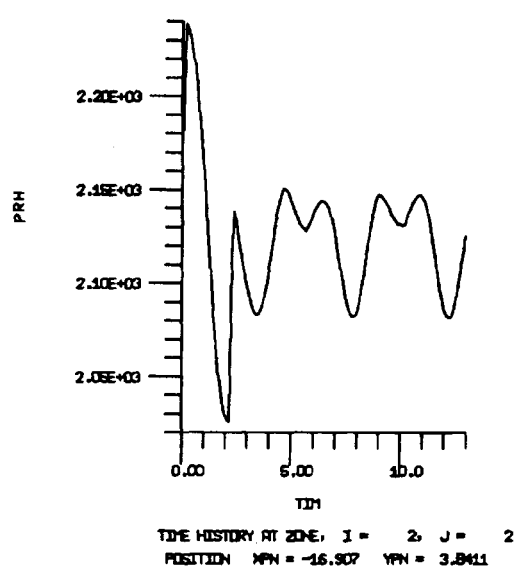


Figure 8.49 (continued)

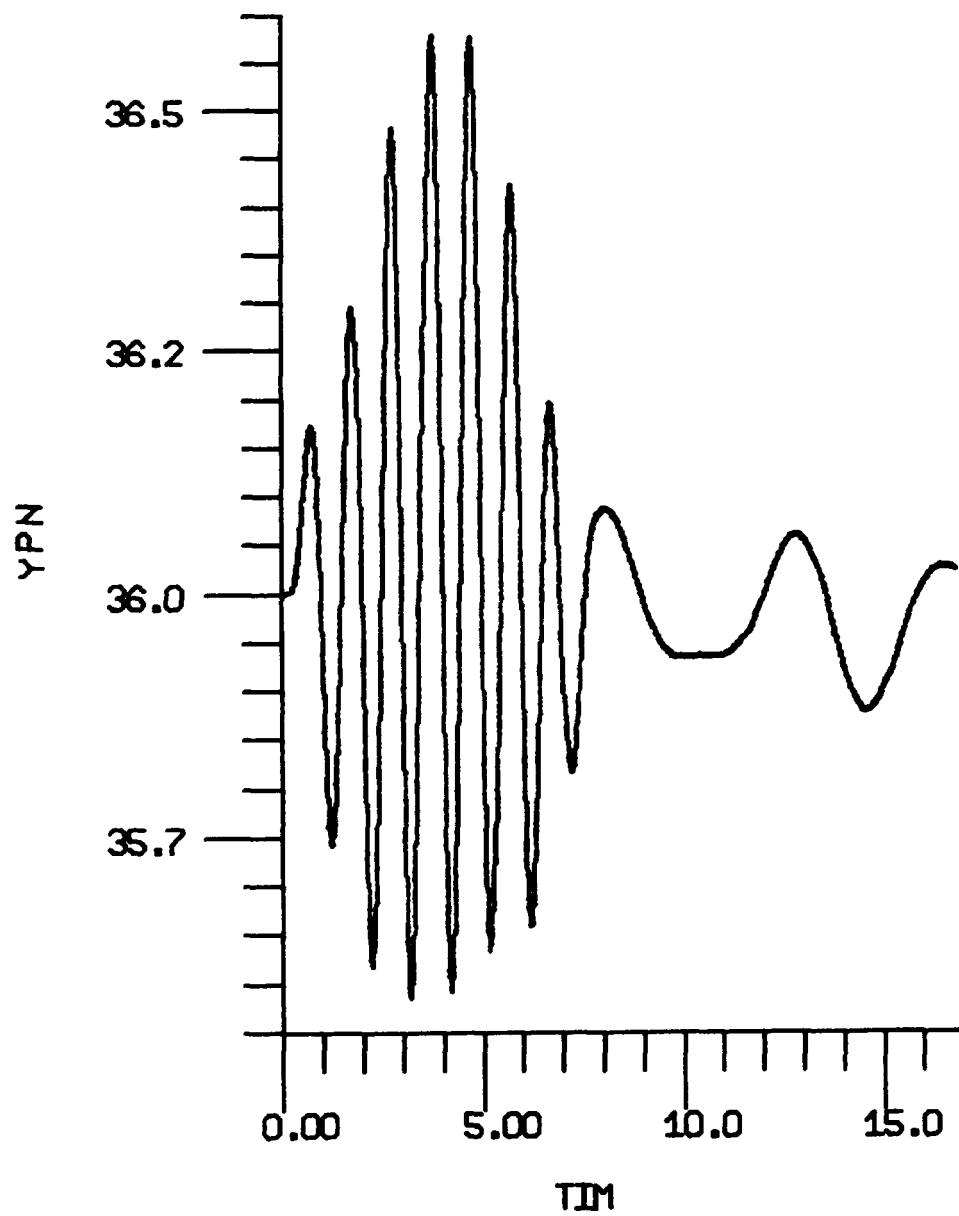


Figure 8.50. Surface height history adjacent to left-hand wall for the fluid sloshing calculation with a simulated earthquake boundary condition.

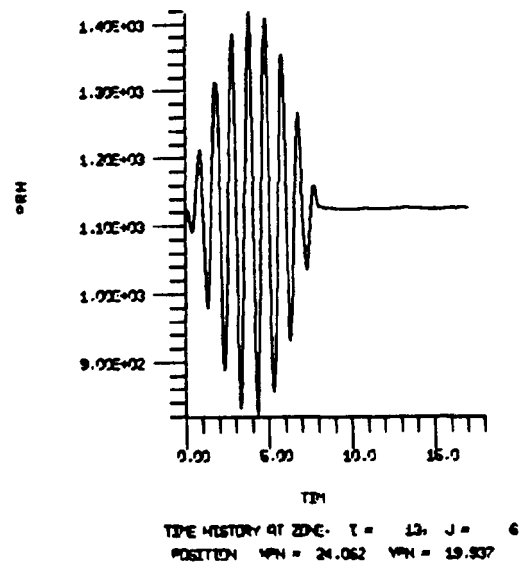
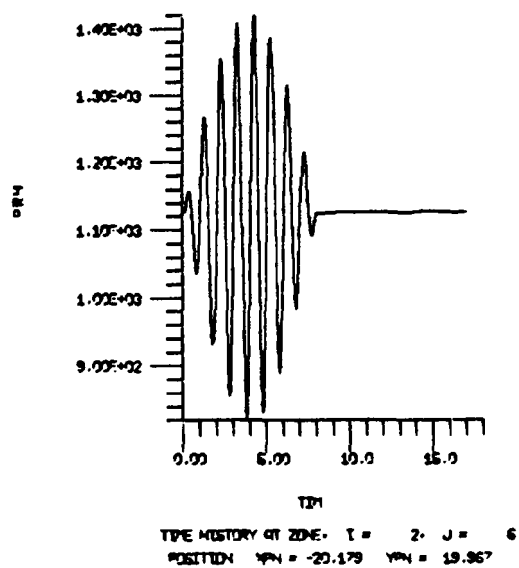
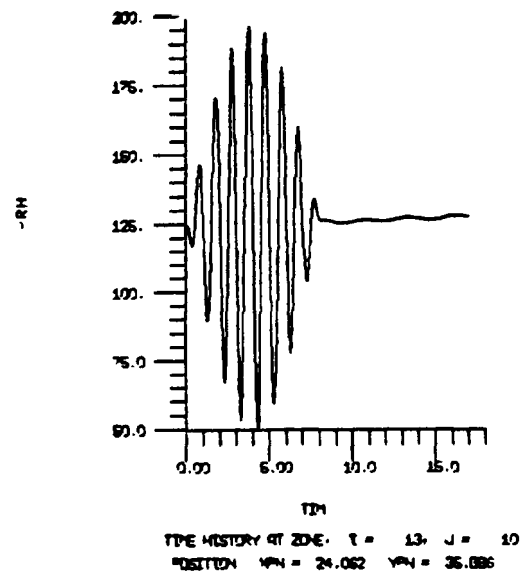
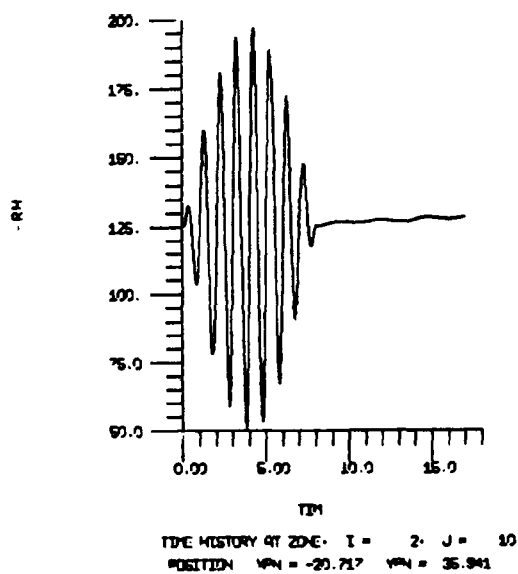


Figure 8.51. Pressure histories at several locations for the fluid sloshing calculation with a simulated earthquake boundary condition.

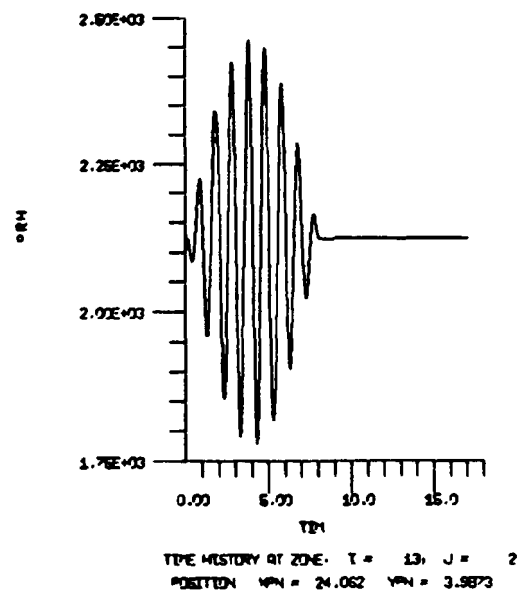
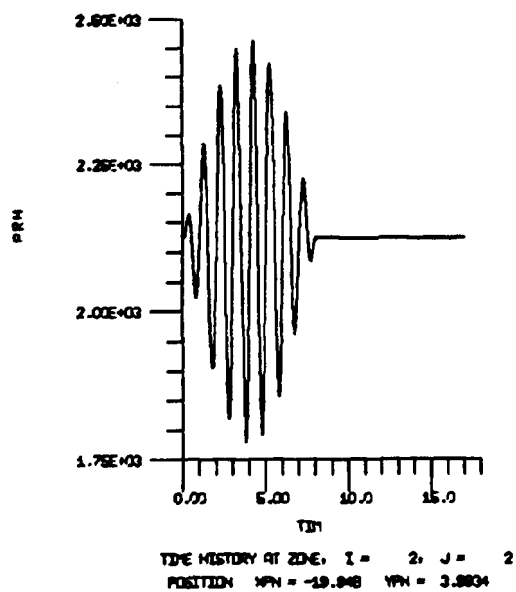
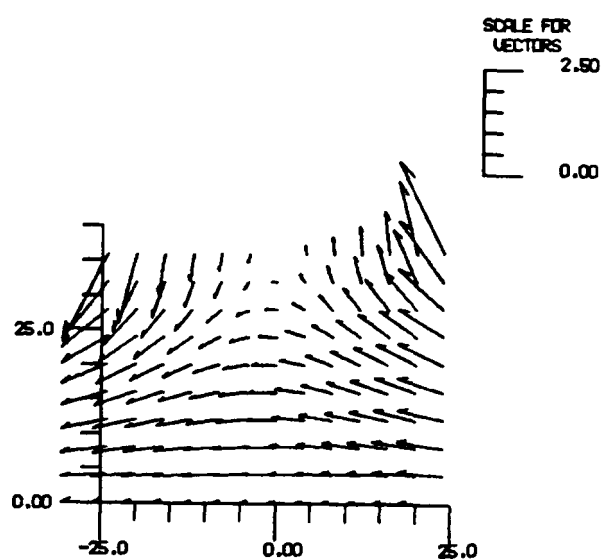
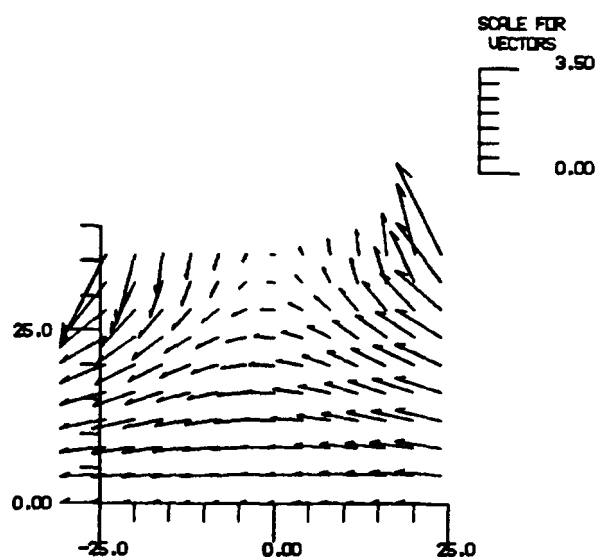


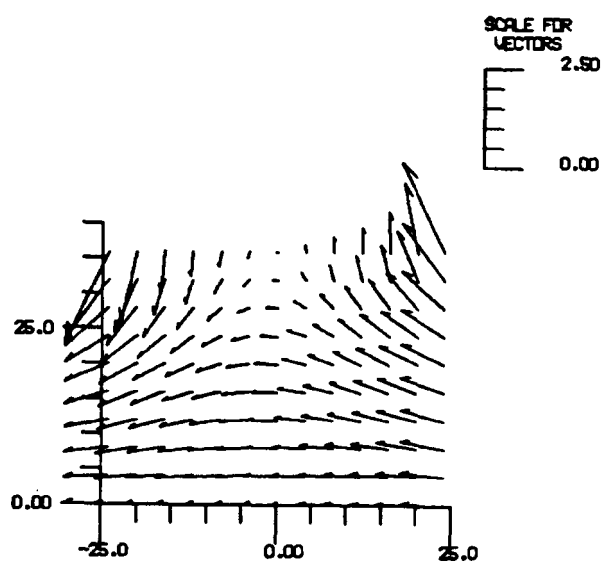
Figure 8.51 (continued)



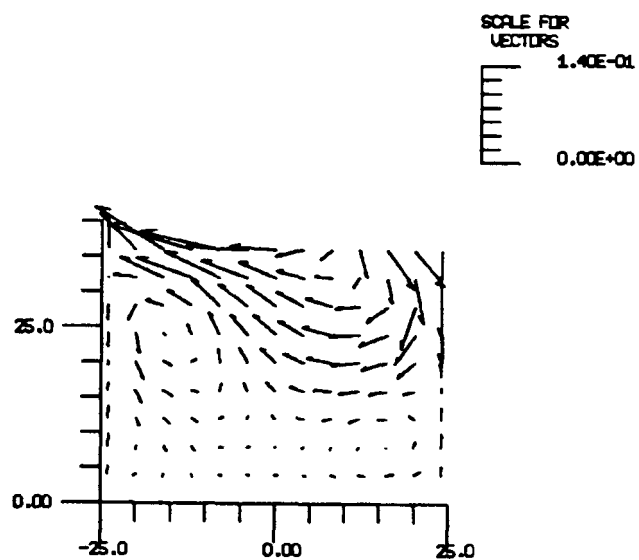
Time = 2.05



Time = 4.05

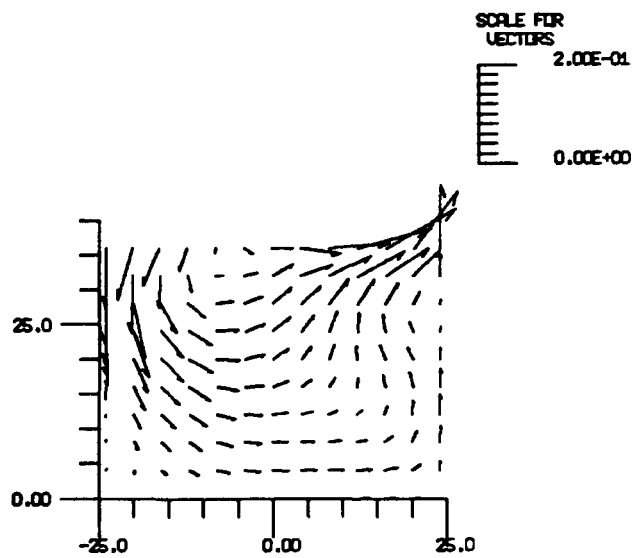


Time = 6.05

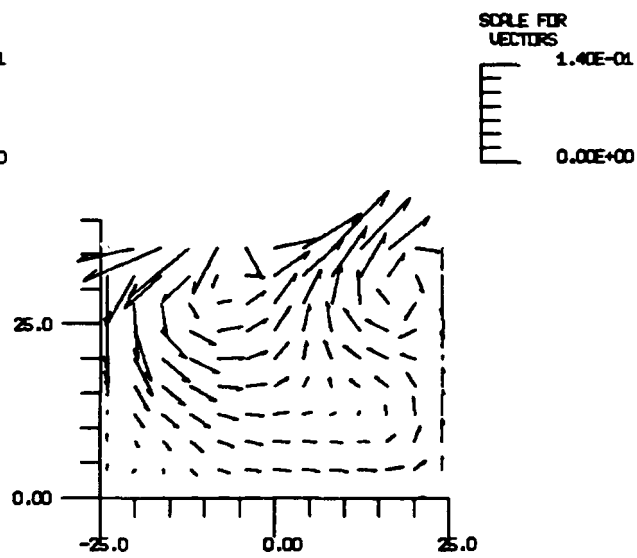


Time = 8.05

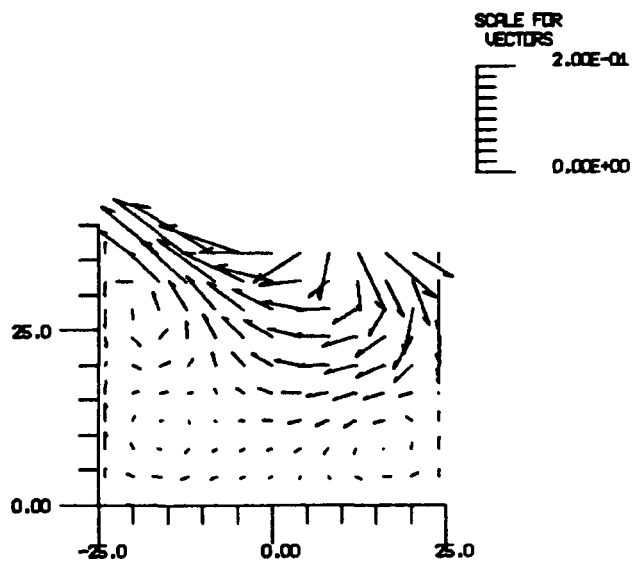
Figure 8.52. Velocity field at several times for the fluid sloshing calculation with a simulated earthquake boundary condition. (Velocity units are ft/sec.)



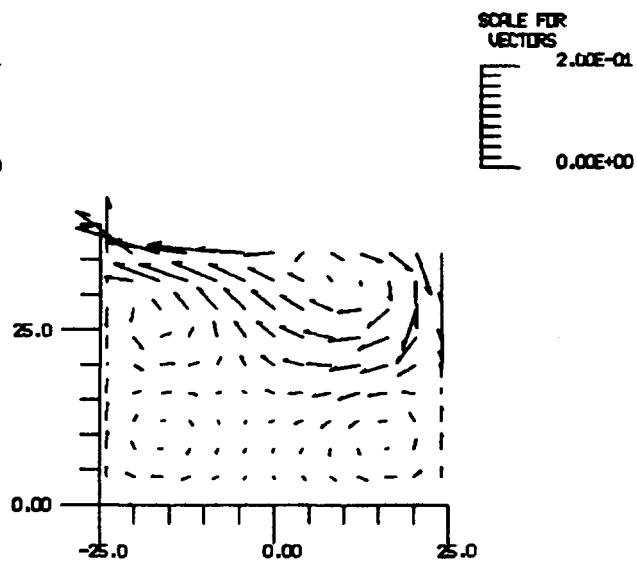
Time = 9.16



Time = 10.2

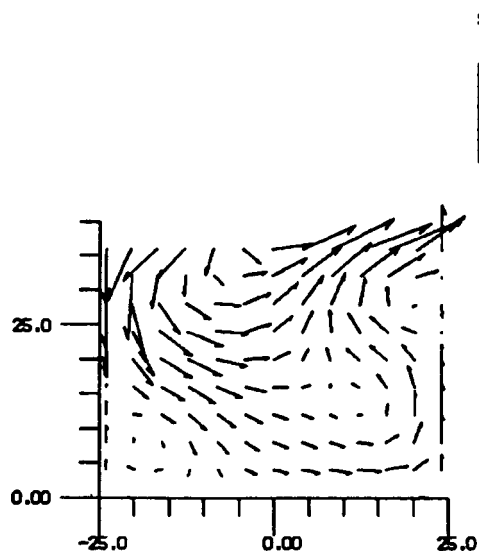


Time = 11.3

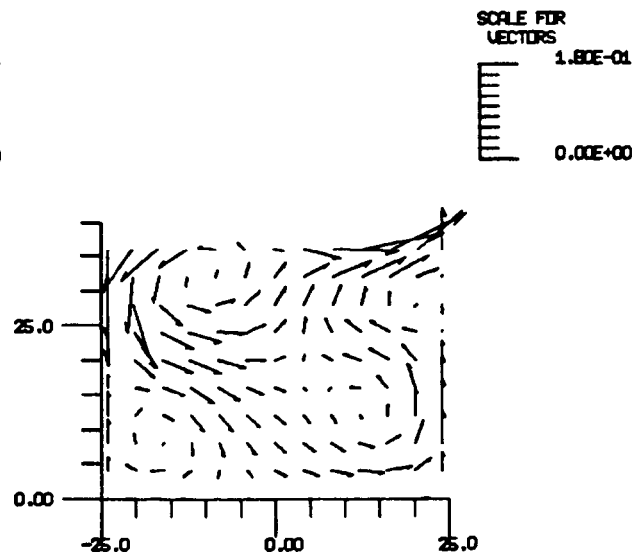


Time = 12.3

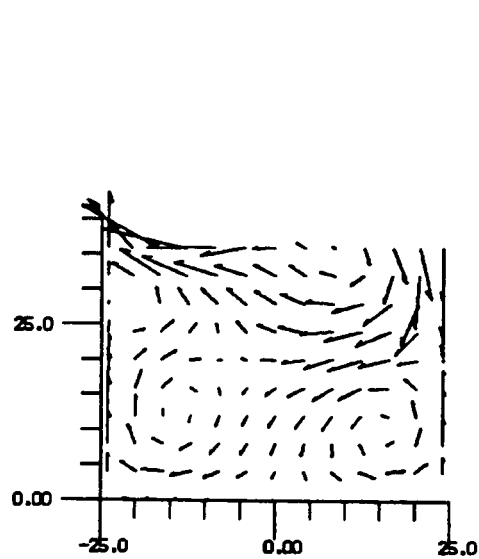
Figure 8.52 (continued)



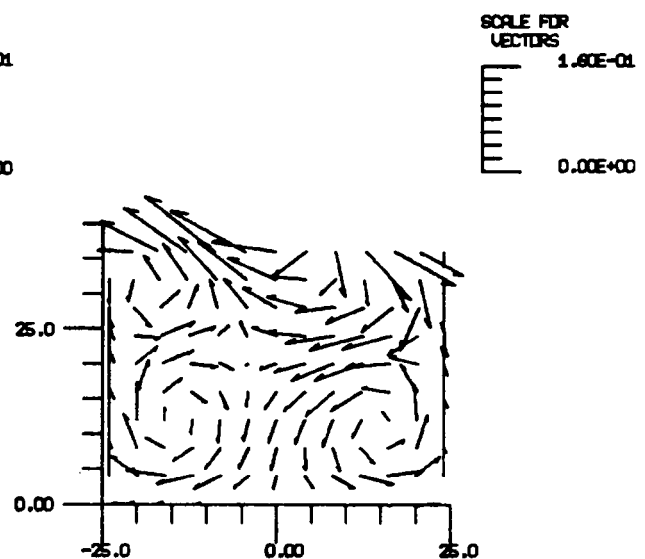
Time = 13.4



Time = 14.5

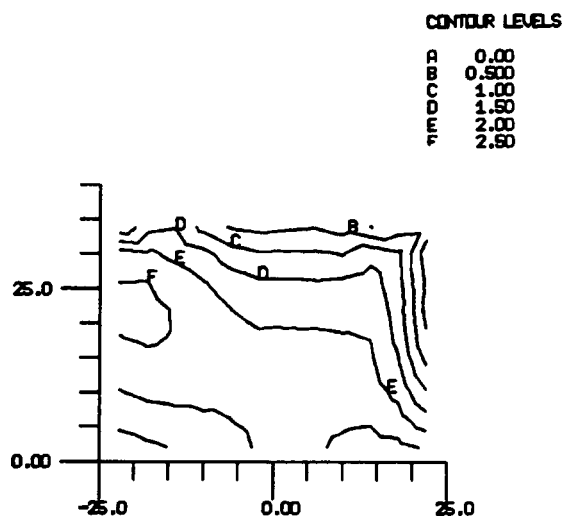


Time = 15.6

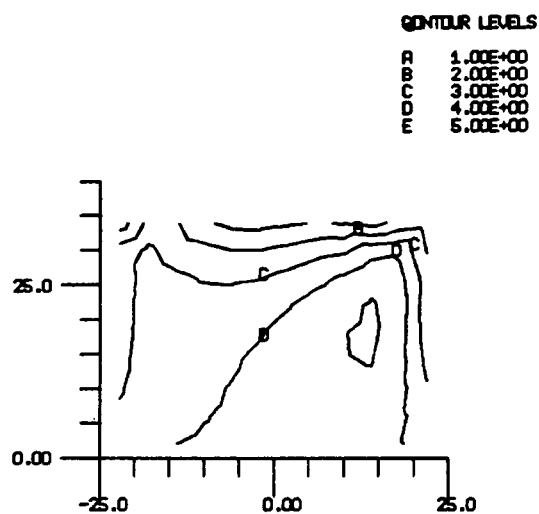


Time = 16.7

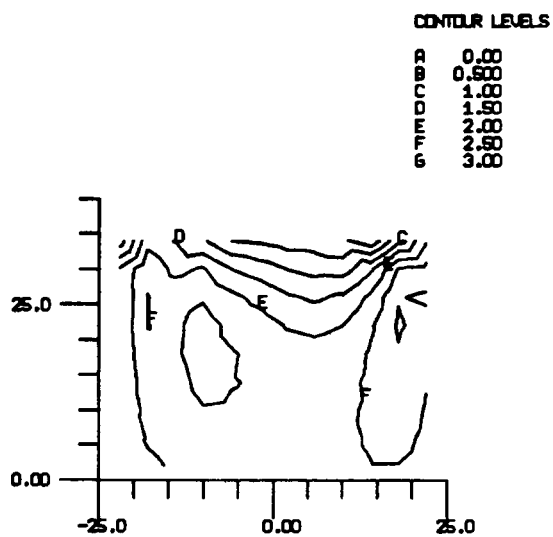
Figure 8.52 (continued)



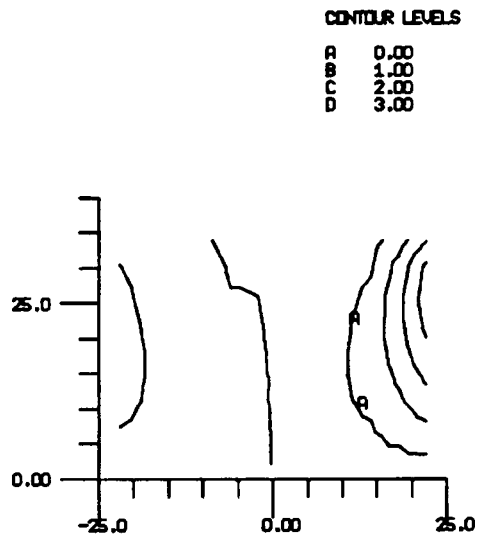
Time = 2.05



Time = 4.05



Time = 6.05

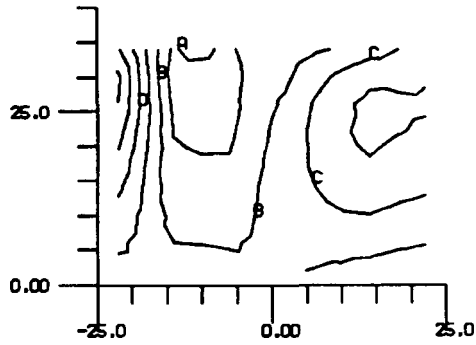


Time = 8.05

Figure 8.53. Contours of $p-p_0$ at several times for the fluid sloshing calculation with a simulated earthquake boundary condition.

CONTOUR LEVELS

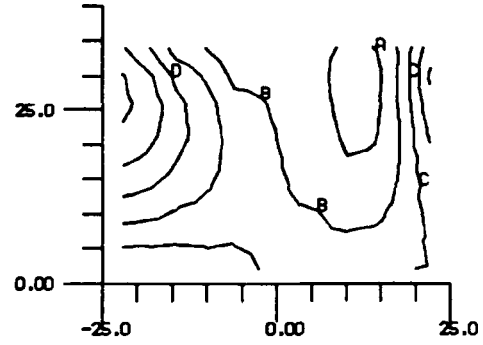
A	-5.00E-01
B	0.00E+00
C	5.00E-01
D	1.00E+00
E	1.50E+00
F	2.00E+00



Time = 9.16

CONTOUR LEVELS

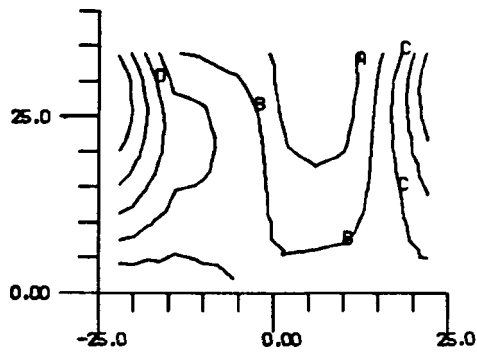
A	-5.00E-01
B	0.00E+00
C	5.00E-01
D	1.00E+00
E	1.50E+00
F	2.00E+00



Time = 10.2

CONTOUR LEVELS

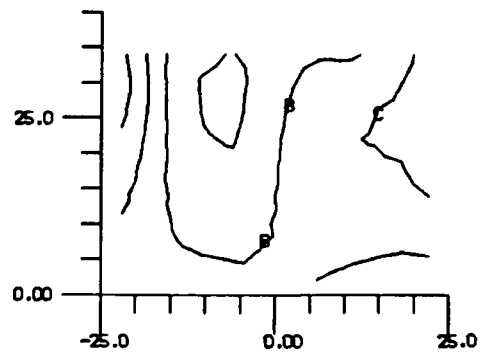
A	-5.00E-01
B	0.00E+00
C	5.00E-01
D	1.00E+00
E	1.50E+00
F	2.00E+00



Time = 11.3

CONTOUR LEVELS

A	-1.00E+00
B	0.00E+00
C	1.00E+00
D	2.00E+00

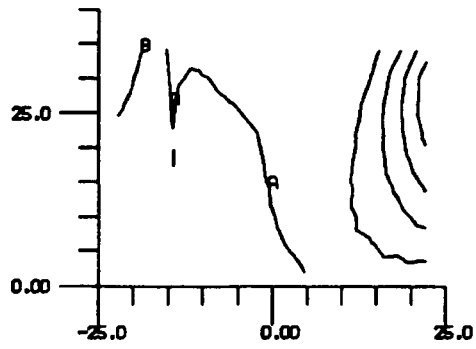


Time = 12.3

Figure 8.53 (continued)

CONTOUR LEVELS

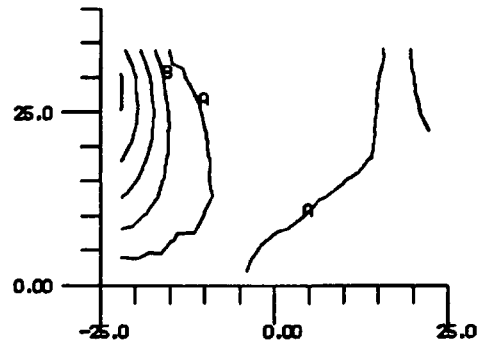
A 0.00
B 1.00
C 2.00
D 3.00



Time = 13.4

CONTOUR LEVELS

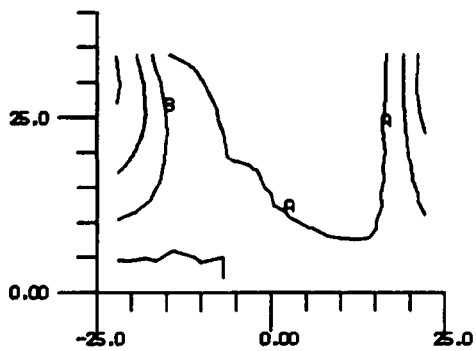
A 0.00
B 1.00
C 2.00
D 3.00
E 4.00



Time = 14.5

CONTOUR LEVELS

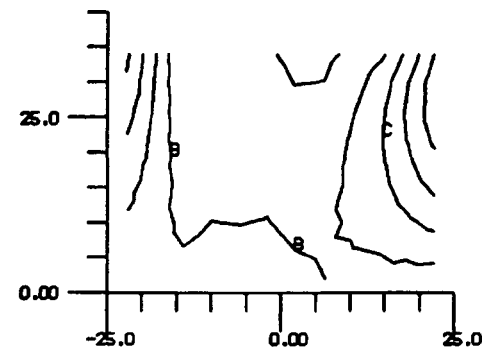
A 0.00
B 1.00
C 2.00
D 3.00



Time = 15.6

CONTOUR LEVELS

A -1.00E+00
B 0.00E+00
C 1.00E+00
D 2.00E+00
E 3.00E+00



Time = 16.7

Figure 8.53 (continued)

TABLE 8.10

DATA DECK FOR FLUID SLOSHING CALCULATION
WITH A SIMPLE SINE WAVE INPUT

```

TTL      LIQUID STORAGE TANK - SIMPLE ACCELERATION
PRB
PRO      2.0
SYM      1.0
MIN
GRV      -32.2      2.0      0.4
GRD      1.0      1.0      13.      10.
ITR      100.      .001      1.5
ALE      3.0      1.0      1.0
CPL      .25
END
MAT
121 RDN  1.0      1.94      2.0
END
GPT
211 ORIG 1.0      1.0      1.0      -24.      2.0      2.0
212 WPT  1.0      -24.      50.      2.0      0.0
212 WPT  2.0      -24.      0.0      1.0
212 WPT  3.0      24.      0.0      1.0
212 WPT  4.0      24.      50.      3.0
221 GPBLK 1.0      1.0      13.      1.0      10.
246 ZWING 1.0      -24.      4.0      0.0      4.0
END
ZON
311 ZBLK  1.0      1.0      13.      1.0      2.0      10.
321 MPN   1.0      1.0
322 SCLR  1.0      1.0
END
BDY
411 TLC   1.0      2.0      10.      1.0      2.0      10.
411 LFT   2.0      1.0      10.      1.0      1.0
411 BOT   3.0      1.0      1.0      13.      1.0
411 RHT   4.0      13.      1.0      13.      10.
412 TLC   1.0      1.0      6.0      2.0
412 LFT   2.0      1.0      6.0      2.0
412 BOT   3.0      1.0      6.0      3.0
412 RHT   4.0      1.0      6.0      4.0
422 MMBD  1.0      1.0
441 XVPNC 1.0      7.0      0.0      2.175
442 XVEL  1.0      2.23      0.46
443 YVPNC 1.0      7.0      0.0      .10
444 YVEL  1.0      0.0      2.0
481      1.0      1.0      4.0
482      1.0      1.0      4.0      5.0      1.0
END
TIM
511 DTSOR 0.1
512 DTLIM .02      0.1
521 MXT/C 13.      130.
END

```

(Continued on next page)

TABLE 8.10 (continued)

EDT					2.0	
616	PLTCY	2.0				
621	PREDT	1.0	0.0	20.	1.09	
622	PRLIM	1.0	13.	1.0	10.	
623	XPM	1.0	11.			
623	YPM	2.0	14.			
623	XVL	3.0	12.			
623	YVL	4.0	15.			
623	PRH	5.0	64.			
623	VSR	6.0	45.			
623	XAC	7.0	13.			
623	EX2	8.0	92.			
631	RSED	1.0	0.0	20.	1.09	
632	RSLIM	1.0	1.0	13.	1.0	10.
671	PLTHS	1.0	0.0	200.	1.0	
674	YPM	1.0	1.0	14.	1.0	001010.
674		2.0	1.0	14.	1.0	007010.
674		3.0	1.0	14.	1.0	013010.
675	PLTS	4.0	3.0			0.0
675		5.0	4.0	92.		1.09
675		6.0	5.0			1.09
675		7.0	4.0	92.		2.18
675		8.0	5.0			2.18
675		9.0	4.0	92.		3.27
675		10.	5.0			3.27
675		11.	4.0	92.		4.35
675		12.	5.0			4.35
675		13.	4.0	92.		5.44
675		14.	5.0			5.44
675		15.	4.0	92.		6.53
675		16.	5.0			6.53
675		17.	4.0	92.		7.62
675		18.	5.0			7.62
675		19.	4.0	92.		8.71
675		20.	5.0			8.71
675		21.	4.0	92.		9.80
675		22.	5.0			9.80
675		23.	4.0	92.		10.89
675		24.	5.0			10.89
675		25.	4.0	92.		11.98
675		26.	5.0			11.98
675		27.	4.0	92.		13.
675		28.	5.0			13.
674		29.	1.0	92.	1.0	002010.
674		30.	1.0	92.	1.0	002006.
674		31.	1.0	92.	1.0	002002.
674		32.	1.0	92.	1.0	013010.
674		33.	1.0	92.	1.0	013006.
674		34.	1.0	92.	1.0	013002.
674		35.	1.0	64.	1.0	002010.
674		36.	1.0	64.	1.0	002006.
674		37.	1.0	64.	1.0	002002.
674		38.	1.0	64.	1.0	013010.
674		39.	1.0	64.	1.0	013006.
674		40.	1.0	64.	1.0	013002.
674		41.	1.0	12.	1.0	001010.
674		42.	1.0	13.	1.0	001010.
674		43.	1.0	15.	1.0	001010.
674		44.	1.0	16.	1.0	001010.

(Continued on next page)

TABLE 8.10 (continued)

675	45.	3.0	1.09
675	46.	3.0	2.18
675	47.	3.0	3.27
675	48.	3.0	4.35
675	49.	3.0	5.44
675	50.	3.0	6.53
675	51.	3.0	7.62
675	52.	3.0	8.71
675	53.	3.0	9.80
675	54.	3.0	10.89
675	55.	3.0	11.98
675	56.	3.0	13.
END			
END			

Table 8.11. In addition to this input some modifications were made to the code for both calculations.

First, the excess pressure needs to be stored in one of the extra arrays for editing and plotting purposes. This involves storing the initial pressure in the EX1 array in Subroutine GENCHK by inserting

```
EX1(I,JT) = PRH(I,JT)
```

immediately after PRH(I,JT) is defined and then inserting the following statements at the beginning of Subroutine ZONNEW:

```
EX1N = EX10  
EX2N = PRHN - EX1N
```

In addition, the simulated earthquake boundary condition for the second calculation requires the following statement in Subroutine MYFNO:

```
VAL = FCA(1) * SIN(FCA(2) * PIE * VAR) +  
*      FCA(3) * SIN(FCA(4) * PIE * VAR) .
```

TABLE 8.11

DATA DECK FOR FLUID SLOSHING CALCULATION
WITH A SIMULATED EARTHQUAKE BOUNDARY CONDITION

```

TTL      LIQUID STORAGE TANK - EARTHQUAKE SIMULATION
PRB
PRO      2.0
SYM      1.0
MIN
GRV      -32.2      2.0      0.4
GRD      1.0      1.0      13.      10.
ITR      100.      .0001      1.5
ALE      3.0      1.0      1.0
CPL      .25
END
MAT
121 RDN  1.0      1.94      2.0
END
CPT
211 ORIG 1.0      1.0      1.0      -24.      2.0      2.0
212 WPT  1.0      -24.      50.      2.0      0.0
212 WPT  2.0      -24.      0.0      1.0
212 WPT  3.0      24.      0.0      1.0
212 WPT  4.0      24.      50.      3.0
221 GPBLK 1.0      1.0      13.      1.0      10.
246 ZNING 1.0      -24.      4.0      0.0      4.0
END
ZON
311 ZBLK  1.0      1.0      13.      1.0      10.
321 WPM  1.0      1.0
322 SCLR  1.0      1.0
END
BDY
411 TLC  1.0      2.0      10.      2.0      1.0      2.0
411 LFT  2.0      1.0      10.      1.0      10.
411 BOT  3.0      1.0      1.0      13.      1.0
411 RHT  4.0      13.      1.0      13.      10.
412 TLC  1.0      1.0      6.0
412 LFT  2.0      1.0      6.0
412 BOT  3.0      1.0      6.0
412 RHT  4.0      1.0      6.0
422 MMBD  1.0      1.0
441 XVFNC 1.0      9.0      0.0      8.0
442 XVEL  1.0      -.7235      2.125      .82      1.875
443 YVFNC 1.0      7.0      0.0      .10
444 YVEL  1.0      0.0      2.0
481      1.0      1.0      4.0
482      1.0      1.0      4.0      5.0      1.0
END
TIM
511 DTSOR .05
512 DTLIM .02      .1
513 DTFCR 1.20      8.0
521 MXT/C 17.      300.
END

```

(Continued on next page)

TABLE 8.11 (continued)

EDT					2.0	
616	PLTCV	2.0				
621	PREDT	1.0	0.0	8.0	2.0	
621	PREDT	2.0	8.0	20.	1.09	
622	PRLIN	1.0	13.	1.0	10.	
623	XPN	1.0	11.			
623	YPN	2.0	14.			
623	XVL	3.0	12.			
623	YVL	4.0	15.			
623	PRH	5.0	64.			
623	VSR	6.0	45.			
623	XAC	7.0	13.			
623	EX2	8.0	92.			
631	RSEDY	1.0	0.0	8.0	2.0	
631	RSEDY	2.0	8.0	20.	1.09	
632	RSLIN	1.0	1.0	13.	1.0	10.
671	PLTHS	1.0	0.0	300.	1.0	
674	YPN	1.0	1.0	14.	1.0	001010.
674		2.0	1.0	14.	1.0	007010.
674		3.0	1.0	14.	1.0	013010.
675	PLTS	4.0	3.0			0.0
675		5.0	4.0	92.		2.0
675		6.0	5.0			2.0
675		7.0	4.0	92.		4.0
675		8.0	5.0			4.0
675		9.0	4.0	92.		6.0
675		10.	5.0			6.0
675		11.	4.0	92.		8.0
675		12.	5.0			8.0
675		13.	4.0	92.		9.09
675		14.	5.0			9.09
675		15.	4.0	92.		10.18
675		16.	5.0			10.18
675		17.	4.0	92.		11.27
675		18.	5.0			11.27
675		19.	4.0	92.		12.35
675		20.	5.0			12.35
675		21.	4.0	92.		13.44
675		22.	5.0			13.44
675		23.	4.0	92.		14.53
675		24.	5.0			14.53
675		25.	4.0	92.		15.62
675		26.	5.0			15.62
675		27.	4.0	92.		16.71
675		28.	5.0			16.71
674		29.	1.0	92.	1.0	002010.
674		30.	1.0	92.	1.0	002006.
674		31.	1.0	92.	1.0	002002.
674		32.	1.0	92.	1.0	013010.
674		33.	1.0	92.	1.0	013006.
674		34.	1.0	92.	1.0	013002.
674		35.	1.0	64.	1.0	002010.
674		36.	1.0	64.	1.0	002006.
674		37.	1.0	64.	1.0	002002.
674		38.	1.0	64.	1.0	013010.
674		39.	1.0	64.	1.0	013006.
674		40.	1.0	64.	1.0	013002.
674		41.	1.0	12.	1.0	001010.
674		42.	1.0	13.	1.0	001010.
674		43.	1.0	15.	1.0	001010.
674		44.	1.0	16.	1.0	001010.
END						
END						

8.3 IMPLICIT, COMPRESSIBLE FLOW TEST PROBLEMS

8.3.1 Pipe Blowdown

8.3.1.1 Problem Description. Several 1D and 2D calculations of the blowdown of a straight pipe filled with pressurized water were performed to test the implicit, compressible flow codes in a regime similar to one that might be experienced in a loss-of-coolant accident (LOCA) in a water-cooled reactor. The calculations were intended to model a set of pipe depressurization experiments performed by Edwards and O'Brien (Reference 14). This problem has been designated Standard Problem 1 by the Nuclear Regulatory Commission and has been used as a test case for a number of different computer codes. Calculations of this problem using the explicit version STEALTH are reported in Volume 2, Article F of the STEALTH documentation.

In the pipe depressurization experiments, water at high pressure (500-2500 psig) and high temperature (467-650°F) was contained in a pipe 13.44 feet long with a 2.88-inch inner diameter. Seven diagnostic stations were placed along the pipe to measure pressure and temperature; X-ray instrumentation was placed at two stations for void fraction measurements.

The experiments were initialed by breaking a glass diaphragm at one end of the pipe with a pellet gun. Diaphragm opening time was estimated to be 1 millisecond. The diaphragm did not break cleanly but reduced the outflow area by an estimated 13%.

Although the experimenters attempted to achieve a uniform initial temperature distribution in the pipe, they were not completely successful. Temperatures measured before the experiment indicated a $\pm 3^{\circ}\text{F}$ variation along the axis of the pipe while the temperature variation over a cross-section was as much as 15°F . For the test modeled here (nominal initial conditions--1000 psig, 467°F), saturation pressures measured during

the experiment suggest a temperature variation along the pipe of about 16°F with a mean temperature considerably below the stated initial temperature.

Since the computed results are extremely sensitive to the initial temperature distribution, the uncertainty in this distribution introduces some ambiguity into the comparisons between the experiment and the computations. To help resolve this situation, the NRC has specified an initial temperature and enthalpy distribution based on the observed saturation pressures. In the calculations performed here, both the uniform distribution and the specified variable distribution were used.

8.3.1.2 Problem Set-Up. Several problems were run using both the 1D and 2D codes, but in all cases the flow was assumed to be completely one-dimensional. Therefore the effects of the 13% area reduction at the diaphragm and the divergence of the steam-water mixture after leaving the pipe were not included. These could have been included in the 2D calculations it was decided to do 2D calculations that would be directly comparable with the 1D calculations.

Two different configurations were calculated. They are shown schematically in Figure 8.54. One involved the full pipe which was 13.44 feet long. The other included only the section of the pipe 2.92 feet in length immediately adjacent to the diaphragm. The short pipe included only two of the seven gauge stations. The purpose of the short pipe configuration was to provide an economical test problem to investigate the early stages of the depressurization process. Both configurations were calculated with the 1D implicit, compressible flow code while only the short pipe configuration was calculated with the 2D code.

For the 1D problems the initial zone size was 2.54 cm so that a total of 160 zones were used for the full pipe configuration while 35 zones were used for the short pipe. The mesh was Lagrangian so the zone sizes increased as the fluid flowed out of the pipe. The symmetry was planar.

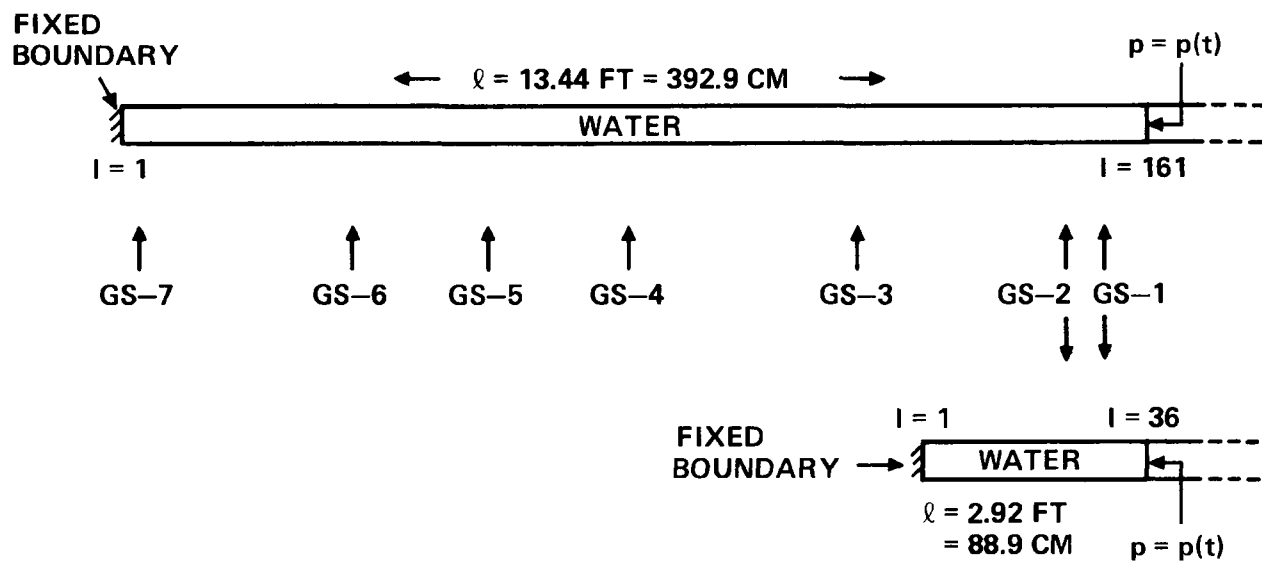


Figure 8.54. Configurations for pipe depressurization calculations showing the 1D problem setup.

In both cases the left boundary was fixed while a time-dependent pressure boundary condition was used at the right boundary to model the diaphragm opening. The gauge stations were located as shown in Figure 8.54.

Two 2D calculations of the short pipe were performed. One had a Lagrangian mesh while the other used the ALE rezoner in the Eulerian mode. The initial 2D mesh configuration for both calculations is shown in Figure 8.55. Cylindrical symmetry is used so that the left boundary is an axis of symmetry. The radial zone size is 2.44 cm and the axial zone size is 2.54 cm (the same as in 1D). The mesh is made up of 3 (radial) x 35 (axial) zones for a total of 105 zones or 144 grid points. The right and left boundaries are free-slip walls which extend a large distance beyond the diaphragm location to maintain one-dimensionality of the escaping fluid. The bottom boundary is fixed. For the Lagrangian calculation a time-dependent pressure boundary condition was used at the top boundary, while for the Eulerian calculation a continuous outflow boundary condition was used at the top. This was done to provide a test for this newly added boundary condition even though it is not as realistic a simulation of the experiment as the time-dependent pressure boundary condition.

The expression for the time-dependent boundary condition which is extended to simulated the diaphragm opening is

$$P(t) = a_1 e^{(a_2 e^{a_3 t})} + a_4$$

where

$$\begin{aligned} a_1 &= 76.219446 \text{ bars,} \\ a_2 &= -0.1, \\ a_3 &= 4.0 \text{ msec,} \\ a_4 &= 1.0137931 \text{ bars.} \end{aligned}$$

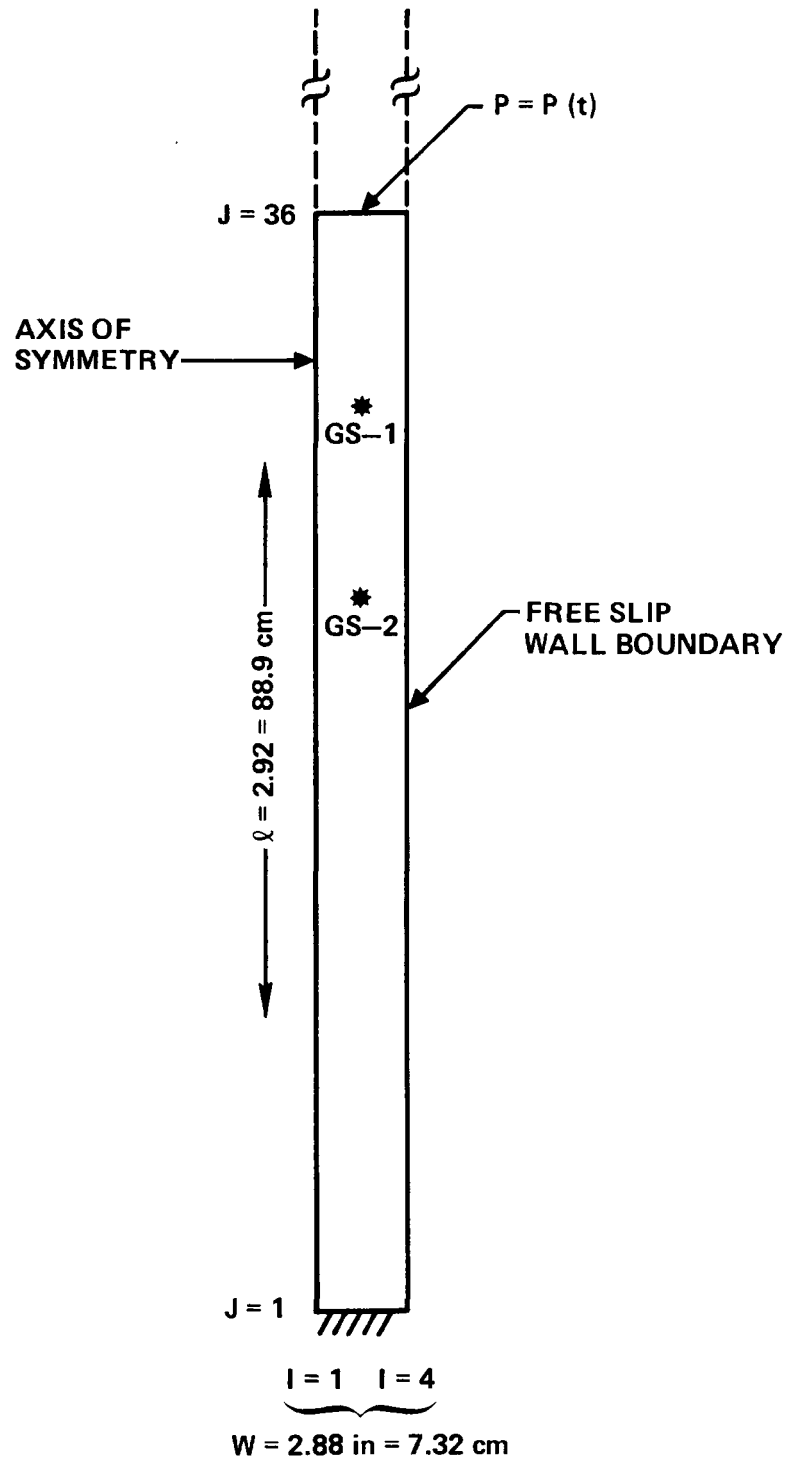


Figure 8.55. Initial configuration for the 2D pipe depressurization calculations.

This function has a value of 69.98 bars at $t = 0$ and drops to 1 atmosphere for $t > 1$ msec. The form of the function up to 1 msec can be seen by examining the function $e^{(a_2 e^{a_3 t})}$ which is plotted in Figure 8.56.

For the calculation using the uniform initial temperature and enthalpy distribution, the initial conditions are

$$\begin{aligned} P_o &= 1014.7 \text{ psi} = 69.98 \text{ bars} \\ t_o &= 467^\circ\text{F} \\ H_o &= 450 \text{ Btu/lbm.} = 1.047 \times 10^4 \text{ bar cm}^3/\text{gm} \\ E_o &= 446.3 \text{ Btu/lbm} = 1.038 \times 10^4 \text{ bar cm}^3/\text{gm} \\ v &= 1.2285 \text{ cm}^3/\text{gm} \end{aligned}$$

For the calculations using the specified initial temperature distribution, the initial conditions at each gauge station are provided in Table 8.12. Linear interpolation is used to define the initial conditions at intermediate points. The initial pressure is uniform with a value of 69.98 bars.

The water equation of state used for these calculations was a simple homogeneous, equilibrium, two-phase model based on the 1967 ASME steam tables (Reference 15). This is an updated version of the equation of state used for the explicit STEALTH calculations of these problems which is described in Volume 2, Article F. Since this is not a standard STEALTH model, it was programmed as a user-supplied model into subroutine MYPRH. A listing of that subroutine is provided at the end of this section.

The initial time step used for these calculations was 0.02 msec which is only about 25% larger than the stable explicit time step. Because of the extreme nonlinearity of the water equation of state at the saturated liquid phase line, it was necessary to use a relatively small time step to maintain a stable iteration in the implicit phase. This was because the problems were run using the Newton-Raphson iteration method which does not

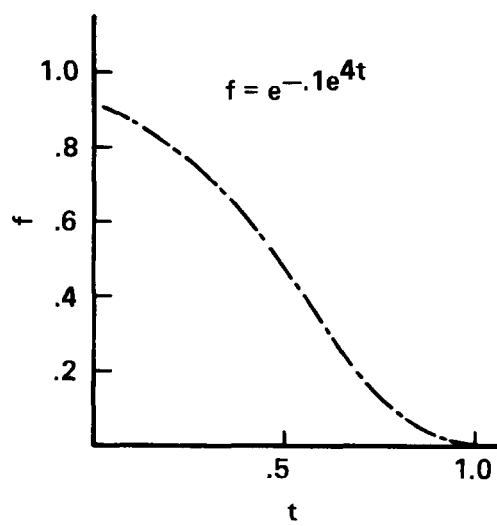


Figure 8.56. Function for pressure boundary condition.

TABLE 8.12

INITIAL CONDITIONS AT GAUGE LOCATIONS
FOR SPECIFIED ENTHALPY DISTRIBUTION

	Guage Station Number						
	1	2	3	4	5	6	7
$T_o (^{\circ}F)$	437.0	436.0	450.0	447.5	450.0	452.0	447.0
H_o (Btu/lbm)	416.0	415.0	430.6	427.0	430.6	433.0	427.0
(10^3 bar-cm ³ /gm)	9.675	9.652	10.014	9.931	10.014	10.070	9.931
E_o (Btu/lbm)	412.4	411.4	426.9	423.4	426.9	429.3	423.4
(10^3 bar-cm ³ /gm)	9.591	9.568	9.929	9.847	9.929	9.852	9.847
V (cm ³ /gm)	1.1942	1.1932	1.2083	1.2047	1.2083	1.2180	1.2047

work well for highly nonlinear problems. The two-sided secant method was added to the codes later to correct this problem, and two of the problems were rerun (1D and 2D short pipe with uniform initial enthalpy). For these calculations the time step was increased to 0.05 msec and probably could have been increased further if the resolution accuracy of the propagating rarefaction had not been an overriding factor.

Later in the calculations, when the entire contents of the pipe had entered the mixed phase region of the equation of state, the time step was allowed to increase by 10% per cycle to a maximum value of 2 msec, although in some cases the automatic time step calculation limited the time step below this maximum value. In the 2D Eulerian calculation, since the zone size remained at 2.54 cm throughout the calculation, the time step was limited to a value substantially below the maximum.

The short pipe calculations were run to a final time of 15 msec, while the full pipe calculations were run to 600 msec in order to observe the late-time venting of the pipe. In the case of the specified initial enthalpy distribution, regions of subcooled liquid persisted for a long time (about 100 msec). Since a relatively small time step was needed for that initial period, that calculation ended up being relatively lengthy (although using the two-sided secant method would have reduced it substantially). Therefore, this calculation is not recommended as a test problem for new users. The short pipe problems, particularly those with uniform initial enthalpy, are considerably less expensive to run. They would make reasonable test problems for those attempting to acquaint themselves with the implicit, compressible flow codes.

8.3.1.3 Results. The results of the 1D calculations for the full pipe are shown in Figures 8.57 - 8.62 and are compared with experimental data. Figures 8.57 - 8.59 show pressure histories during the early stages of the blowdown at gauge stations 1, 3, and 6. Figures 8.60 - 8.62 show pressure histories for the same gauge stations over the entire 600 msec duration of the calculation.

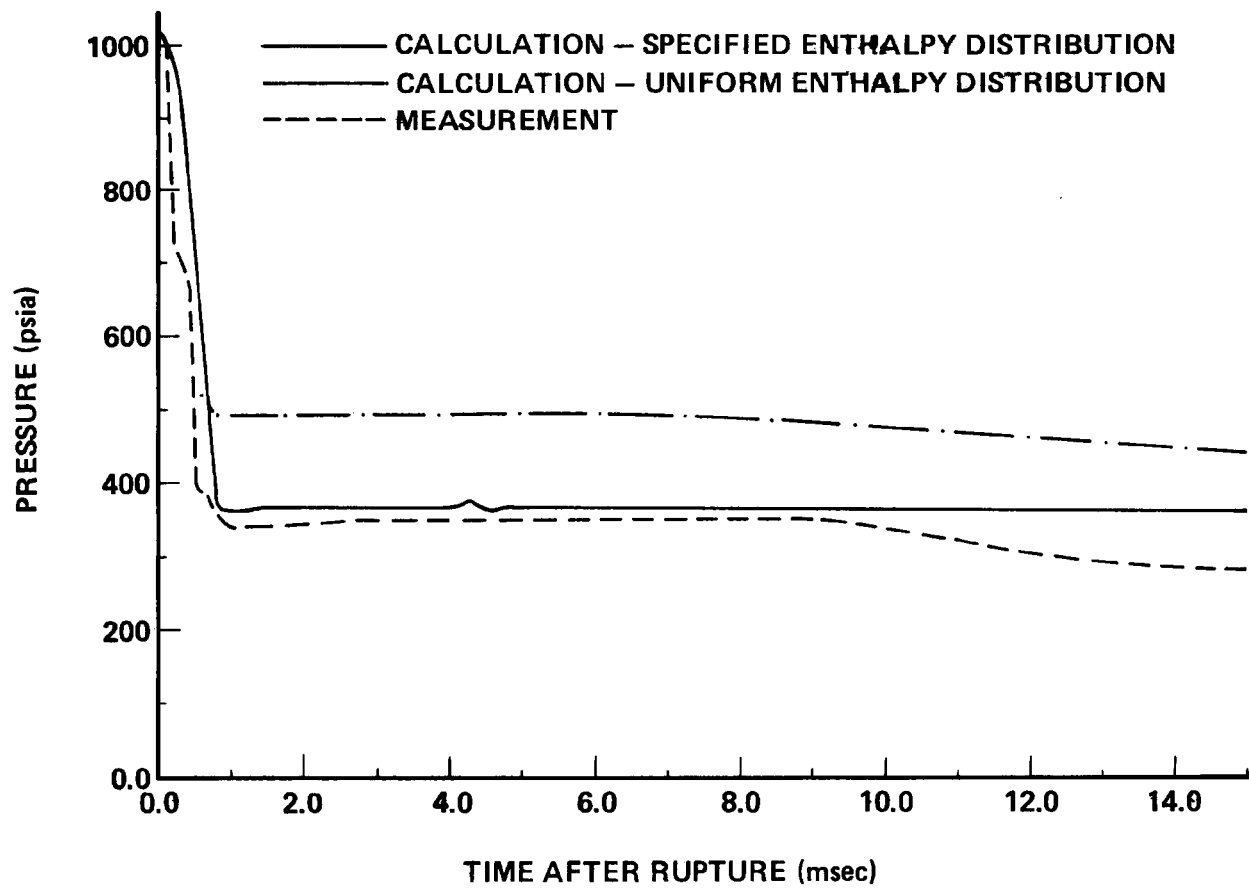


Figure 8.57. Comparison of pressure histories at gauge station 1 for the first 15 msec of the 1D full pipe depressurization calculations.

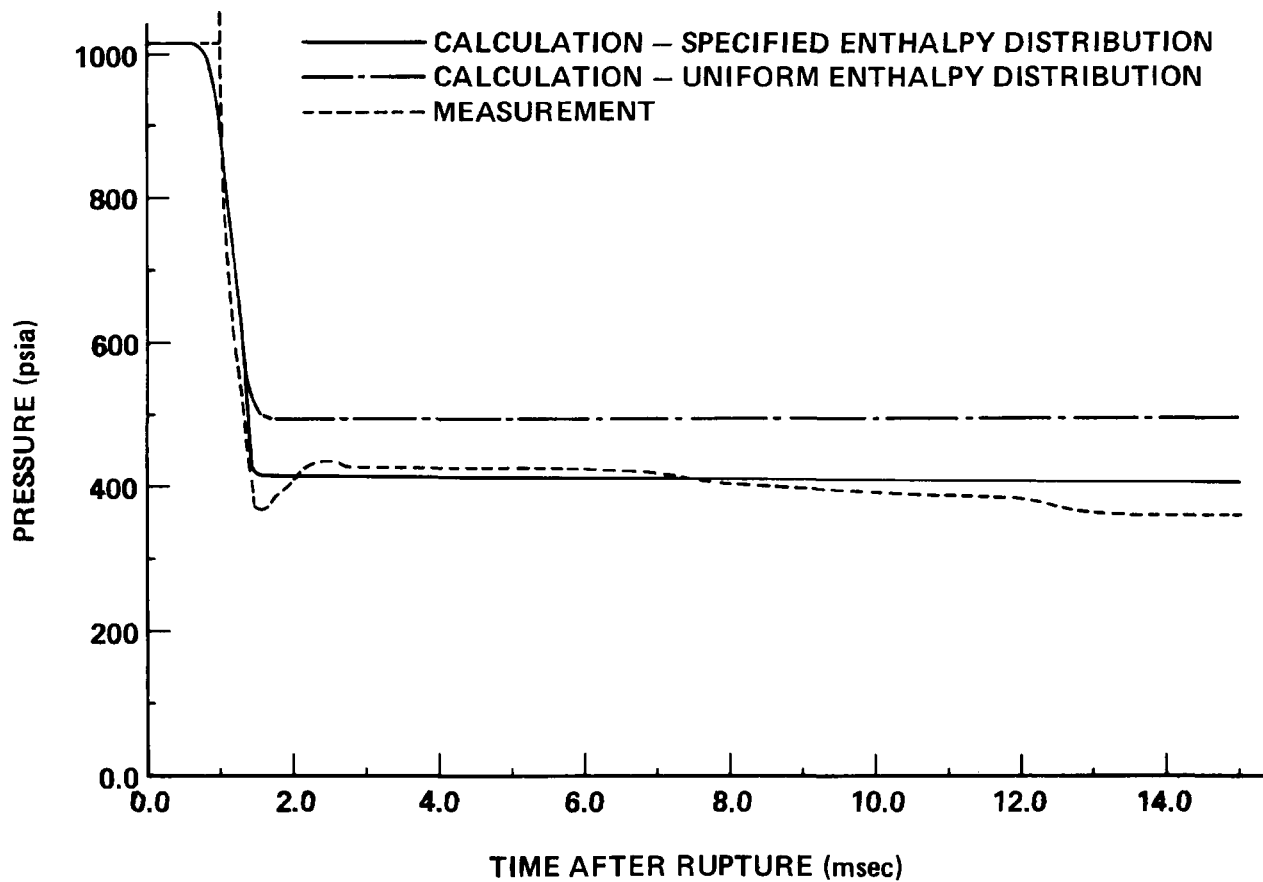


Figure 8.58. Comparison of pressure histories at gauge station 3 for the first 15 msec of the 1D full pipe depressurization calculations.

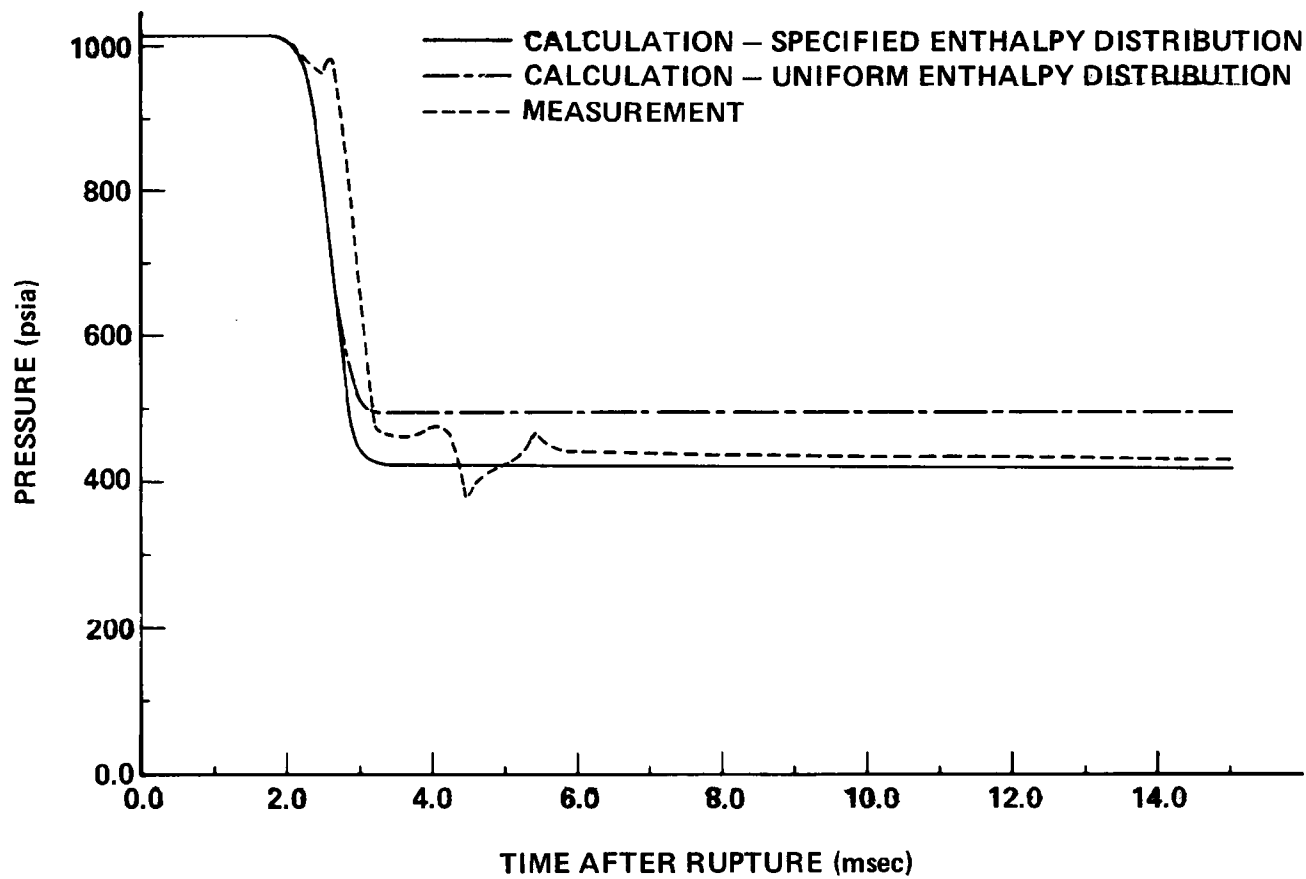


Figure 8.59. Comparison of pressure histories at gauge station 6 for the first 15 msec of the 1D full pipe depressurization calculations.

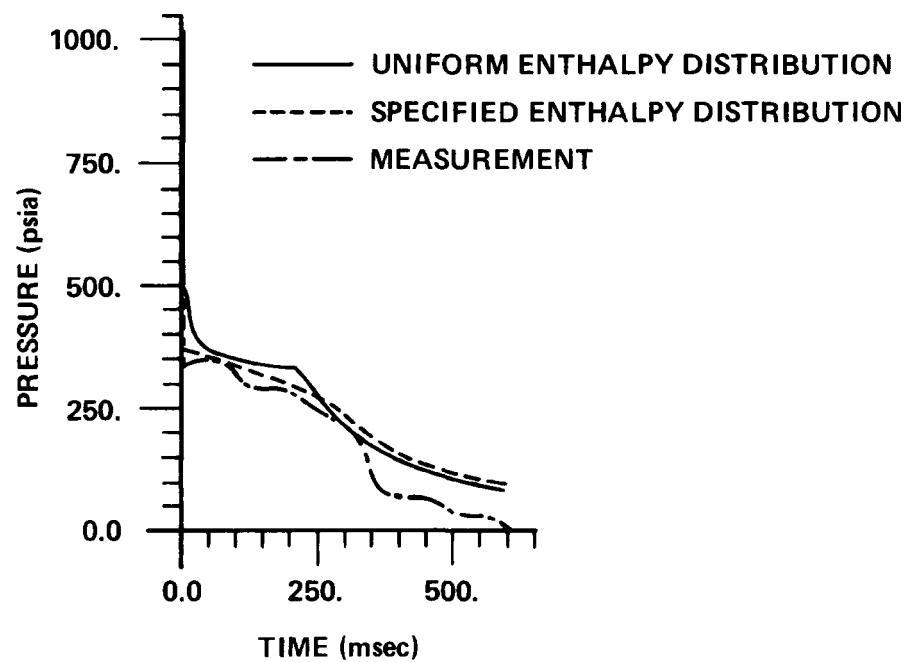


Figure 8.60. Comparison of the entire pressure histories at gauge station 1 for the 1D full pipe depressurization calculations.

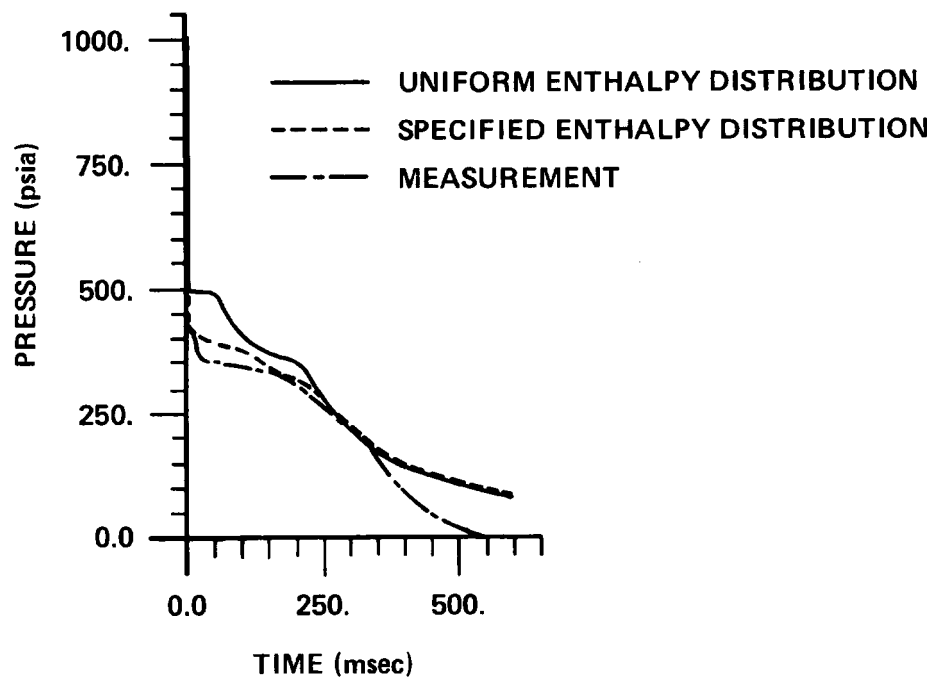


Figure 8.61. Comparison of the entire pressure histories at gauge station 3 for the 1D full pipe depressurization calculations.

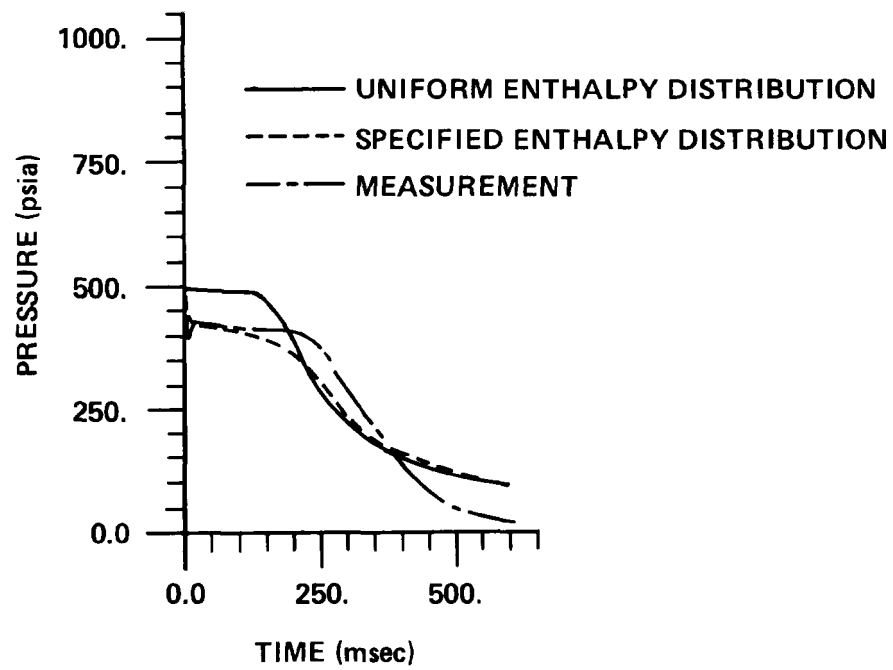


Figure 8.62. Comparison of the entire pressure histories at gauge station 6 for the 1D full pipe depressurization calculations.

During the early stages, the calculation using the specified initial enthalpy distribution agrees reasonably well with the measured pressures. The calculation using the uniform initial enthalpy distribution predicts a considerably higher pressure. The same thing was found by other calculators (Reference 16). During the later stages the agreement between the specified enthalpy calculation and the measurements continues to be good until times on the order of 300-400 msec where the measured pressures drop more quickly to zero. The failure of the calculations to predict this behavior is most likely caused by the 1D approximation for the expanding steam-water mixture. Surprisingly, at late times the two calculations agree quite closely despite the larger differences at early times.

Figure 8.63 provides a comparison of the results for the calculations of the short pipe calculations. This configuration was calculated using the 1D code as well as the 2D code with both Lagrangian and Eulerian meshes. Both the uniform and specified enthalpy distributions were calculated with the 1D codes while only the uniform distribution was calculated in 2D. All the calculations were run to a time of 15 msec which covers only the early stages of the blowdown.

The uniform enthalpy calculations agree very closely. They are essentially identical out to a time of about 6 msec at which time the 2D calculations begin to predict slightly lower pressures. The initial pressure drop in the 2D Eulerian calculation occurs somewhat earlier than in the other calculations because of the absence of the pressure boundary condition simulating the diaphragm opening. For times greater than 6 msec the pressure from the 2D Eulerian calculation is somewhat lower than in the 2D Lagrangian calculation. This can perhaps also be attributed to the absence of the pressure boundary condition which at late times ($t \geq 1$ msec) applies a constant pressure of 1 atmosphere at the boundary.

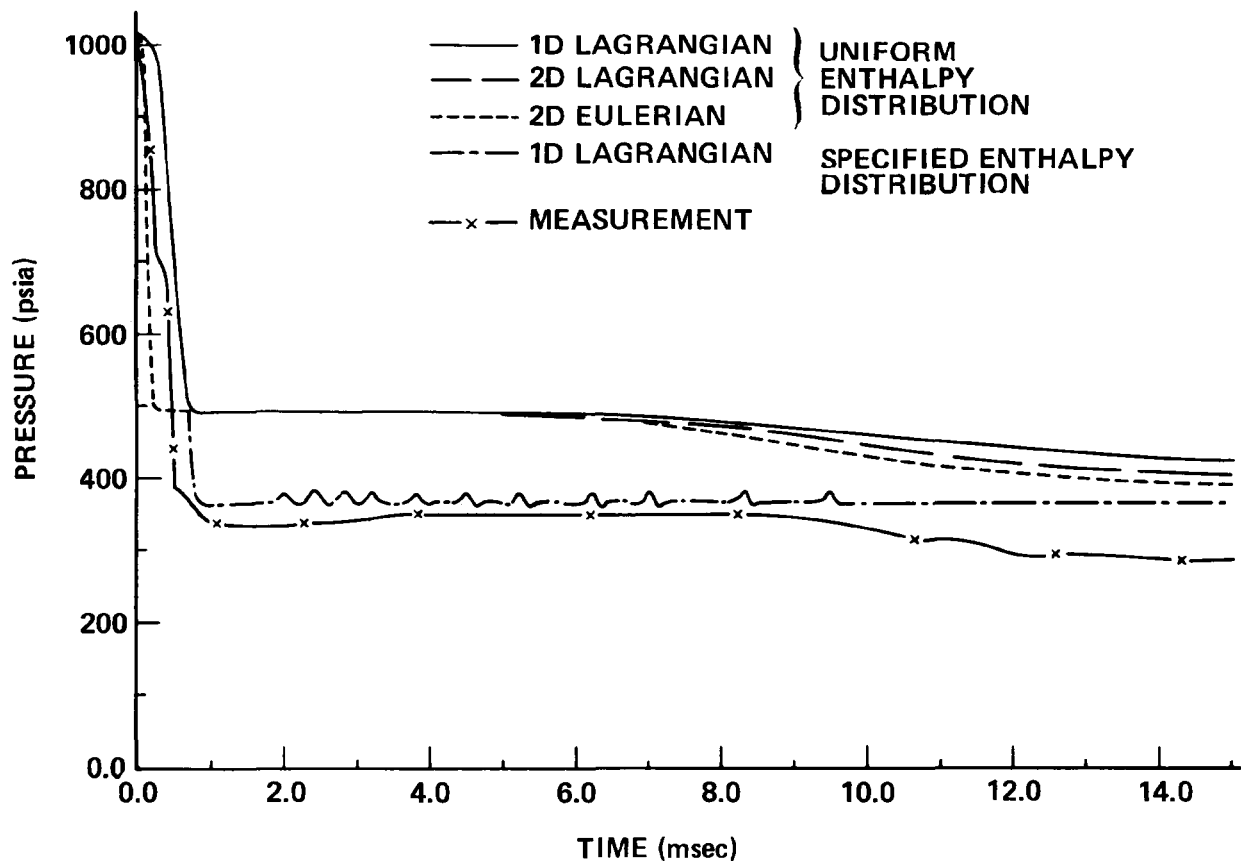


Figure 8.63. Comparison of pressure histories at gauge station 1 for the 1D short pipe depressurization calculations.

The 1D calculation of the specified enthalpy problems compares reasonably well with the experimental data over this range of time. In fact it is virtually identical to the equivalent full pipe calculation with the exception of some small amplitude perturbations. These are caused reflections of pressure waves from local regions of subcooled liquid and from the ends of the pipe. Because the pipe is much shorter these oscillations seem to occur much more frequently.

For comparison with the the calculations done here, the results of similar calculations performed using the 1D explicit STEALTH codes as well as some performed by Aerojet Nuclear are presented in Figure 8.64. The STEALTH calculations are for the short pipe configurations while the Aerojet Nuclear calculations are for the full pipe. Because they overlay almost exactly on the 1D calculations shown in Figure 8.63, they are presented here in a separate figure.

8.3.1.4 Input Decks. The input decks for the four calculations using the uniform enthalpy distribution are provided in Tables 8.13 - 8.16. The specified enthalpy distribution was not initialized by standard input, but rather the STEALTH generator was modified to calculate the required variables directly. Therefore, input decks for those calculations are not included here since they are of no use without the generator modifications.

8.3.2 Thermally Driven Cavity

8.3.2.1 Problem Description. This problem consists of a gas filled cylindrical container heated on the vertical boundary. The gas is initially in hydrostatic equilibrium at a constant temperature of 300°K while the vertical wall is kept at a constant temperature of 304°K . As the gas adjacent to the wall is heated, buoyancy causes an upward flow in that region resulting in a counter-clockwise circulation. The problem parameters are such that a single convection cell results.

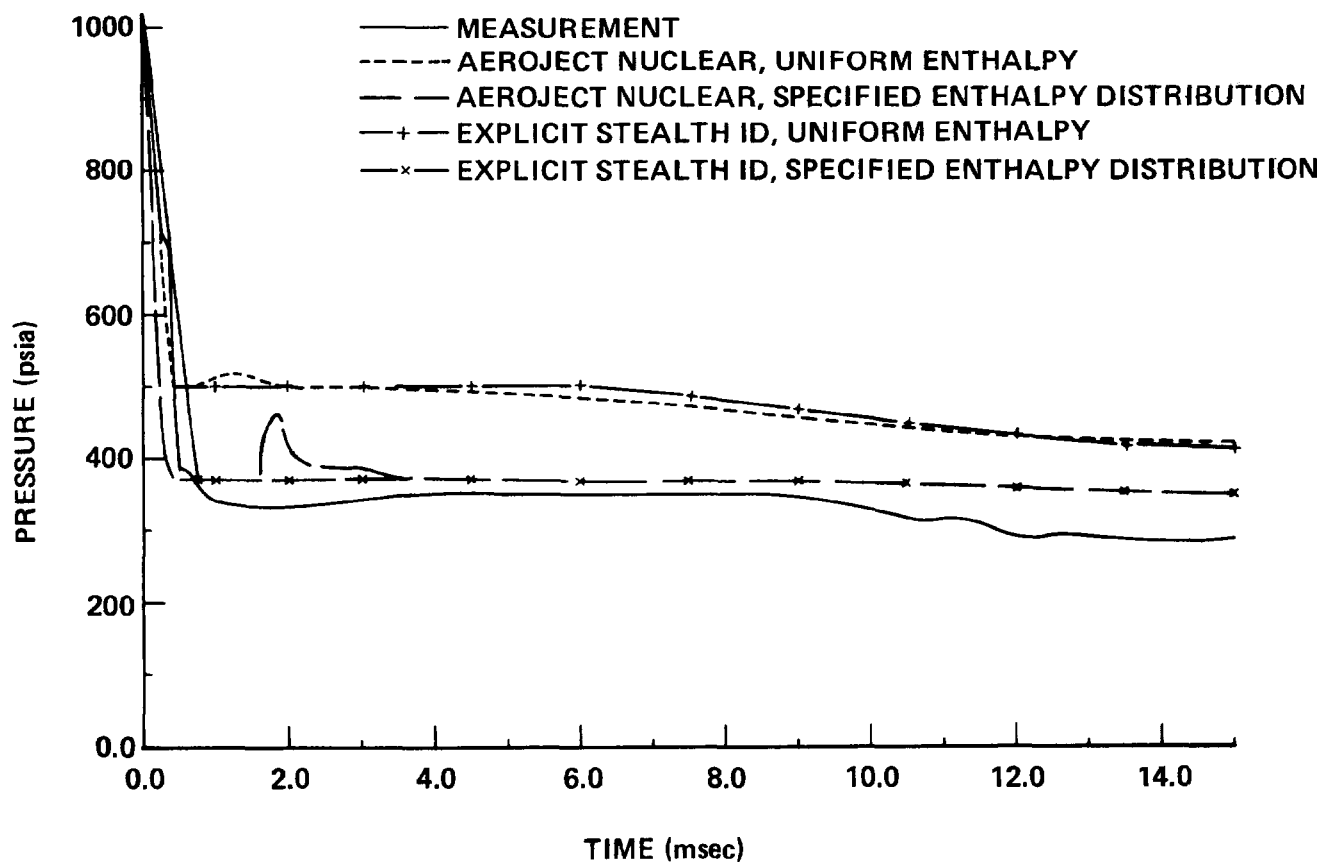


Figure 8.64. Pressure histories at gauge station 1 for pipe depressurization calculations performed with other codes.

TABLE 8.13

DATA DECK FOR 1D FULL PIPE DEPRESSURIZATION CALCULATION
WITH UNIFORM ENTHALPY DISTRIBUTION

TTL	STD. PROB. 1 - UNIFORM ENTHALPY, FULL PIPE, 1D				
PRB					2.0
PRO	1.0				
MIN	1.0	.000001	.000001	.000001	.05
GRD	1.0	1.0	161.		
ITR	200.	.001	1.0		
END					
MAT					2.0
111	1.0	6.0			
121	1.0	1.0			
122	1.0	1.0	0.0	20000.	
171	1.0	.00000001			
END					
GPT					2.0
211	1.0	1.0		0.0	0.0
221	1.0	1.0	161.		
241	1.0	160.	0.0	409.65	0.0
END					
ZON					2.0
311	1.0	1.0	161.		
321	1.0	1.0			
322	1.0	1.2284943	10380.03		69.98
341	1.0	-69.98	-69.98	-69.98	
END					
BDY					2.0
421	1.0	5.0	5.0		
421	161.	2.0	5.0	1.0	
422	1.0	1.0			
431	1.0	5.0	0.0	1000.	
432	1.0	76.219446	-0.1	4.0	1.0137931
END					
TIM					2.0
511	.02				
512	.01	2.0			
513	1.1		4.0		
521	600.	1000.			
END					
EDT					2.0
621	1.0	0.0	1.0	.25	
621	2.0	1.0	4.0	1.0	
621	3.0	5.0	20.	5.0	
621	4.0	25.	25.	25.	
621	5.0	50.	50.	50.	
621	6.0	100.	500.	100.	
622	1.0	161.			
623	1.0	11.			
623	2.0	12.			
623	3.0	64.			
623	4.0	45.			
623	5.0	42.			
623	6.0	51.			
623	7.0	55.			
623	8.0	66.			
END					
END					

TABLE 8.14

DATA DECK FOR 1D SHORT PIPE DEPRESSURIZATION CALCULATION
WITH UNIFORM ENTHALPY DISTRIBUTION

TTL	STD. PROB. 1 - UNIFORM ENTHALPY, SHORT PIPE, 1D				
PRB					2.0
PRO	1.0				
MIN	1.0	.000001	.000001	.000001	.05
GRD	1.0	1.0	36.		
ITR	200.	.001	1.0		
END					
MAT					2.0
111	1.0	6.0			
121	1.0	1.0			
122	1.0	1.0	0.0	20000.	
171	1.0	.00000001			
END					
GPT					2.0
211	1.0	1.0		0.0	0.0
221	1.0	1.0	36.		
243	1.0	35.	0.0	2.54	0.0
END					
ZON					2.0
311	1.0	1.0	36.		
321	1.0	1.0			
322	1.0	1.2284943	10380.03		69.98
341	1.0	-69.98	-69.98	-69.98	
END					
BDY				2.0	2.0
421	1.0	5.0	5.0		
421	36.	2.0	5.0	1.0	
422	1.0	1.0			
431	1.0	5.0	0.0	50.	
432	1.0	76.219446	-0.1	4.0	1.0137931
END					
TIM					2.0
511	.02				
512	.01	2.0			
513	1.01		2.0		
521	15.	500.			
END					
EDT					2.0
621	1.0	0.0	0.1	.05	
621	2.0	0.1	0.9	0.1	
621	3.0	1.0	4.0	0.5	
621	4.0	5.0	10.	1.0	
622	1.0	36.			
623	1.0	11.			
623	2.0	12.			
623	3.0	64.			
623	4.0	45.			
623	5.0	42.			
623	6.0	51.			
623	7.0	55.			
623	8.0	66.			
END					
END					

TABLE 8.15

DATA DECK FOR 2D LAGRANGIAN SHORT PIPE DEPRESSURIZATION
 CALCULATION WITH UNIFORM ENTHALPY DISTRIBUTION

TTL	STD. PROB. 1 - UNIFORM ENTHALPY, SHORT PIPE, 2D LAGRANGIAN				
PRB	2.0				
PRO	2.0				
SYM	2.0				
MIN	1.0	.000001	.000001	.000001	.00000001
GRD	1.0	1.0	4.0	36.	
ITR	200.	.001	1.0		
END					
MAT					2.0
111	1.0	6.0			
121	1.0	1.0			
122	1.0	1.0	0.0	20000.	
171	1.0	.000000001			
END					
GPT				2.0	2.0
211	1.0	1.0	1.0	0.0	0.0
212	1.0	0.0	267.	2.0	
212	2.0	0.0	0.0	1.0	
212	3.0	7.3152	0.0	1.0	
212	4.0	7.3152	267.	3.0	
221	1.0	1.0	4.0	1.0	36.
246	1.0	0.0	2.4384	0.0	2.54
END					
ZON					2.0
311	1.0	1.0	4.0	1.0	36.
321	1.0	1.0			
322	1.0	1.2284943	10380.03		69.98
341	1.0	-69.98	-69.98	-69.98	
END					
BDY					2.0
411	1.0	1.0	1.0	4.0	1.0
411	2.0	4.0	1.0	4.0	35.
411	3.0	4.0	35.	4.0	36.
411	4.0	4.0	36.	1.0	36.
411	5.0	1.0	36.	1.0	1.0
412	1.0	1.0	6.0	5.0	3.0
412	2.0	1.0	6.0	5.0	4.0
412	3.0	1.0	2.0	5.0	1.0
412	4.0	1.0	2.0	5.0	1.0
412	5.0	1.0	6.0	5.0	2.0
422	1.0	1.0			
431	1.0	5.0	0.0	50.	
432	1.0	76.2194	-0.1	4.0	1.01379
481	1.0	1.0	4.0		
482	1.0	1.0	5.0	5.0	0.5
END					
TIM					2.0
511	.02				
512	.01	2.0			
513	1.01		2.0		
521	15.	1000.			
END					

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TABLE 8.15 (continued)

EDT					2.0
611	1.0				
621	1.0	0.0	0.1	0.05	
621	2.0	0.1	0.9	0.1	
621	3.0	1.0	4.0	1.0	
621	4.0	5.0	10.	2.0	
622	1.0	4.0	1.0	36.	
623	1.0	11.			
623	2.0	14.			
623	3.0	12.			
623	4.0	15.			
623	5.0	64.			
623	6.0	66.			
623	7.0	92.			
623	8.0	51.			
END					
END					

TABLE 8.16

DATA DECK FOR 2D EULERIAN SHORT PIPE DEPRESSURIZATION
 CALCULATION WITH UNIFORM ENTHALPY DISTRIBUTION

STD. PROB. 1 - UNIFORM ENTHALPY, SHORT PIPE, 2D EULERIAN					
TTL					
PRB					2.0
PRO	2.0				
SYM	2.0				
MIN	1.0	.000001	.000001	.000001	.00000001
GRD	1.0	1.0	4.0	36.	
ITR	200.	.001	1.0		
ALE	2.0	1.0	1.0		
END					
MAT					2.0
111	1.0	6.0			
121	1.0	1.0			
122	1.0	1.0	0.0	20000.	
171	1.0	.00000001			
END					
GPT				2.0	2.0
211	1.0	1.0	1.0	0.0	0.0
212	1.0	0.0	267.	2.0	
212	2.0	0.0	0.0	1.0	
212	3.0	7.3152	0.0	1.0	
212	4.0	7.3152	267.	3.0	
221	1.0	1.0	4.0	1.0	36.
246	1.0	0.0	2.4384	0.0	2.54
END					
ZON					2.0
311	1.0	1.0	4.0	1.0	36.
321	1.0	1.0			
322	1.0	1.2284943	10380.03		69.98
341	1.0	-69.98	-69.98	-69.98	
END					
BDY					2.0
411	1.0	1.0	1.0	4.0	1.0
411	2.0	4.0	1.0	4.0	35.
411	3.0	4.0	35.	4.0	36.
411	4.0	4.0	36.	1.0	36.
411	5.0	1.0	36.	1.0	1.0
412	1.0	1.0	6.0	5.0	3.0
412	2.0	1.0	6.0	5.0	4.0
412	3.0	1.0	9.0	5.0	
412	4.0	1.0	9.0	5.0	
412	5.0	1.0	6.0	5.0	2.0
481	1.0	1.0	4.0		
482	1.0	1.0	5.0	5.0	0.5
END					
TIM					2.0
511	.02				
512	.01	2.0			
513	1.01	.25	2.0		
521	15.	1000.			
END					

(Continued on next page)

TABLE 8.16 (continued)

EDT					2.0
611	1.0				
621	1.0	0.0	0.1	0.05	
621	2.0	0.1	0.9	0.1	
621	3.0	1.0	4.0	1.0	
621	4.0	5.0	10.	2.0	
622	1.0	4.0	1.0	36.	
623	1.0	11.			
623	2.0	14.			
623	3.0	12.			
623	4.0	15.			
623	5.0	64.			
623	6.0	42.			
623	7.0	45.			
623	8.0	51.			
END					
END					

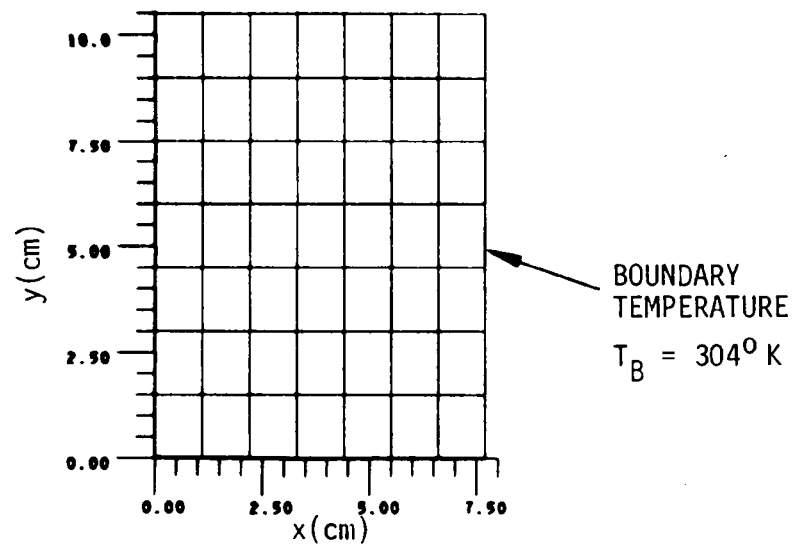
8.3.2.2 Problem Set-Up. The problem was previously used as a test problem for the SOLA-ICE code (Reference 5). Therefore, in setting up the STEALTH calculation the configuration used for the SOLA-ICE calculation was followed as closely as possible in order to make a comparison of the results.

The problem was modeled with the 2D implicit, compressible STEALTH code as shown in Figure 8.65. The Eulerian mesh is 8 x 8 with a cell size of 1.1 x 1.5 cm. The symmetry is cylindrical with the left boundary being an axis of symmetry. All four walls have a rigid, free-slip mechanical boundary condition. For the thermal boundary conditions the right wall has a constant temperature of 304 while the other three are adiabatic.

The initial interior temperature is 300°K and the initial pressure is such that hydrostatic equilibrium exists for a gravitational acceleration of $g_y = -10^{-3} \text{ cm/sec}^2$. This is achieved by setting the initial relative volumes as shown in the input deck (Section 8.3.2.4).

The interior fluid is modeled as a polytropic gas with a reference density of $\rho = 10^{-4} \text{ gm/cm}^2$ and $\gamma = 1.4$. The shear viscosity coefficient, specific heat and thermal conductivity are provided in Figure 8.65.

The fluid velocity generated by the buoyancy effects is very small (the Mach number is $\sim 10^{-4}$) so that it takes a long time for a flow field to become established that even approaches steady state. Therefore it is necessary to use a relatively large time step. The time step was chosen to be 1×10^{-2} seconds initially, building up by 10% per cycle to a maximum, value of 7.5×10^{-4} , which is the time step used in the SOLA-ICE calculation. This is a factor of about 24 larger than the stable explicit time step, but about a factor of 70 smaller than the stable implicit time step calculated by the automatic time step calculation. A larger time step was impractical, however, because of the large number of iterations



INITIAL CONDITIONS

$$\rho_0 = 10^{-4}$$

$$E_0 = 2.1727 \times 10^9 \text{ ergs/cm}$$

$$T_0 = 300^0 \text{ K}$$

$$G_y = -10^{-3}$$

MATERIAL PROPERTIES

$$\gamma = 1.4$$

$$\mu = 4 \times 10^{-4} \text{ poise}$$

$$C_v = 7.2424 \times 10^6 \text{ ergs/cm } ^0\text{K}$$

$$K = 5.71233 \times 10^2 \text{ ergs/}^0\text{K-cm-sec}$$

Figure 8.65. Configuration for thermally driven cavity problem.

required during the initial transient phase while the steady state flow was being established.

The convergence variable was chosen to be the same as was used in the SOLA-ICE calculation i.e., $\epsilon = 5 \times 10^{-8}$. It is claimed in Reference 5 that this is necessary to maintain stability of the initial hydrostatic pressure gradient. The value was established empirically.

8.3.2.3 Results. The calculated velocity vector field at several times is shown in Figures 8.66 - 8.69. Initially the flow is primarily to the left as shown in Figure 8.66. This is produced by the initial increase in pressure on the right caused by heat conduction from the constant temperature wall. Subsequent figures show that buoyancy effect gradually assert themselves so that a convection cell is established by the final problem time of 0.2 seconds.

The results of this calculation were compared with those from the SOLA-ICE calculation at a time close to the final time of 0.2 seconds. The velocities, pressures and temperatures all second to agree reasonably well. The SOLA-ICE calculation was actually continued to a time of 4.5 seconds or for 6001 cycles. This requires the use of more computer time than was warranted for this STEALTH test problem. Therefore the STEALTH calculation was stopped after 280 cycles at a time of 0.2 seconds since the results appeared to compare favorably with the SOLA-ICE results at that point.

8.3.2.4 Input Deck. The STEALTH input deck for the thermally driven cavity problem is provided in Table 8.17.

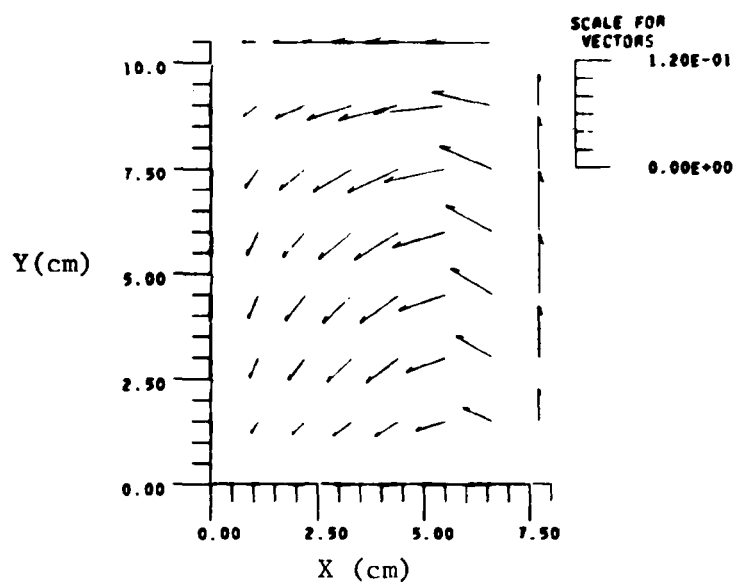


Figure 8.66. Velocity vector field for the thermally driven cavity calculation at cycle 81, $t = 0.51390$.

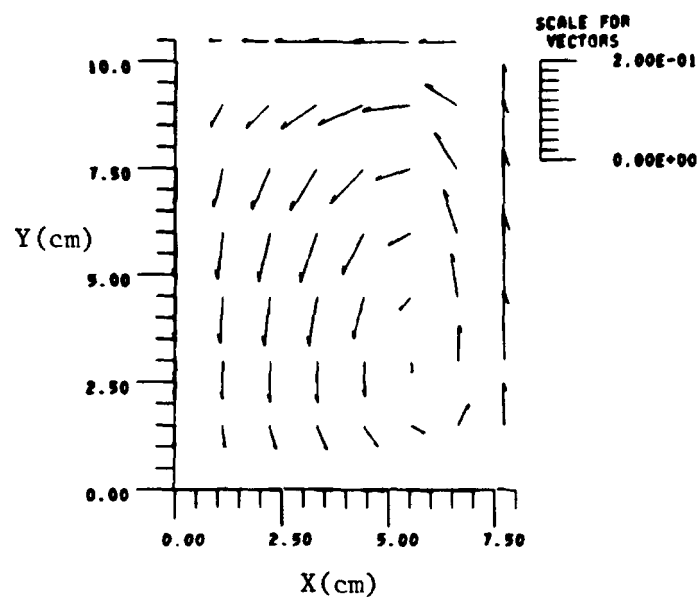


Figure 8.67. Velocity vector field for the thermally driven cavity calculation at cycle 147, $t = 0.10089$.

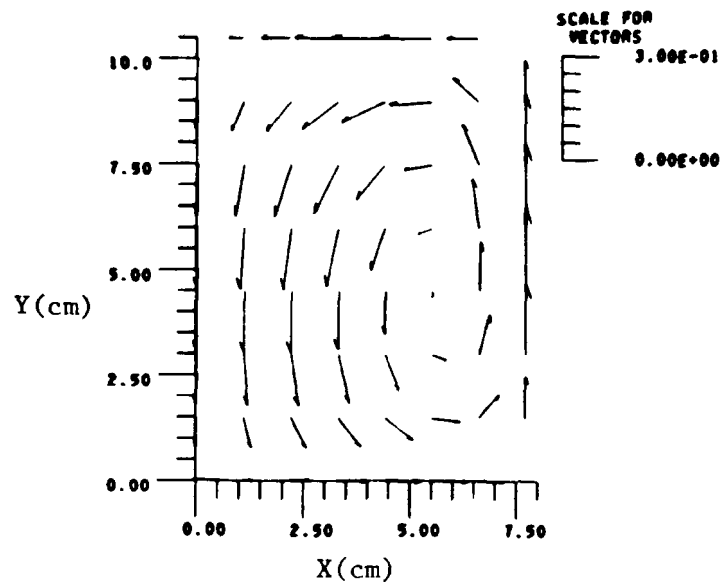


Figure 8.68. Velocity vector field for the thermally driven cavity calculation at cycle 213, $t = 0.15039$.

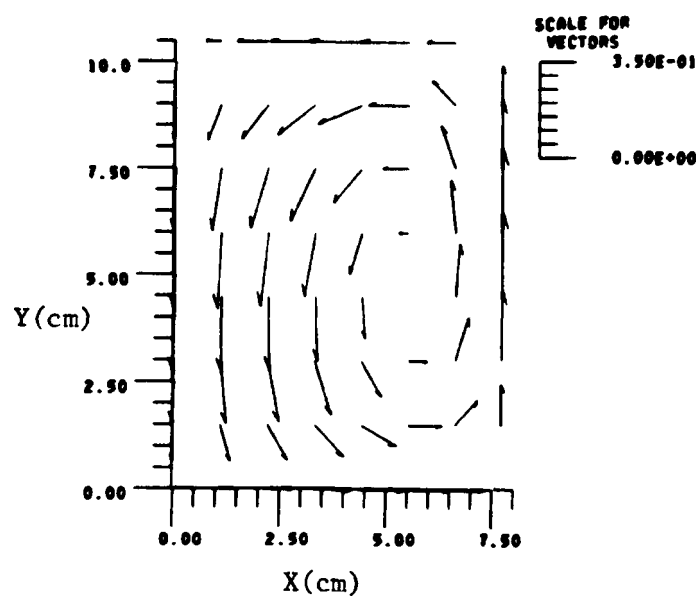


Figure 8.69. Velocity vector field for the thermally driven cavity calculation at cycle 280, $t = 0.20064$.

TABLE 8.17

DATA DECK FOR THE THERMALLY DRIVEN CAVITY CALCULATION

TTL	THERMALLY DRIVEN CAVITY					
PRB						2.0
PRO	2.0					
SYM	2.0					
MIN						0.20
GRV		-1000.		2.0		
GRD	1.0	1.0	8.0	8.0		
DTS	4.0					
ITR	500.	.00000005	1.5			
ALE	2.0	1.0	1.0			
END						
MAT						2.0
111	1.0	3.0				
112	1.0		2.0			
114	1.0	2.0	2.0			
115	1.0					
121	1.0	0.0001				
122	1.0	1.0				
123	1.0	-1.0	100.	1.0	0.4	0.4
134	1.0	.0004				
152	1.0	5712.33				
154	1.0	724.24				
171	1.0	.00000001				
END						
GPT				2.0		2.0
211	1.0	1.0	1.0	0.0		0.0
212	1.0	0.0	10.5	2.0		
212	2.0	0.0	0.0	1.0		
212	3.0	7.7	0.0	1.0		
212	4.0	7.7	10.5	1.0		
212	5.0	0.0	10.5	1.0		
212	6.0	0.0	0.0	1.0		
212	7.0	7.7	0.0	3.0		
221	1.0	1.0	8.0	1.0		8.0
247	1.0	0.0	7.7	0.0		10.5
END						
ZON						2.0
311	1.0	1.0	8.0	1.0		2.0
311	2.0	1.0	8.0	2.0		3.0
311	3.0	1.0	8.0	3.0		4.0
311	4.0	1.0	8.0	4.0		5.0
311	5.0	1.0	8.0	5.0		6.0
311	6.0	1.0	8.0	6.0		7.0
311	7.0	1.0	8.0	7.0		8.0
321	1.0	1.0				
321	2.0	1.0				
321	3.0	1.0				
321	4.0	1.0				
321	5.0	1.0				
321	6.0	1.0				
321	7.0	1.0				
322	1.0	.999988781217270.		300.		0.0
322	2.0	.999990507217270.		300.		0.0
322	3.0	.999992233217270.		300.		0.0
322	4.0	.999993959217270.		300.		0.0
322	5.0	.999995685217270.		300.		0.0
322	6.0	.999997411217270.		300.		0.0
322	7.0	.999999137217270.		300.		0.0
END						

(Continued on next page)

TABLE 8.17 (continued)

BDY					2.0	
411	1.0	1.0	1.0	8.0	1.0	
411	2.0	8.0	1.0	8.0	8.0	
411	3.0	8.0	8.0	1.0	8.0	
411	4.0	1.0	8.0	1.0	1.0	
412	1.0	1.0	6.0	5.0	3.0	
412	2.0	1.0	6.0	2.0	4.0	
412	3.0	1.0	6.0	5.0	5.0	
412	4.0	1.0	6.0	5.0	6.0	
423	4.0	1.0				
451	1.0	1.0	0.0	1000.		
452	1.0	304.				
481	1.0	1.0	7.0			
482	1.0	1.0	5.0	5.0		
END						
TIN					2.0	
511	0.0001					
512	0.00001	0.00075				
513	1.10		0.0			
521	0.2	600.				
END						
EDT					2.0	
621	1.0	0.0	0.2	0.025		
622	1.0	8.0	1.0	8.0		
623	1.0	12.				
623	2.0	15.				
623	3.0	64.				
623	4.0	61.				
623	5.0	51.				
623	6.0	53.				
623	7.0	52.				
623	8.0	62.				
641	1.0	0.0	0.2	0.05		
671	1.0	0.0	0.2	0.0010		
674	1.0	1.0	61.	1.0	8002.	
674	2.0	1.0	61.	1.0	8004.	
674	3.0	1.0	61.	1.0	8006.	
674	4.0	1.0	61.	1.0	8008.	
675	5.0	4.0	61.			0.025
675	6.0	4.0	61.			0.050
675	7.0	4.0	61.			0.10
675	8.0	4.0	61.			0.20
675	9.0	5.0				0.025
675	10.	5.0				0.050
675	11.	5.0				0.10
675	12.	5.0				0.20
END						
END						

8.3.3 Calculations of Pressure Release Transients in Prototype PWR Geometries

A hypothetical loss of coolant accident in a pressurized water reactor could result in large loads being placed on internal structural members of the reactor. To predict these loads accurately requires a two-dimensional or three-dimensional hydrodynamics computer code that can calculate fluid flow accurately in geometrically complicated regions.

To test the 2D implicit, fluid mechanics versions of the STEALTH codes for problems of this type, a series of four calculations of pressure relief transients or rarefaction waves was performed. The test problems were defined by the NRC to check computer codes used for licensing studies. They were meant to model very approximately, in two dimensions, flow in regions of a pressure vessel following a cold leg break.

An identical set of calculations was performed by Hirt and Romero⁽¹⁷⁾ LASL using the SOLA-ICE⁽³⁾ codes. One of the objectives of the study described here was to compare the STEALTH and SOLA-ICE results. This comparison is discussed below in the analysis of the results of the calculations.

8.3.3.1 Problem Description and Set-Up. The series of four calculations discussed here consists of the following problems:

- Cylindrical rarefaction
- Cylindrical rarefaction with obstacles in the flow
- Rarefaction in a cold leg-downcomer junction geometry
- Rarefaction in a long, narrow channel containing a central obstruction.

In each calculation the fluid was treated as an inviscid, single phase liquid which was initially at rest at a pressure of 14.4 MPa (2086 psia) and a temperature of 557.4°K (544°F). The liquid was described by a linear equation of state of the form

$$p = p_o + K\left(\frac{\rho}{\rho_o} - 1\right)$$

where $p_o = 6.897$ MPa (1000 psia) and $\rho_o = 741.5$ kg/m³ (46.3 lb-m/ft³) are the saturation pressure and density of water corresponding to the initial temperature. The sound speed of water at this initial temperature and pressure is 1060 m/s (3479 ft/s) which corresponds to a bulk modulus of $K = 833.2$ MPa (1.21×10^5 psia). The pressure relief transient was produced in all cases by one or more cells that were held at a constant pressure of 11.7 MPa (1700 psia). These cells acted as a constant-pressure sink for the fluid.

A rectangular, Eulerian mesh was used for all calculations. The mesh configuration was made to correspond to that used in the SOLA-ICE calculations in order to facilitate direct comparison of the two sets of calculations. For the last two cases the calculations were repeated with finer zoning to improve the accuracy of the STEALTH solutions. In all cases the exterior mesh boundaries were treated as frictionless walls. For interior obstacles, however, a zero velocity boundary condition was used because the current versions of STEALTH do not have a frictionless wall option available for interior boundaries. The SOLA-ICE calculations, on the other hand, used frictionless wall boundary conditions for all boundaries. The effects of this difference are discussed below in the analysis of the results of the calculations.

Cylindrical Rarefaction:

This calculation was intended to model an infinite plane region of uniform thickness which is perturbed at $t = 0$ by a constant-pressure sink with 0.093 m^2 (1 ft^2) cross-sectional area. This is actually a 1D, cylindrically symmetric problem, but it was modeled in 2D by computing a 90° section of the problem.

The mesh configuration for the calculation is shown in Figure 8.70. A square mesh with cell dimensions of 0.1524 m (0.5 ft) was used. The sink region consisted of one cell (shown shaded) in the lower, left-hand corner of the mesh. The frictionless walls on the left and bottom of the mesh provided symmetry planes for the 90° sector of the cylindrical problem. The time domain for the calculation was such that the other boundaries did not interact with the flow. Although the sink region was square, it looked essentially like a point source at distances large compared to the cell size. Therefore, this calculation should have been a reasonable approximation for the cylindrically symmetric problem in all regions except near the sink.

Cylindrical Rarefaction with Obstacles in the Flow:

This problem was intended to model the effect of obstacles placed in the cylindrical flow field produced in the first problem. In this case the constant-pressure sink was a square region of area 0.37 m^2 (4 ft^2). One of the two obstacles in the flow was a 0.84 m^2 (9 ft^2) square region located 1.68 m (5 ft) to the right of the center of the sink. The other obstacle was a rigid wall parallel to the x-axis located 1.83 m (6 ft) above the center of the sink. Because of the presence of the obstacles this is no longer a 1D problem. It was modeled as a 180° sector of a 2D planar problem by placing a rigid, frictionless wall along the y-axis through the center of the sink to provide a symmetry plane. This implies that there was another square obstacle to the left of the sink (i.e., a mirror image).

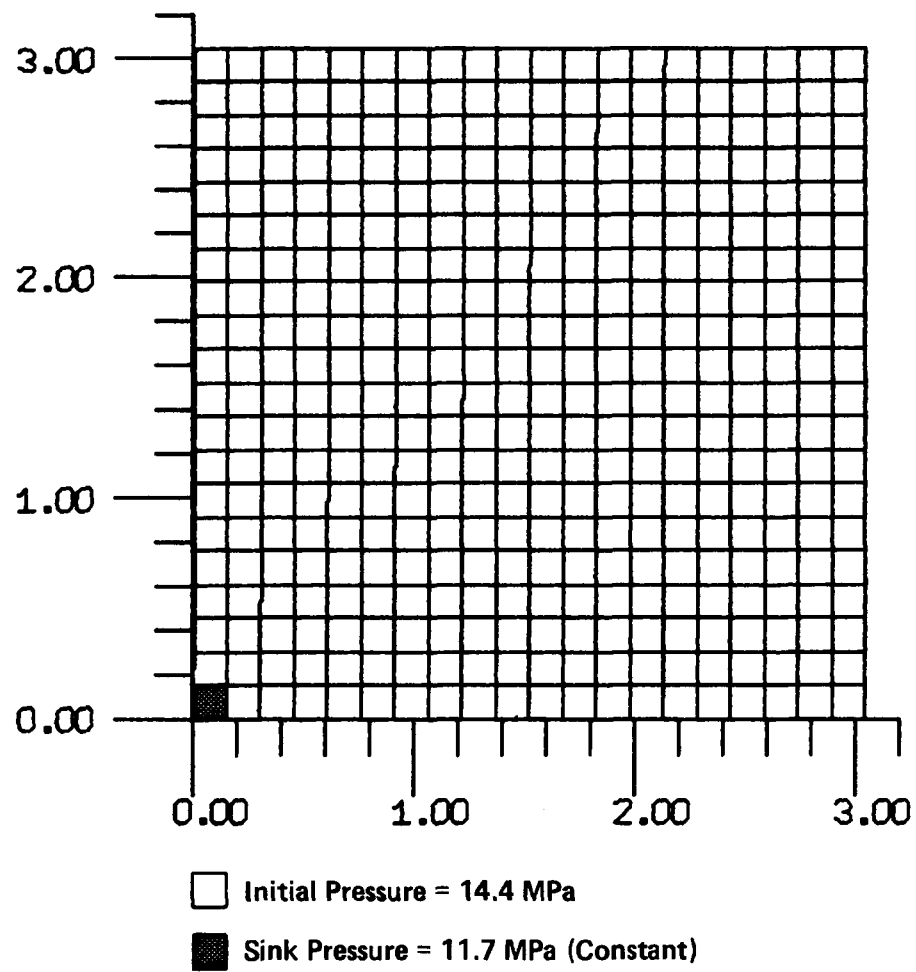


Figure 8.70. Configuration for the calculation of a quarter section of a cylindrical rarefaction.

In the original problem specification the constant-pressure sink and the obstacle to the right of it were defined as circular regions. Hirt and Romero were forced to model these as square regions because SOLA-ICE is restricted to rectangular zoning. Although STEALTH has no such zoning restriction, we decided to use the same rectangular mesh as was used in the SOLA-ICE calculation. This was done for two reasons. First of all, one of our primary objectives in this series of calculations was to compare our results with those obtained from the SOLA-ICE calculations. We felt that a much more straightforward comparison could be made if identical zoning was used. Secondly, although STEALTH has the capability of utilizing non-rectangular zoning in relatively complicated geometrical configurations, the particular configuration (i.e., two circles) would have been difficult to model accurately without using a mesh generator that was specially programmed for this problem.

The mesh configuration for this second problem is shown in Figure 8.71. The cell dimensions, 0.1524 m (0.5 ft), were the same as were used in the first problem. The sink region (shaded) in this case was modeled with 8 cells while the square obstacle was made up of 36 cells. This provided reasonably accurate definition of both regions, although it should be noted that the separation between the two regions and their separation from the top boundary were not large enough for the rectangular representation to be a good approximation for the originally defined circular regions.

As stated before, the left boundary was a frictionless wall which provided a symmetry plane. The top boundary was also a frictionless wall which was intended to interact with the flow as a rigid obstacle. The other exterior boundaries were located so that they would not interact with the flow during the problem time. A zero velocity boundary condition was used for the interior boundaries, i.e., the square obstacle.

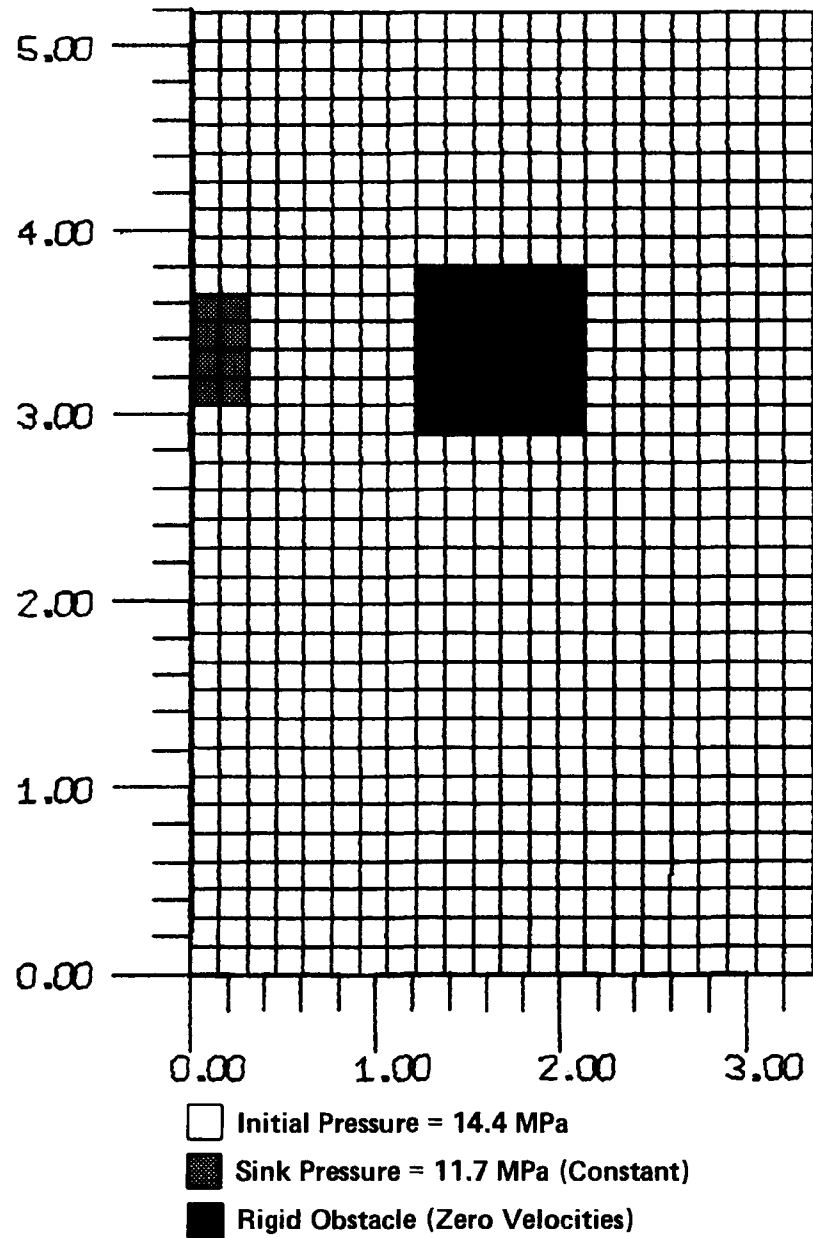


Figure 8.71. Configuration for the calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow.

Rarefaction in a Cold Leg-Downcomer Junction Geometry:

Unlike the first two problems which were planar, this problem involves a 2D, axisymmetric region. The geometry is meant to approximate a cold leg-downcomer junction with a central obstruction, such as a thermal shield, in the downcomer.

Two calculations of this problem were performed. In the first, the mesh was identical to that used in the SOLA-ICE calculation of this problem. In the second, finer zoning was used in an attempt to improve the accuracy of the calculation and to eliminate some of the problems caused by the zero velocity boundary condition used in STEALTH for interior boundaries. This is discussed later in more detail.

The mesh configuration corresponding to the SOLA-ICE calculation of this problem is shown in Figure 8.72. Rectangular cells with dimensions $\Delta x = 2\Delta y = 0.1219$ m (0.4 ft) were used. The sink region (shaded) consisted of three cells at the top of the cold leg region. The axis of symmetry was on the left and a rigid wall was placed at the bottom of the mesh. Frictionless sliding boundary conditions were used for both of these boundaries.

The other important boundaries in the problem were formed by using the zero velocity condition that is used to define interior obstacles in STEALTH. This condition was applied to the regions of the mesh that are blacked out. Besides providing the boundaries for one side of the cold leg and the downcomer, this was also used to model the central obstruction in the downcomer.

The more finely zoned mesh configuration is shown in Figure 8.73. In the downcomer region near the bottom of the mesh, the cell dimensions were $\Delta x = 3\Delta y = 0.0914$ m (0.3 ft). In the cold leg region Δx remained constant, but Δy increased uniformly by a factor of two in going from the

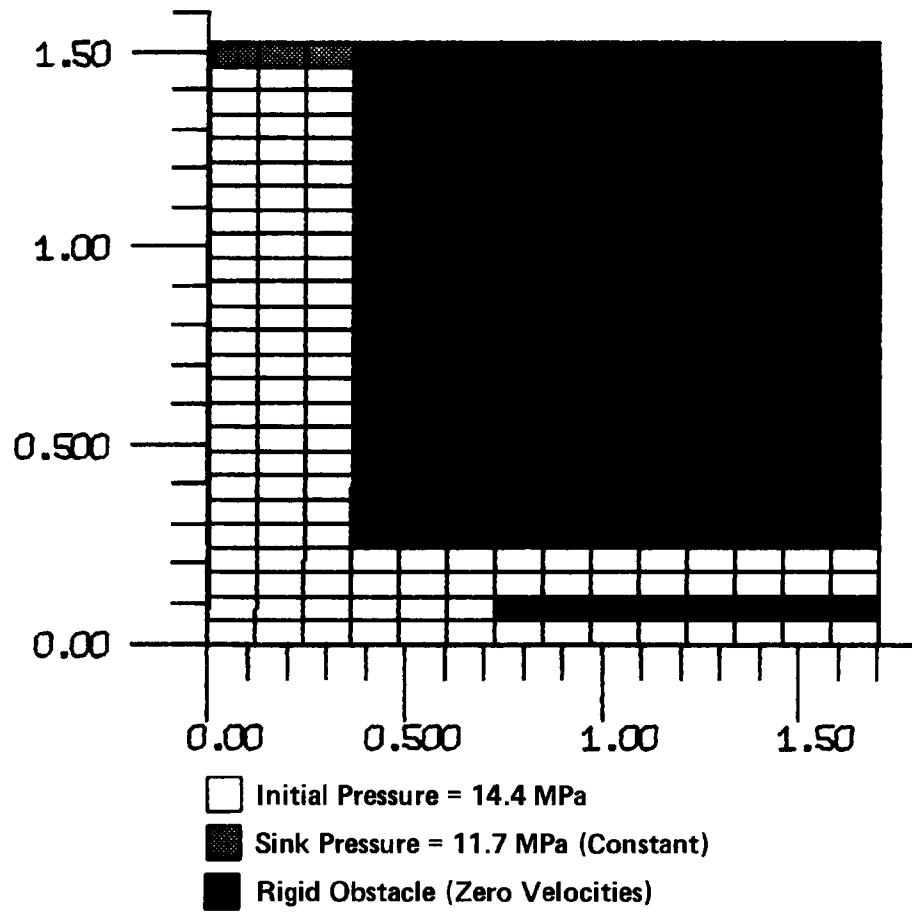


Figure 8.72. Configuration for the more coarsely zoned calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction.

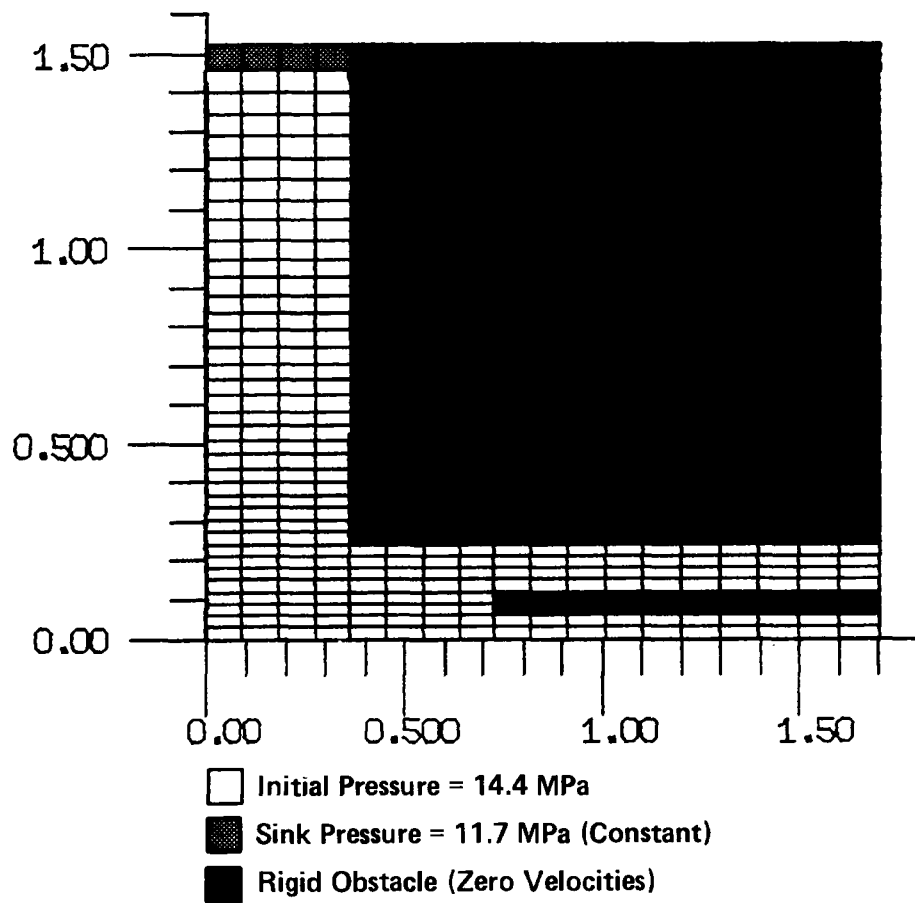


Figure 8.73. Configuration for the more finely zoned calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction.

intersection with the downcomer up to the sink region. This zoning provided an extra column of cells in the cold leg region and doubled the number of rows of cells on either side of the central obstruction in the downcomer. All boundaries were treated the same as in the more coarsely zoned calculation.

Rarefaction in a Narrow Channel Containing a Central Obstruction:

This problem was intended to model in planar geometry a portion of the previous problem, i.e., the channel formed by the downcomer containing the central obstruction. In this case the downcomer region was extended so that the problem consisted of a long narrow channel (aspect ratio $\sim 30:1$) with the pressure relieved at one end. This problem was also calculated twice -- once with the same zoning as was used in the SOLA-ICE calculation and once with finer zoning.

The more coarsely zoned mesh configuration corresponding to the SOLA-ICE mesh is shown in Figure 8.74. Note that in this figure the scale in the x-direction is magnified by nearly a factor of 20 compared to the scale in the y-direction. Rectangular cells with dimensions $\Delta x = 0.0381$ m (0.125 ft) and $\Delta y = 0.3048$ m (1 ft) were used for the calculation. The constant-pressure sink region (shaded) consisted of a single row of 8 cells at the bottom of the mesh. All exterior boundaries were treated as frictionless walls while the boundaries of the internal obstacle had a zero velocity condition imposed.

The more finely zoned configuration is shown in Figure 8.75. The dimensions of the cells used for most of the mesh were $\Delta x = 0.0254$ m (0.083 ft) and $\Delta y = 0.2078$ m (0.68 ft). The bottom row of cells, the sink region, was made to have the same y-dimension as in the more coarsely zoned calculation, i.e., $\Delta y = 0.3048$ m (1 ft). Also, in order for the obstacle to have exactly the same location and overall dimensions in both problems, it was necessary to reduce the y-dimension of the three rows of cells

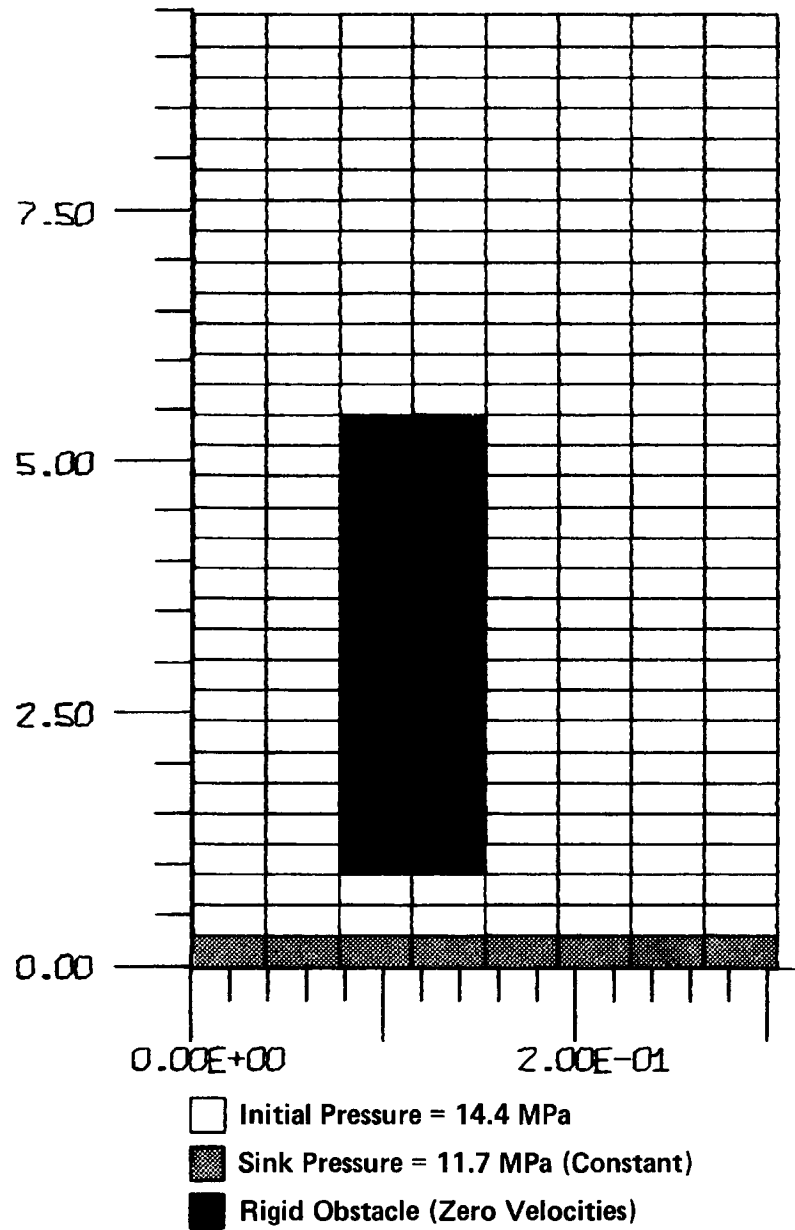


Figure 8.74. Configuration for the more coarsely zoned calculation of a rarefaction in a narrow channel with a central obstruction.

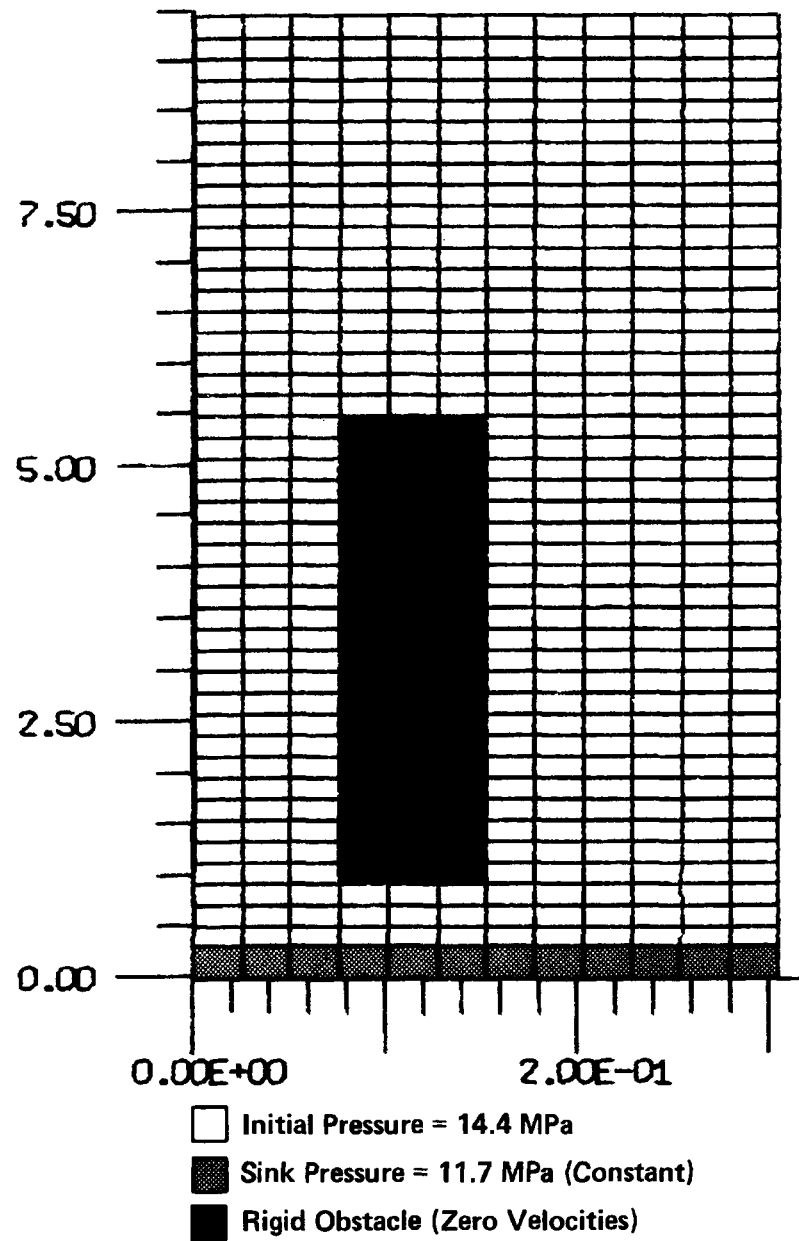


Figure 8.75. Configuration for the more finely zoned calculation of a rarefaction in a narrow channel with a central obstruction.

between the sink and the obstacle to $\Delta y = 0.2032 \text{ m}$ (0.67 ft), which is only slightly smaller than the y-dimension throughout the rest of the mesh. With the exception of the sink region, the ratio of cell dimensions between the coarsely and finely zoned calculations is about 3:2. All boundaries were treated the same in both calculations.

8.3.3.2 Results. In this section we present the results of the four calculations described above. In addition we provide comparisons with corresponding SOLA-ICE calculations done by Hirt and Romero⁽¹⁷⁾ and a discussion of any differences found.

Cylindrical Rarefaction:

Plots of pressure contours are provided at times of 0.55, 1.03, 1.44, 2.04, 2.55, and 3.05 msec in Figures 8.76 - 8.81. Velocity vector plots at the same six times are provided in Figures 8.82 - 8.87. Close examination of the pressure contours shows that cylindrical symmetry is accurately preserved except in the region immediately adjacent to the sink and in regions where the wave interacts with the top and right boundaries. The only other deviation from perfectly cylindrical contours is the 14.4 MPa contour on several plots. However, this contour is not particularly meaningful on any of the contour plots for any of the four problems for the reasons given below.

The 14.4 MPa contour represents the initial pressure that existed throughout the mesh at the start of the problem. Therefore, it represents the location of the first disturbance that propagates at the front of the rarefaction wave. In finite-difference calculations this first signal is usually a non-physical precursor that is produced by an accumulation of truncation errors or by small errors in the finite-difference formulation. This numerical precursor is usually at least several orders of magnitude smaller than the main signal and, therefore, has essentially no effect on the solution.

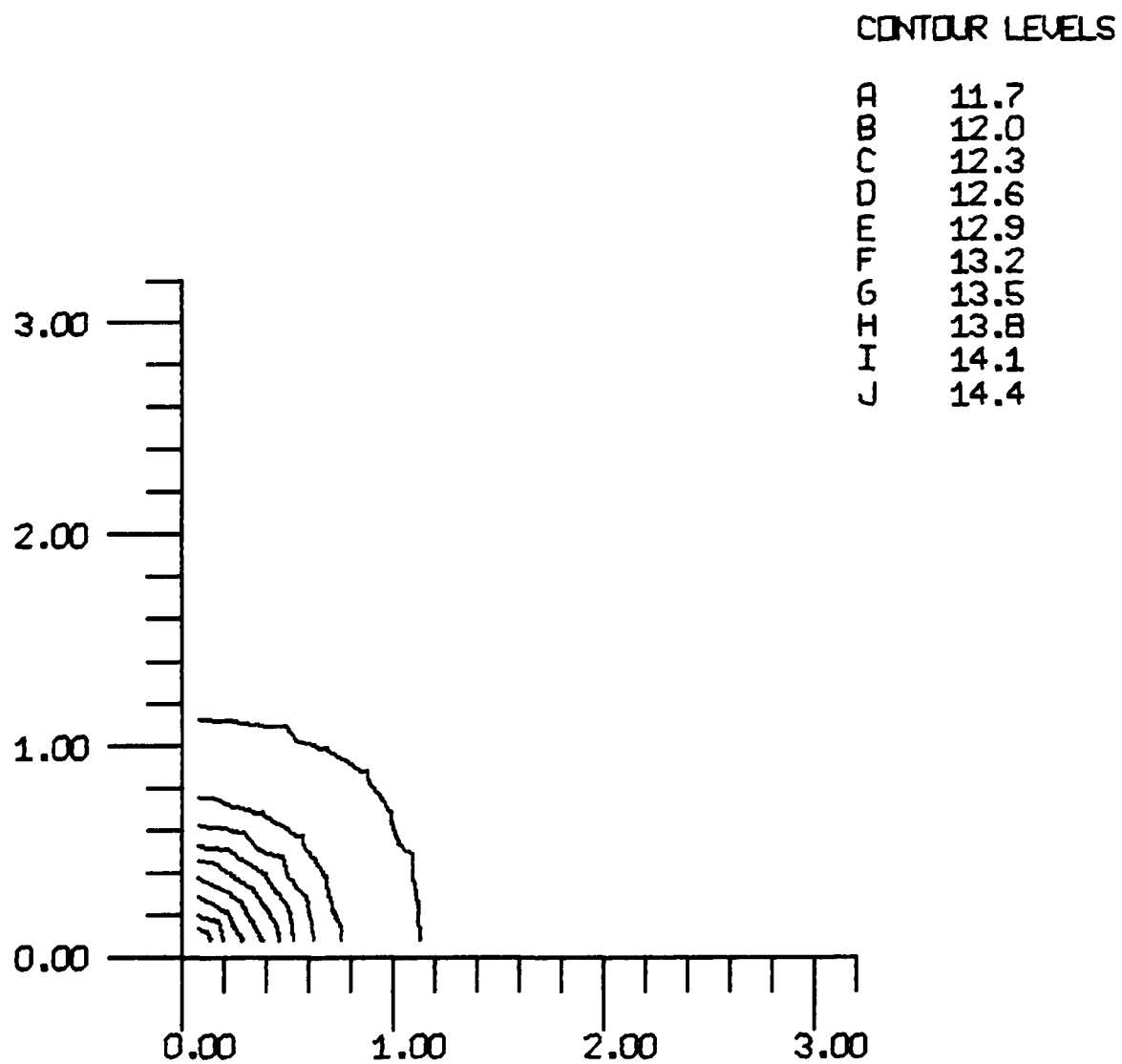


Figure 8.76. Calculation of a quarter section of a cylindrical rarefaction: pressure contours at cycle 11, time = 0.55.

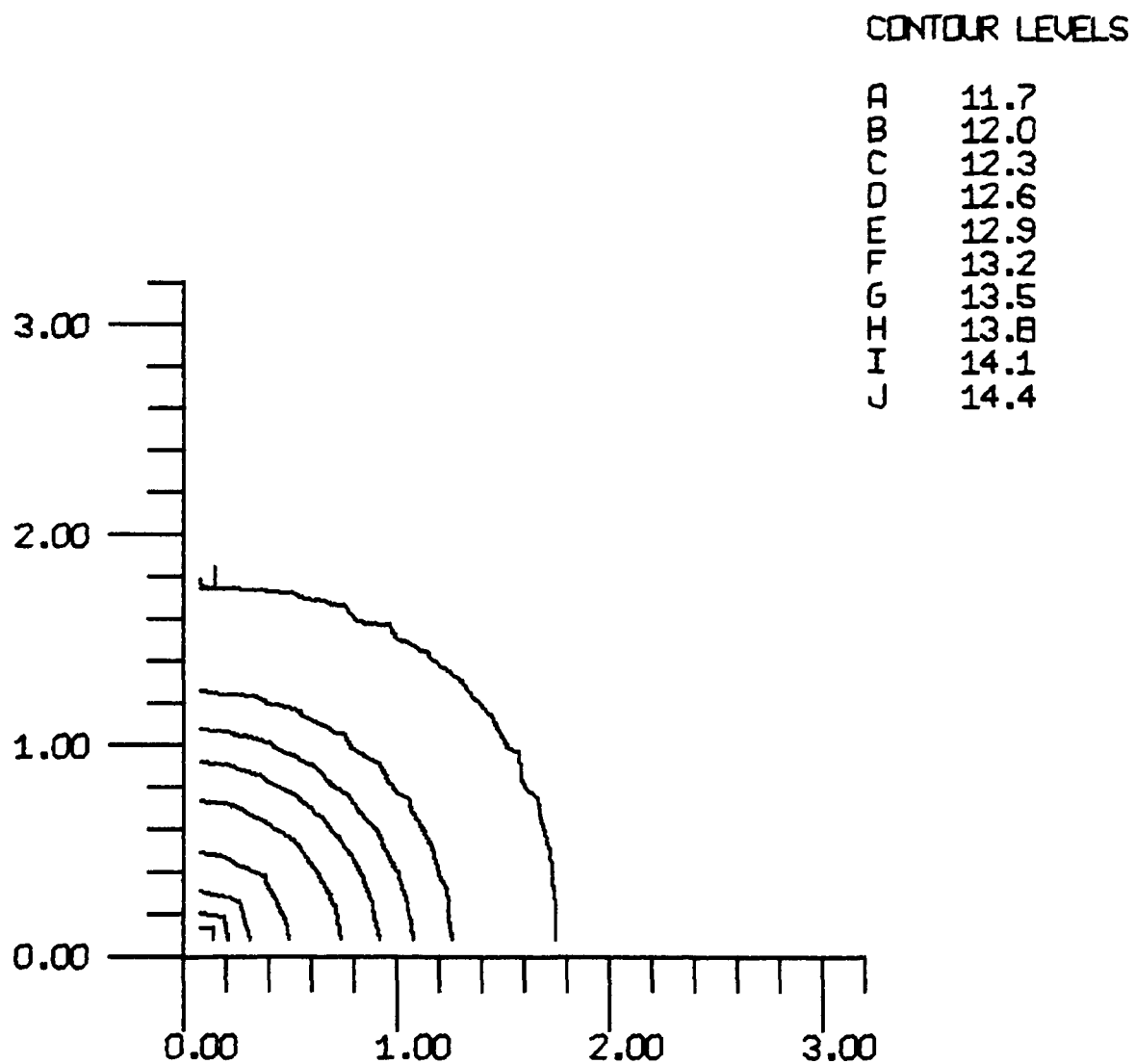


Figure 8.77. Calculation of a quarter section of a cylindrical rarefaction: pressure contours at cycle 21, time = 1.05.

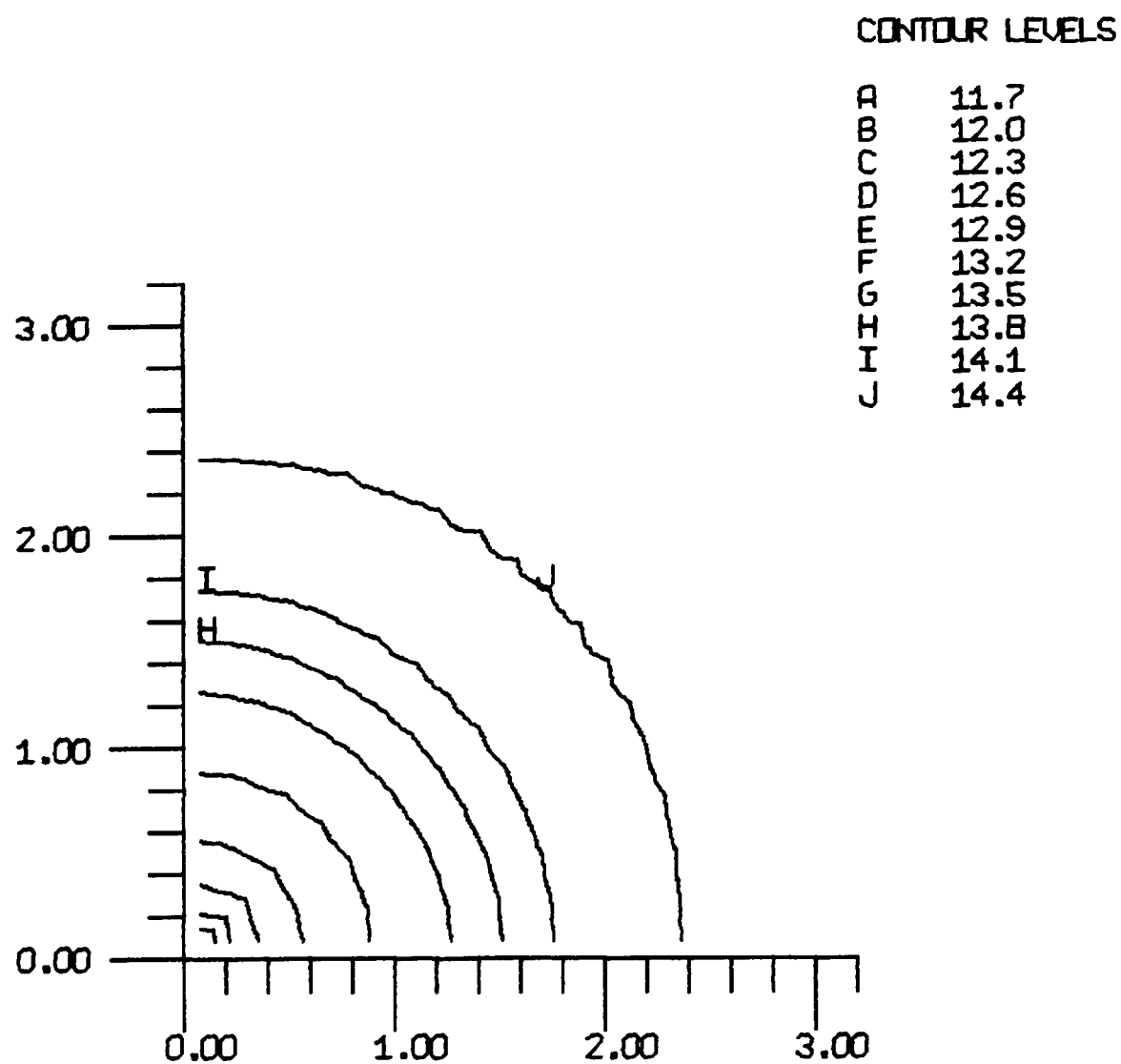


Figure 8.78. Calculation of a quarter section of a cylindrical rarefaction: pressure contours at cycle 31, time = 1.55.

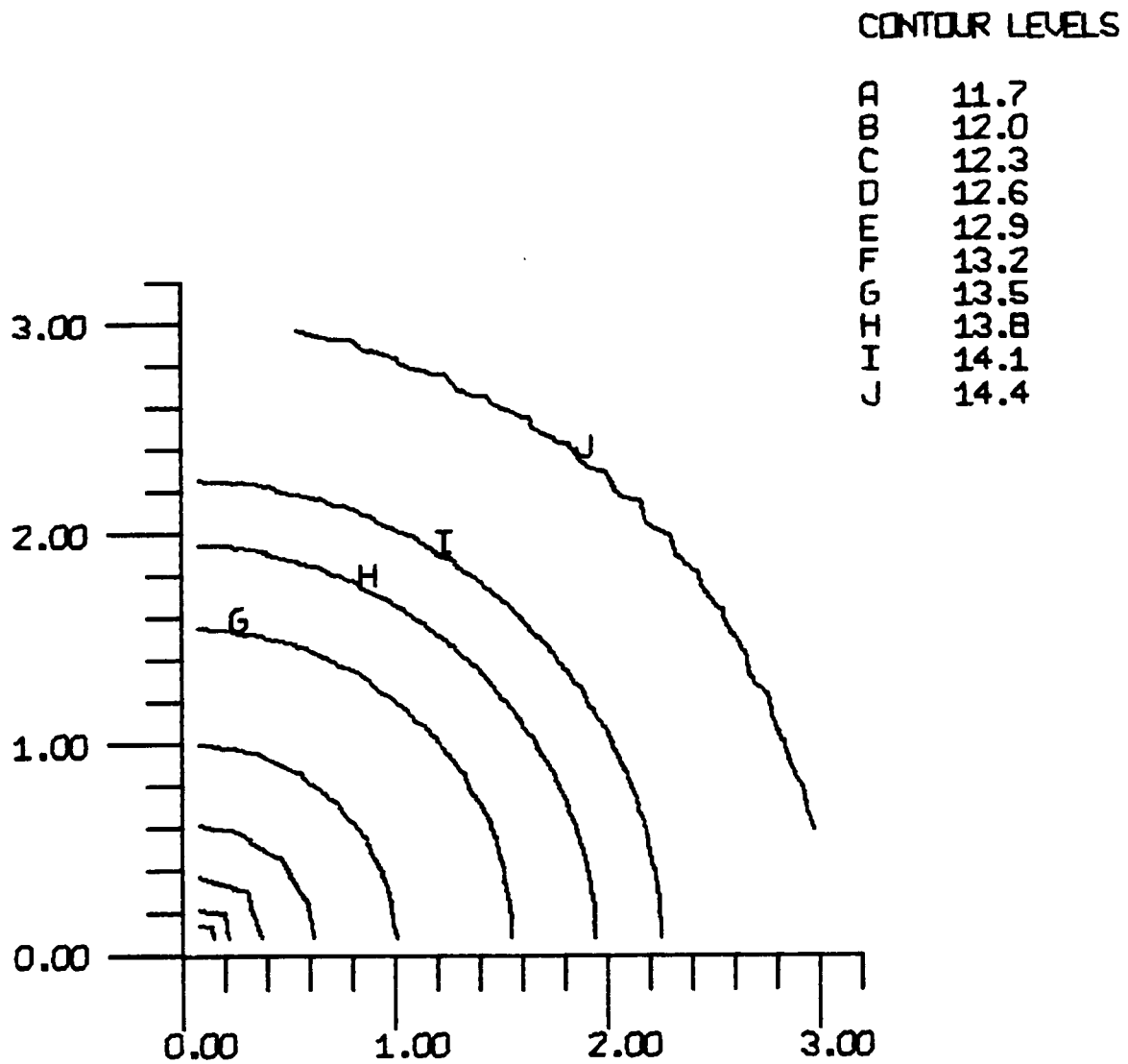
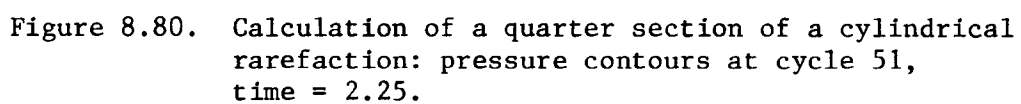


Figure 8.79. Calculation of a quarter section of a cylindrical rarefaction: pressure contours at cycle 41, time = 2.05.



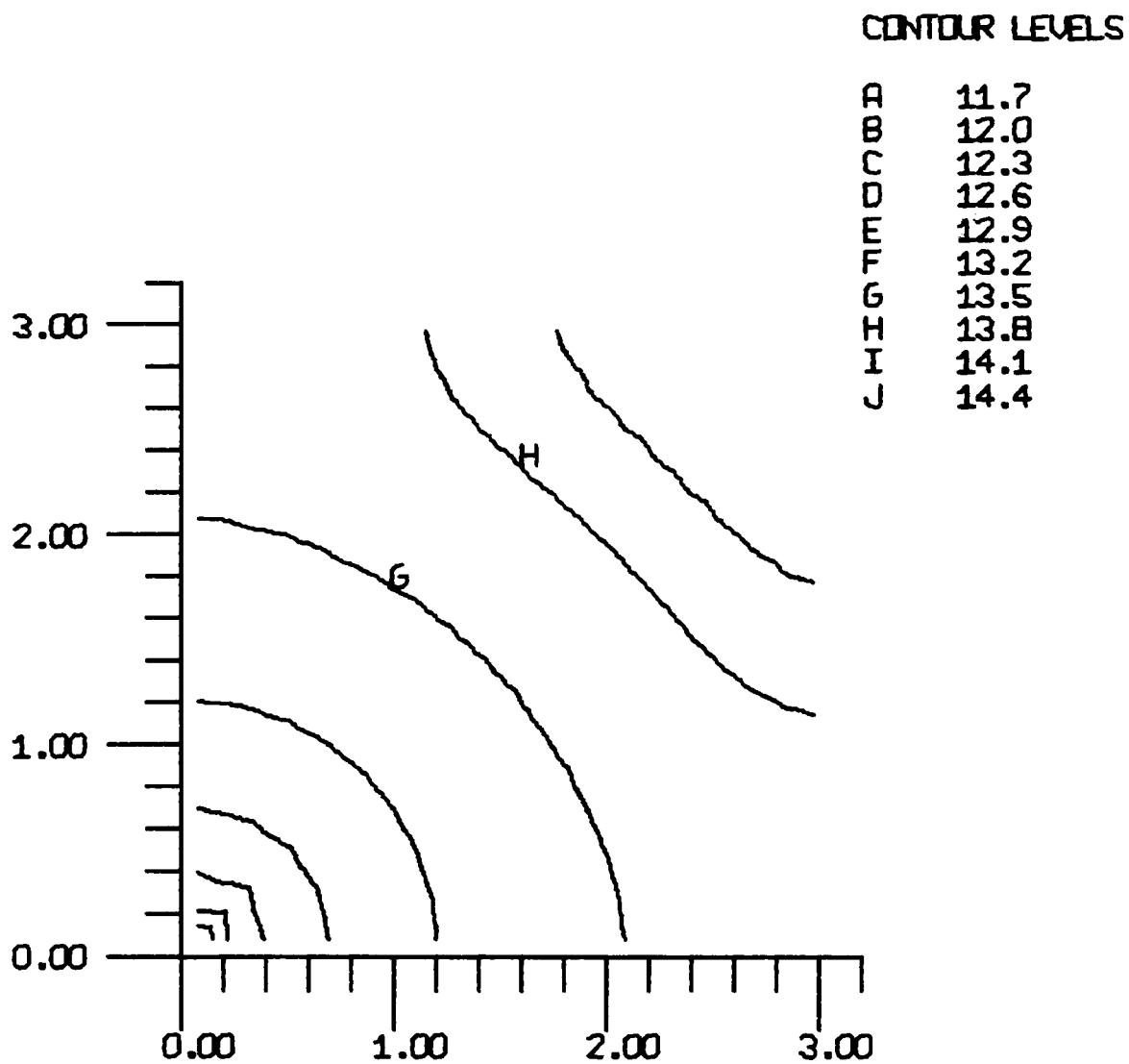


Figure 8.81. Calculation of a quarter section of a cylindrical rarefaction: pressure contours at cycle 61, time = 3.05.

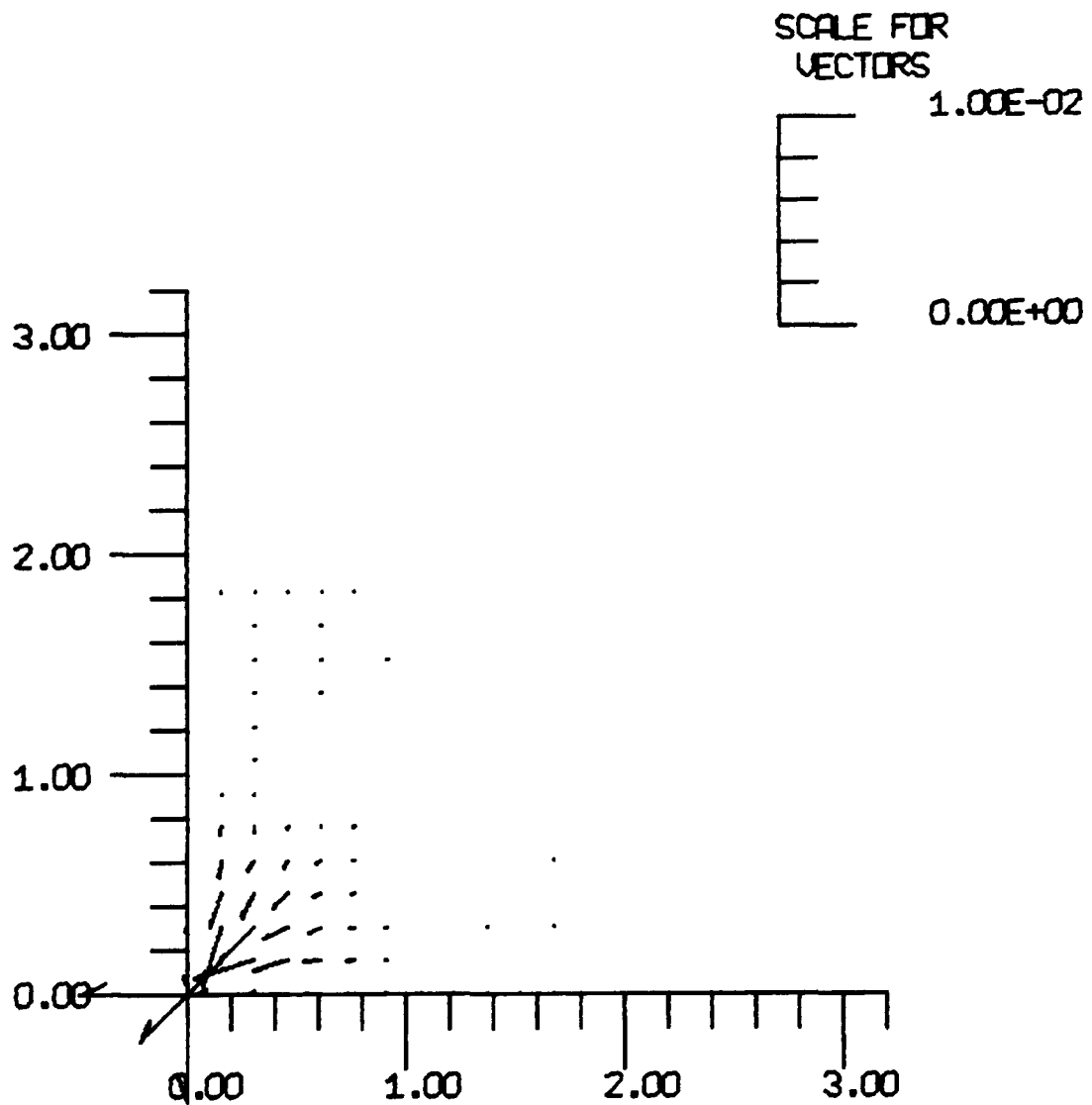


Figure 8.82. Calculation of a quarter section of a cylindrical rarefaction: velocity vectors at cycle 11, time = 0.55.

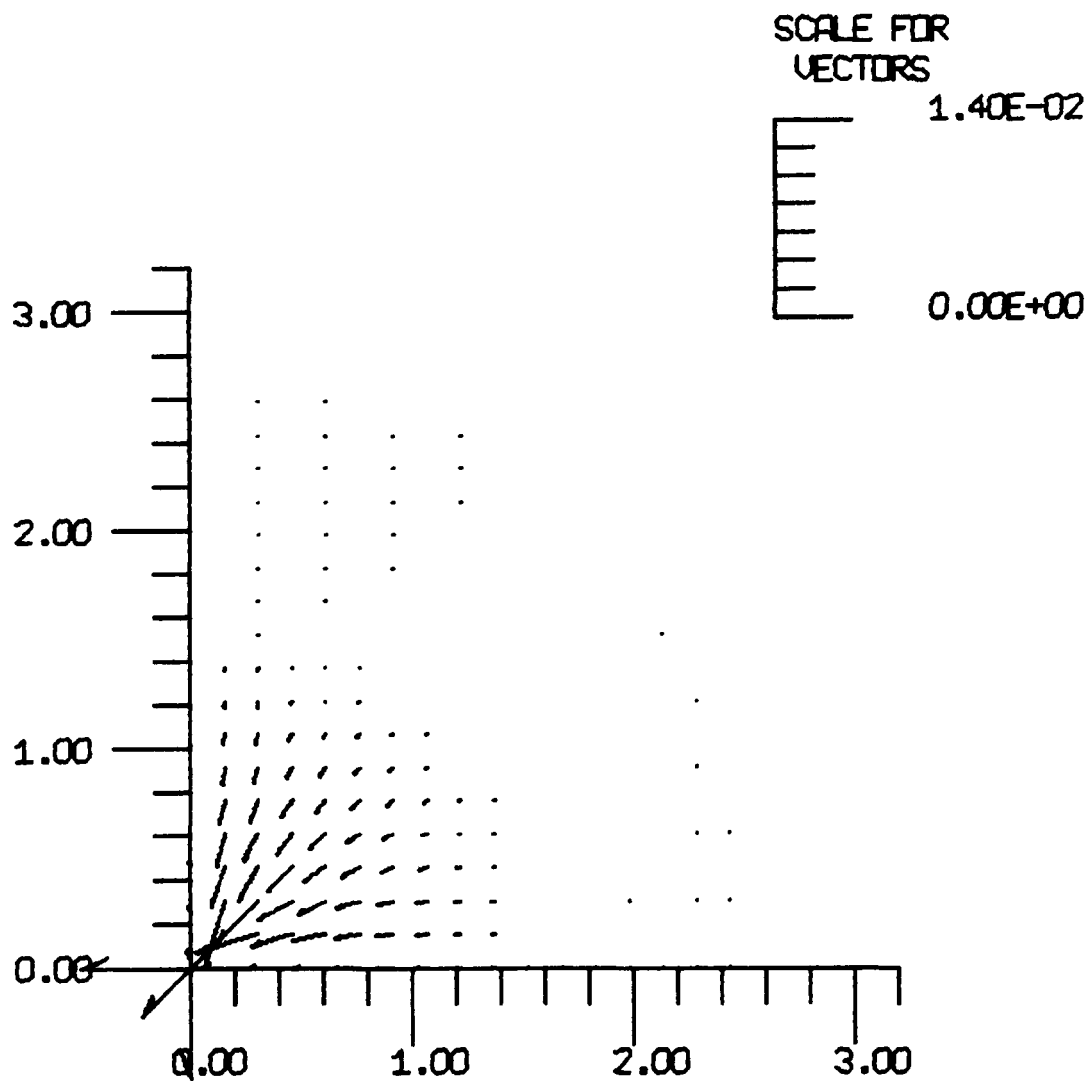


Figure 8.83. Calculation of a quarter section of a cylindrical rarefaction: velocity vectors at cycle 21, time = 1.05.

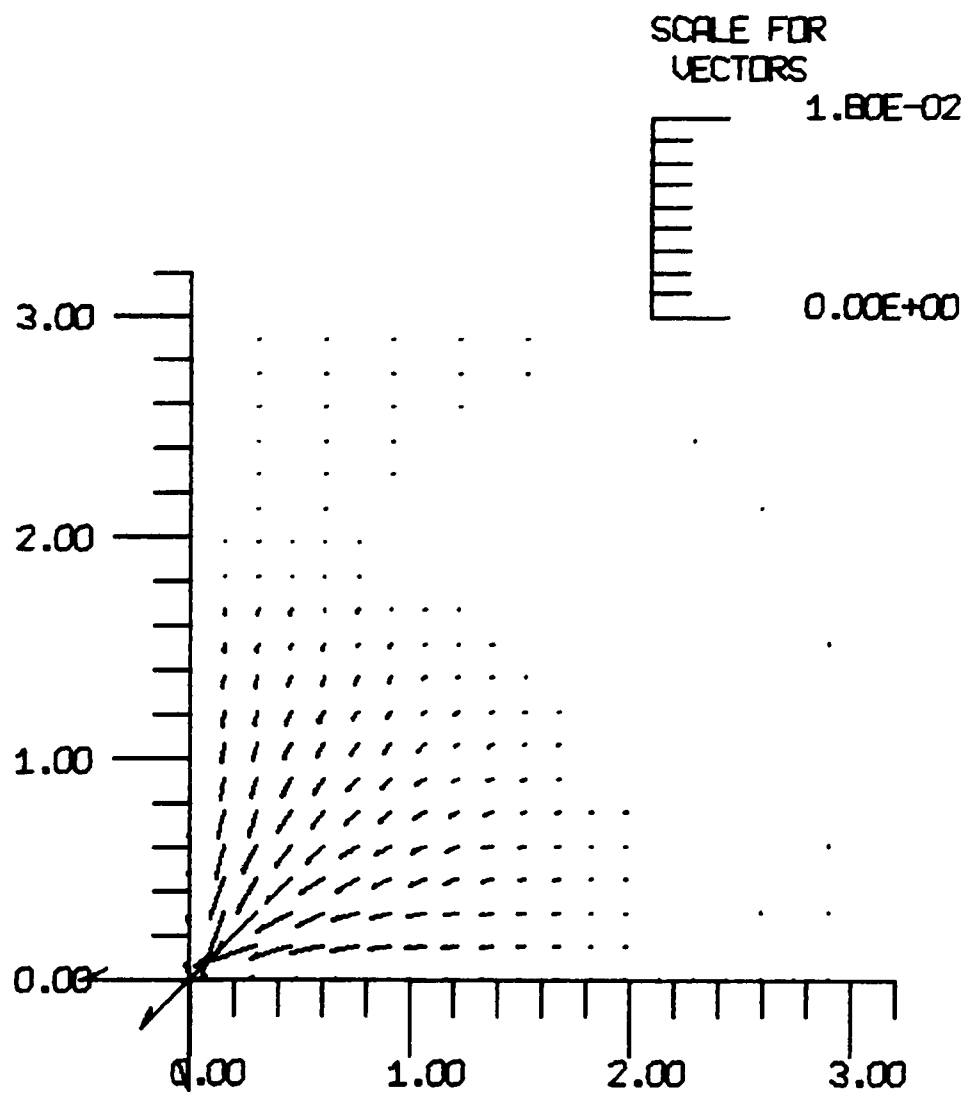


Figure 8.84. Calculation of a quarter section of a cylindrical rarefaction: velocity vectors at cycle 31, time = 1.55.

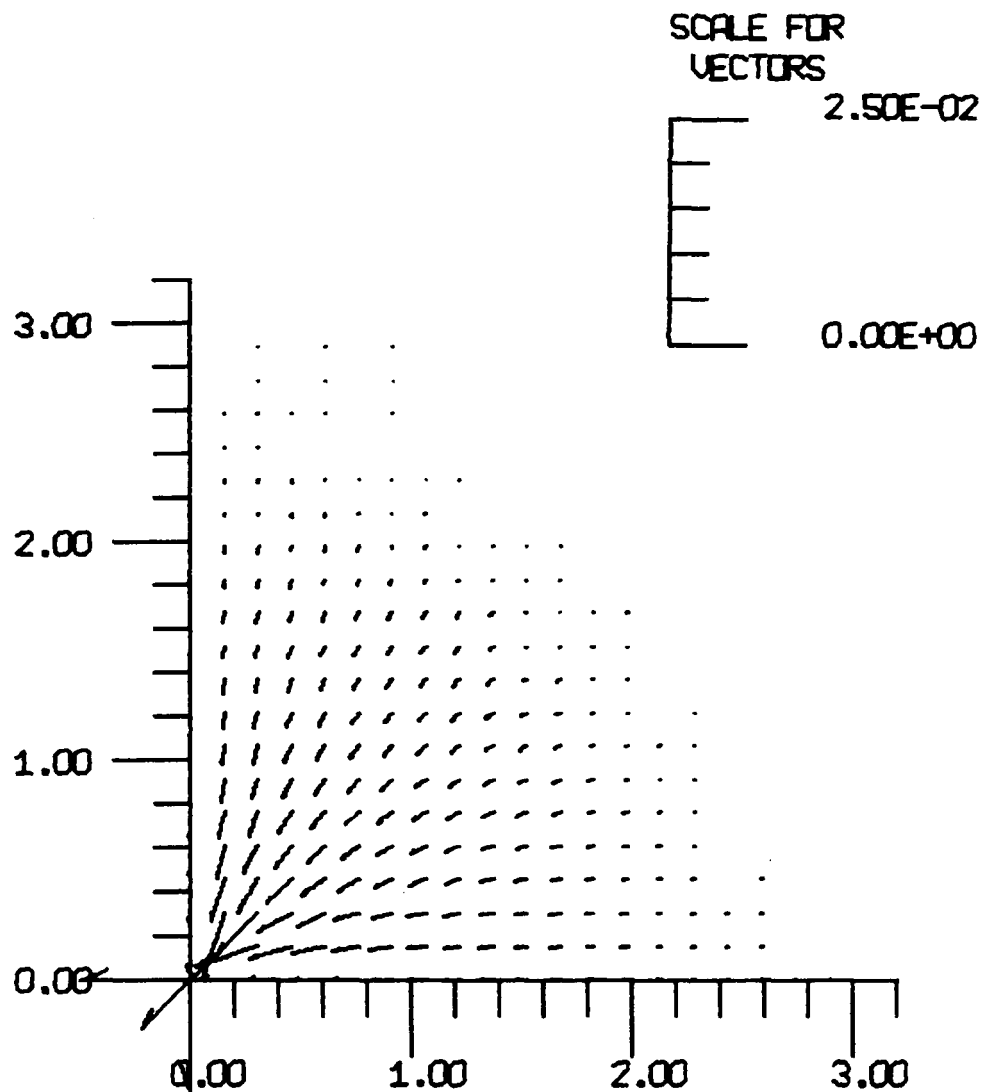


Figure 8.85. Calculation of a quarter section of a cylindrical rarefaction: velocity vectors at cycle 41, time = 2.05.

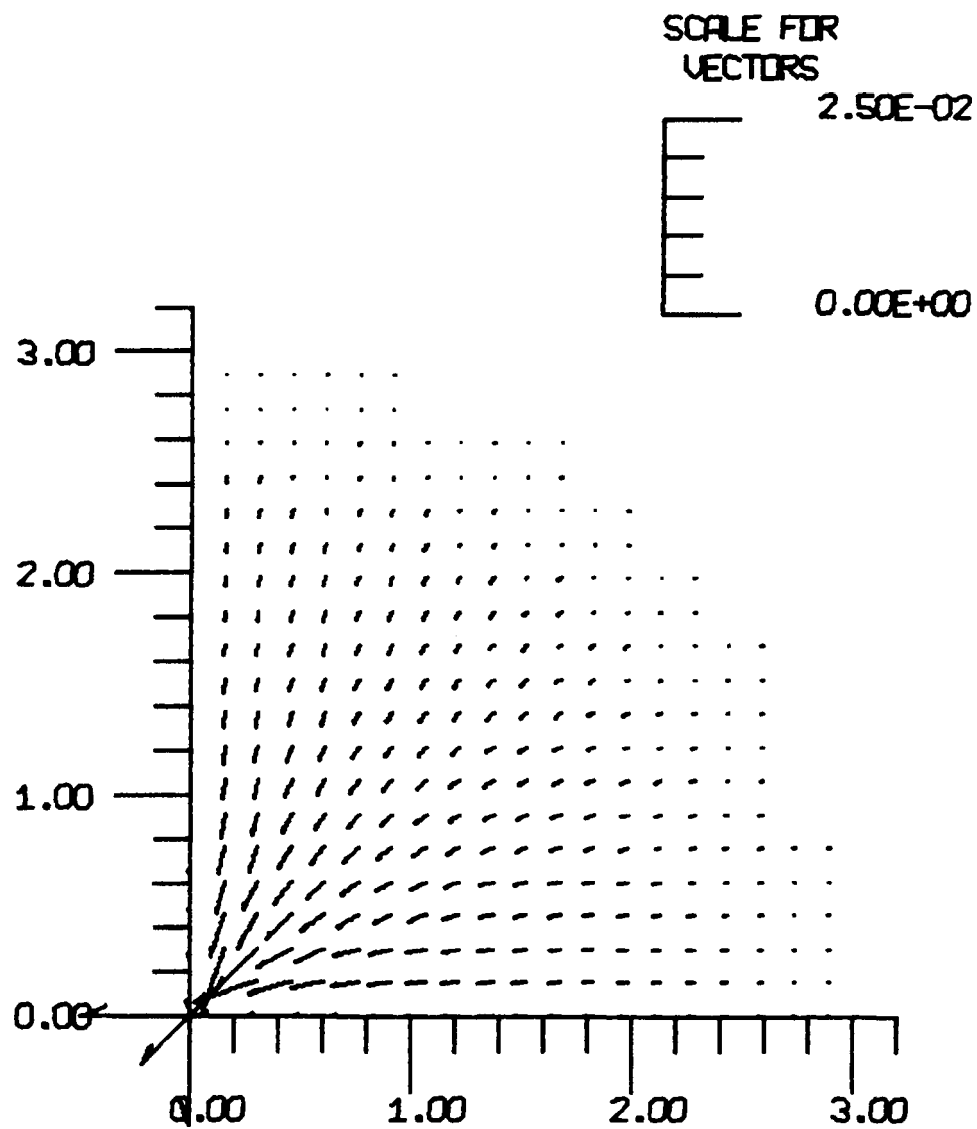


Figure 8.86. Calculation of a quarter section of a cylindrical rarefaction: velocity vectors at cycle 51, time = 2.55.

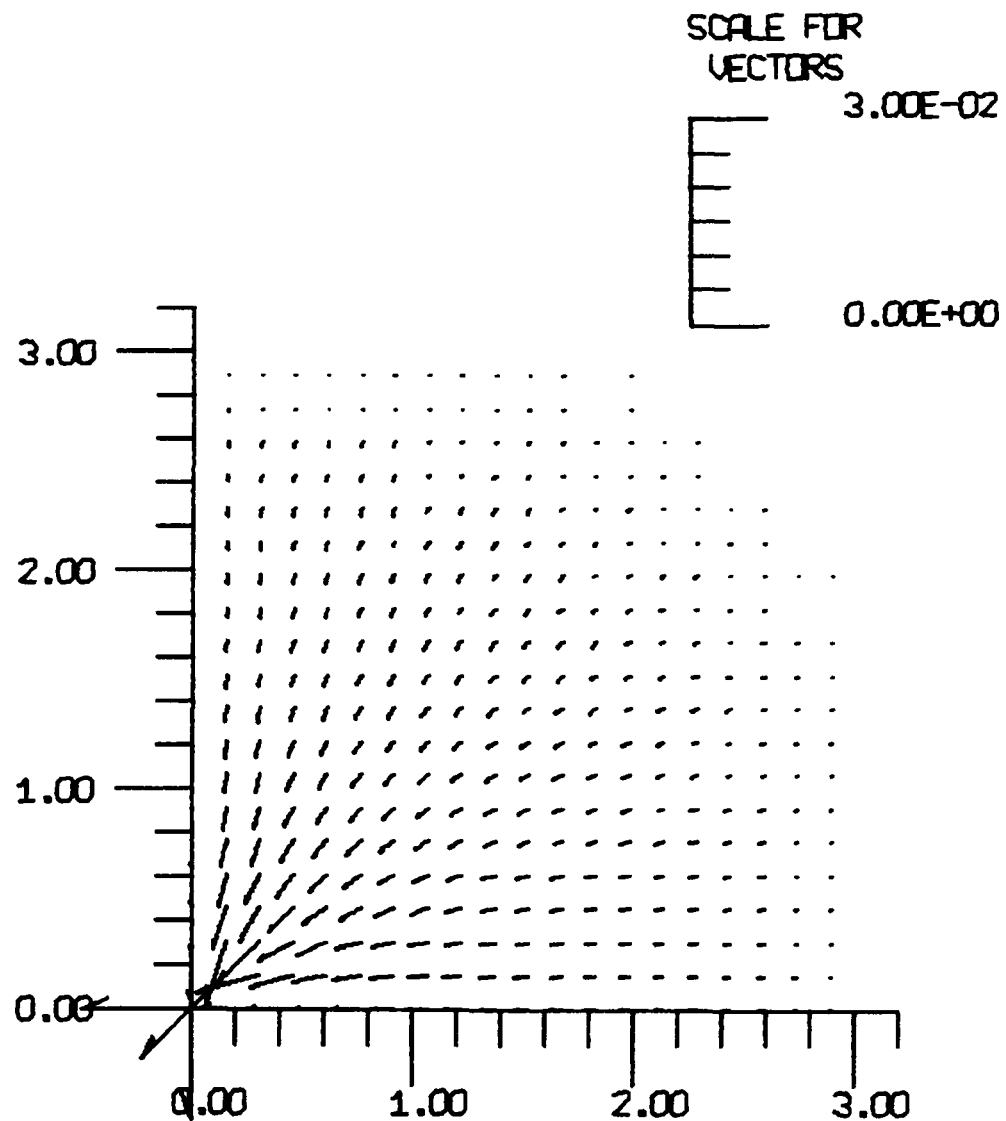


Figure 8.87. Calculation of a quarter section of a cylindrical rarefaction: velocity vectors at cycle 61, time = 3.05.

In this problem the geometry was very simple and, therefore, the propagation of the numerical precursor was relatively uniform throughout the mesh. Intuitively one would expect signals of this type to propagate preferentially along the directions of the grid lines. This would tend to make the 14.4 MPa contour more rectangular in this problem. In other problems where the geometry of the flow is more complicated and where the boundary conditions (which seem to be more subject to small errors) more strongly affect the flow, the propagation of these numerical noise signals is less uniform. This would tend to make the 14.4 MPa contour very irregular, which was the case in the final two problems discussed here. However, because this contour represents very low level, nonphysical signals, it can be ignored.

To compare the STEALTH calculation of this problem with the corresponding SOLA-ICE calculation, pressure profiles from the two calculations at times near 2 msec are plotted in Figure 8.88. These profiles were taken along a radius extending directly upward from the sink i.e., along the column of cells adjacent to the y-axis. Since profiles along other radii were virtually identical, only these profiles are given.

The data for the STEALTH profile was taken directly from the printout of the calculation; however, the data for the SOLA-ICE profile was measured from pressure contour plots since printouts were not available. Therefore there is some measurement error associated with the points that make up the SOLA-ICE profile. This is true for similar SOLA-ICE profiles reported below for the other three calculations.

The agreement between the results of the two calculations is extremely close. To put the observable differences into perspective, the width of the cells used in the calculations is also shown in Figure 8.88. The maximum difference between the profiles at a given pressure level is on the order of one half of a cell width. We consider this very close agreement.

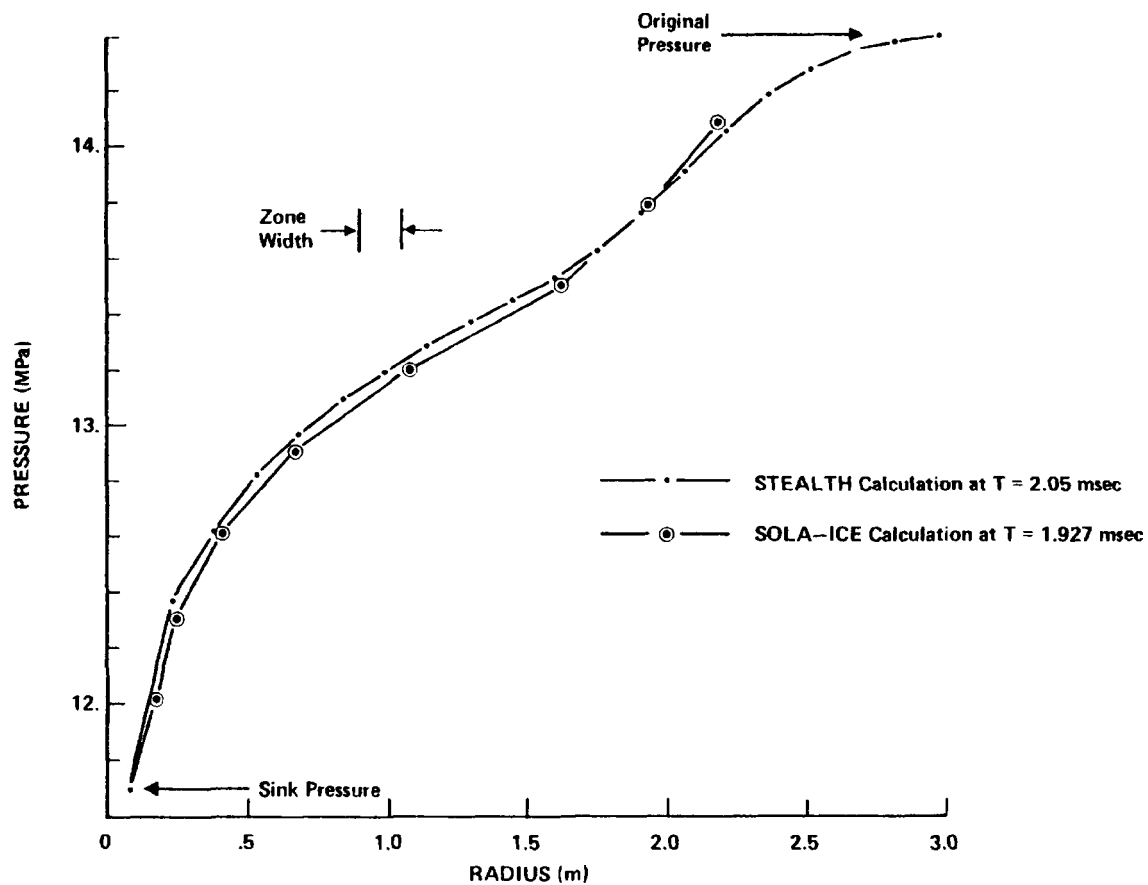


Figure 8.88. Comparison of STEALTH and SOLA-ICE calculations of a cylindrical rarefaction: pressure profiles along a radius extending directly upward.

Cylindrical Rarefaction with Obstacles in the Flow:

Plots of pressure contours at times of 0.52, 1.01, 1.53, 2.03, 2.52, and 3.04 msec are provided in Figures 8.89 - 8.94. Velocity vector plots at the same six times are provided in Figure 8.95 - 8.100.

Comparison between the pressure contour plots at various times for the STEALTH and SOLA-ICE calculations shows good qualitative agreement. A better quantitative measure of agreement, however, can be obtained by comparing pressure profiles along different lines through the flow field. Two horizontal lines passing near the square obstacle were chosen for this comparison. The first passes about 0.4 m (3 cells) below the bottom surface of the obstacle. This is at a height of about $y = 2.5$ m (see the grid configuration in Figure 8.71). The second line passes about 0.4 m above the square obstacle or at a height of about $y = 4.2$ m. The first line passes through the region where the flow has been affected only by the square obstacle. Along the second line the flow has interacted with both the square obstacle and the rigid wall at the top of the mesh.

Pressure profiles along these two lines at a time of approximately 2.5 msec are shown in Figure 8.101 and 8.102. The maximum difference between the STEALTH and SOLA-ICE calculations occurred near the left side of the mesh, i.e., close to the source. In that region both sets of profiles differ by about one zone width. In the other regions the difference is smaller. We consider this good agreement, particularly considering the difference in the times at which the STEALTH and SOLA-ICE profiles are taken (as indicated on the figure).

The STEALTH pressure profiles from this calculation are not as smooth as those from the other three. This is probably because of two factors. First, unlike the other three calculations, the lines along which the profiles were taken were not exactly in the direction of propagation of the rarefaction wave; i.e., they were not orthogonal to the pressure contours.

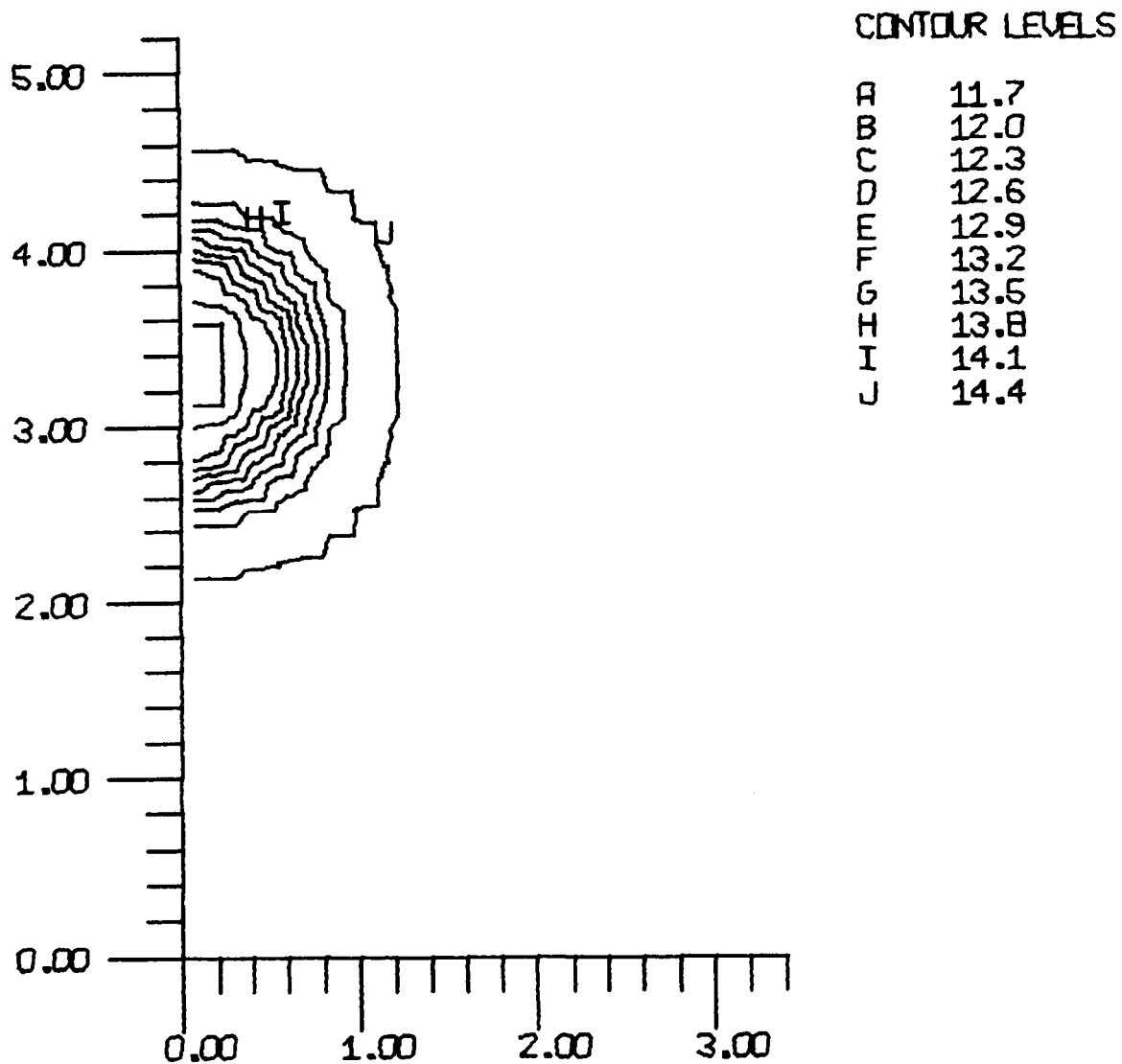


Figure 8.89. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: pressure contours at cycle 19, time = 0.52.

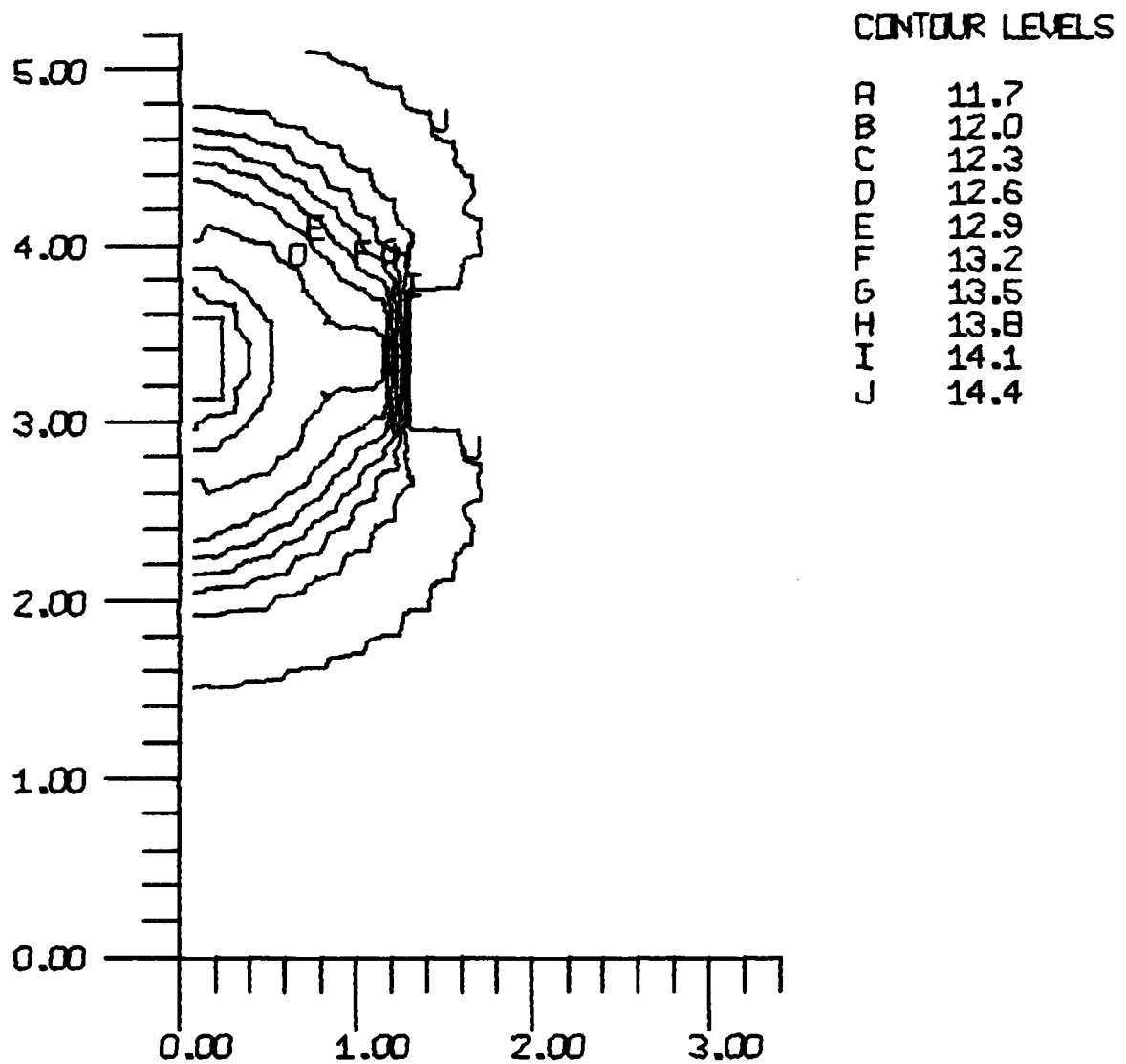


Figure 8.90. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: pressure contours at cycle 34, time = 1.00.

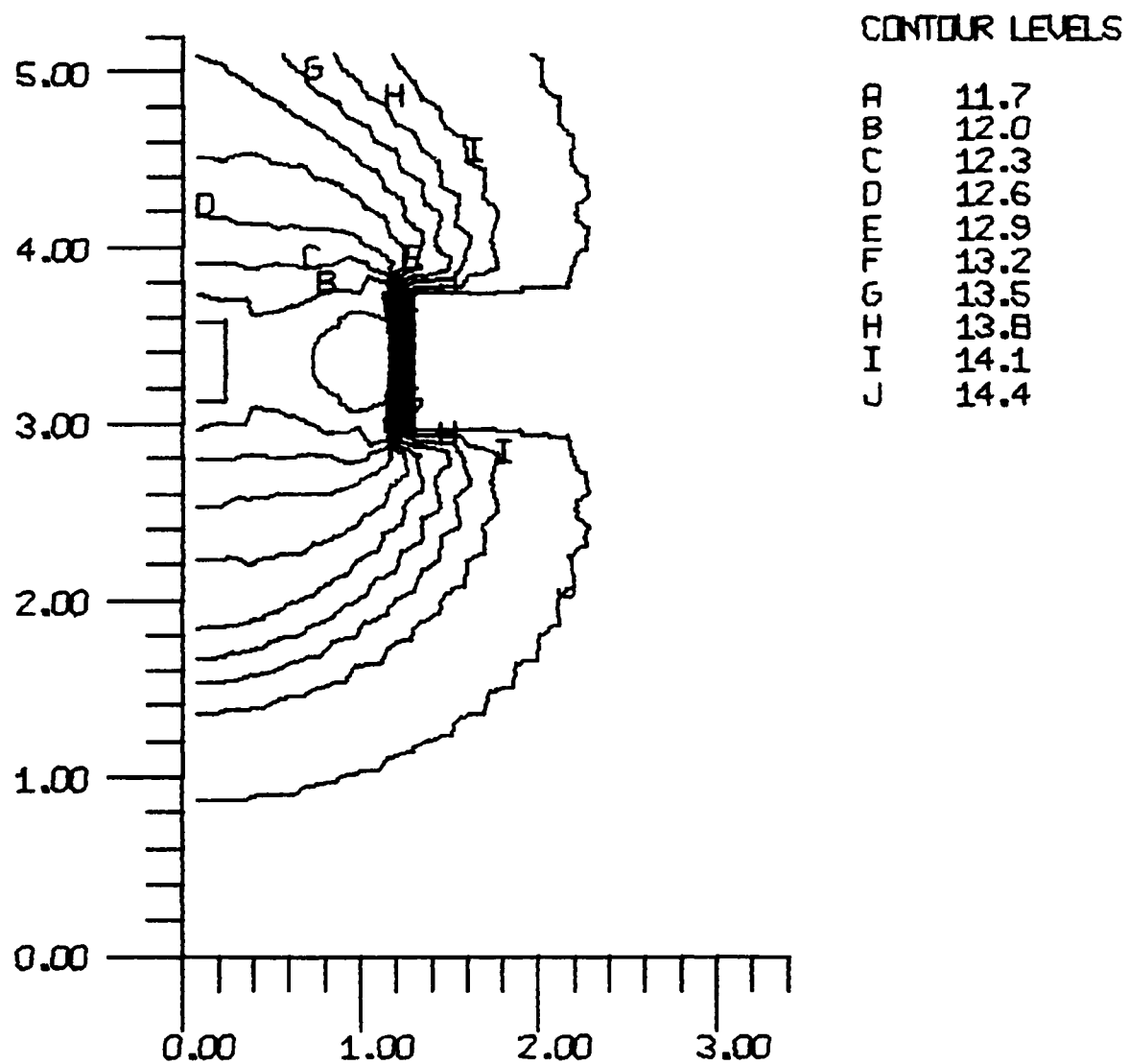


Figure 8.91. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: pressure contours at cycle 48, time = 1.53.

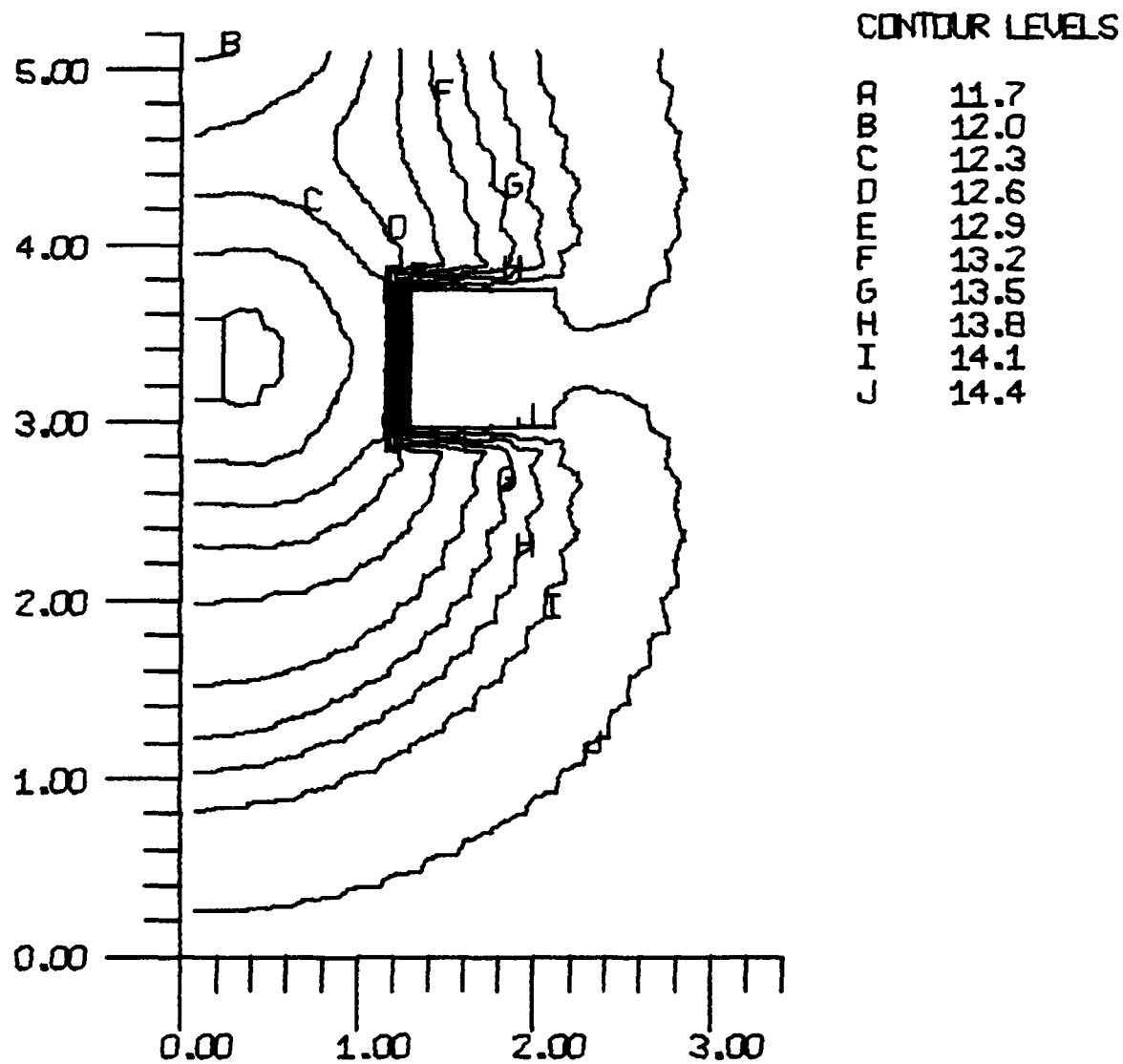


Figure 8.92. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: pressure contours at cycle 60, time = 2.04.

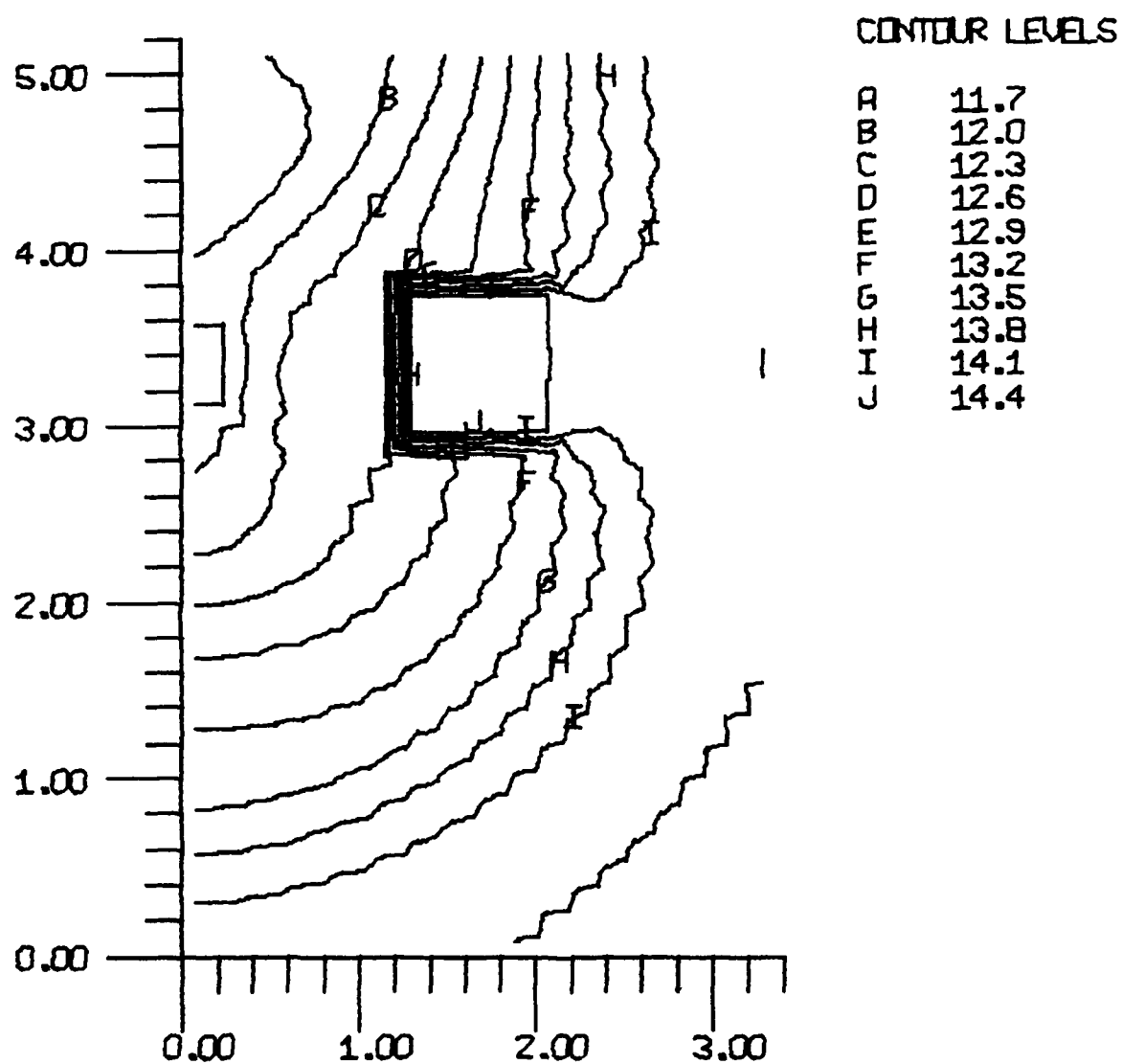


Figure 8.93. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: pressure contours at cycle 70, time = 2.51.

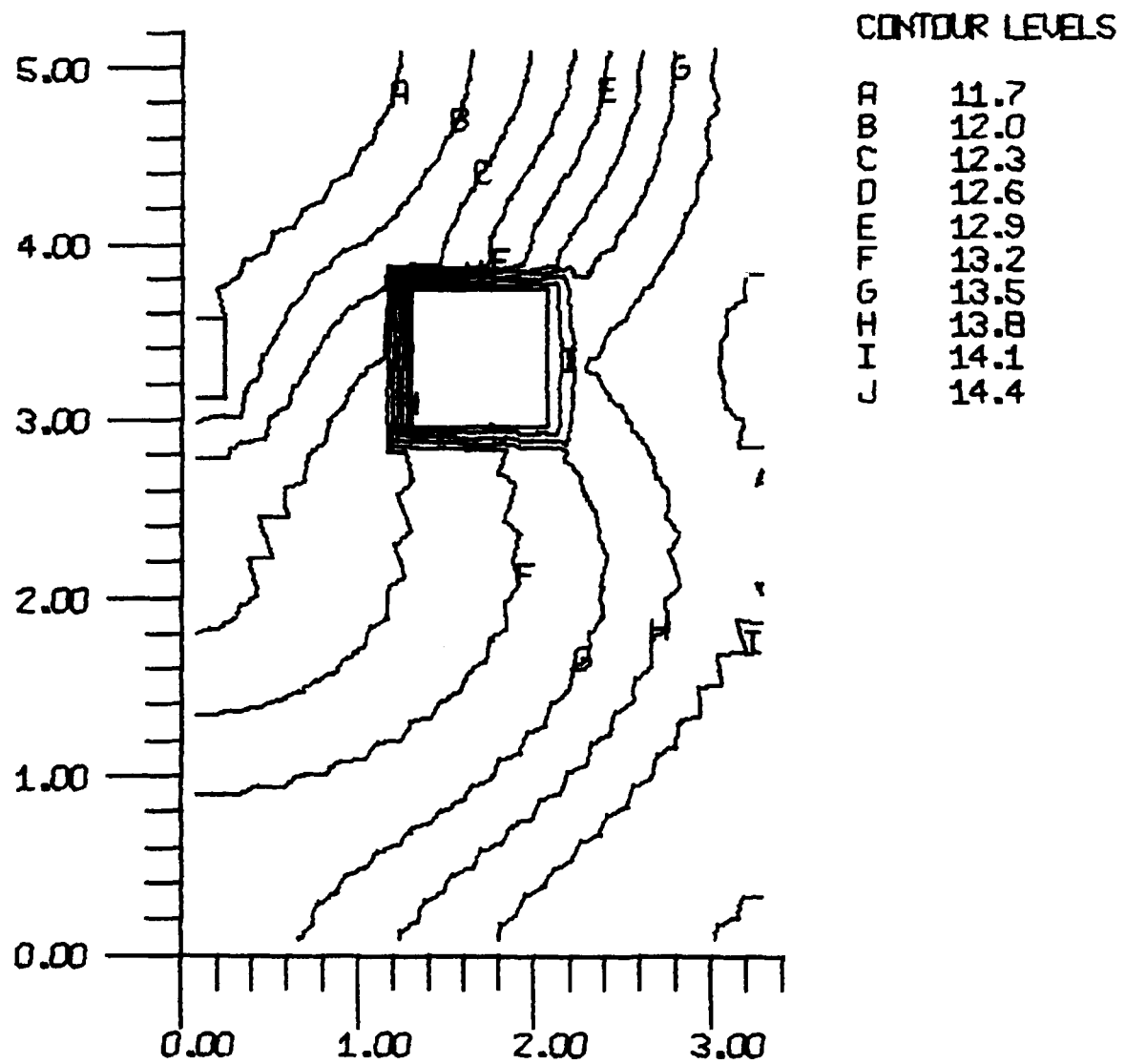


Figure 8.94. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: pressure contours at cycle 80, time = 3.04.

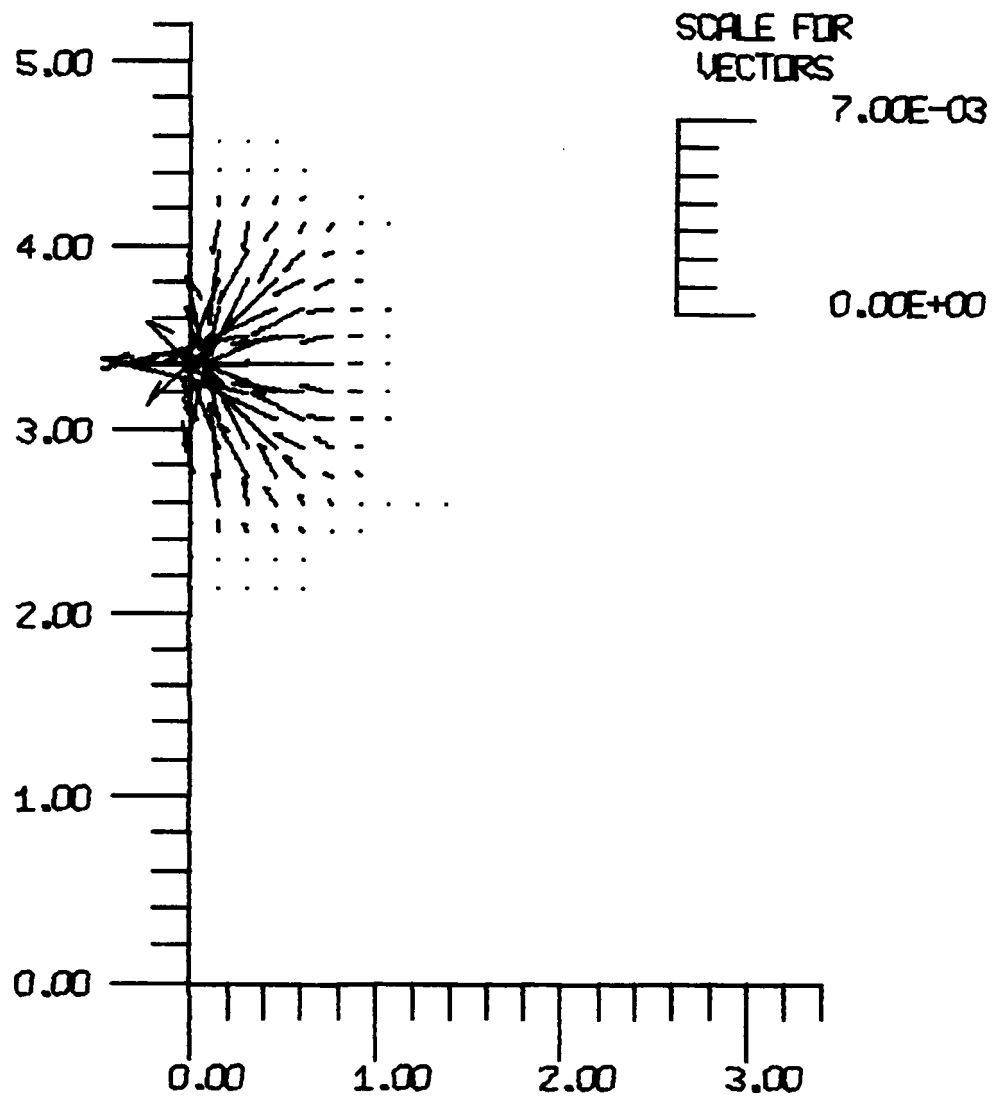


Figure 8.95. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: velocity vectors at cycle 19, time = 0.52.

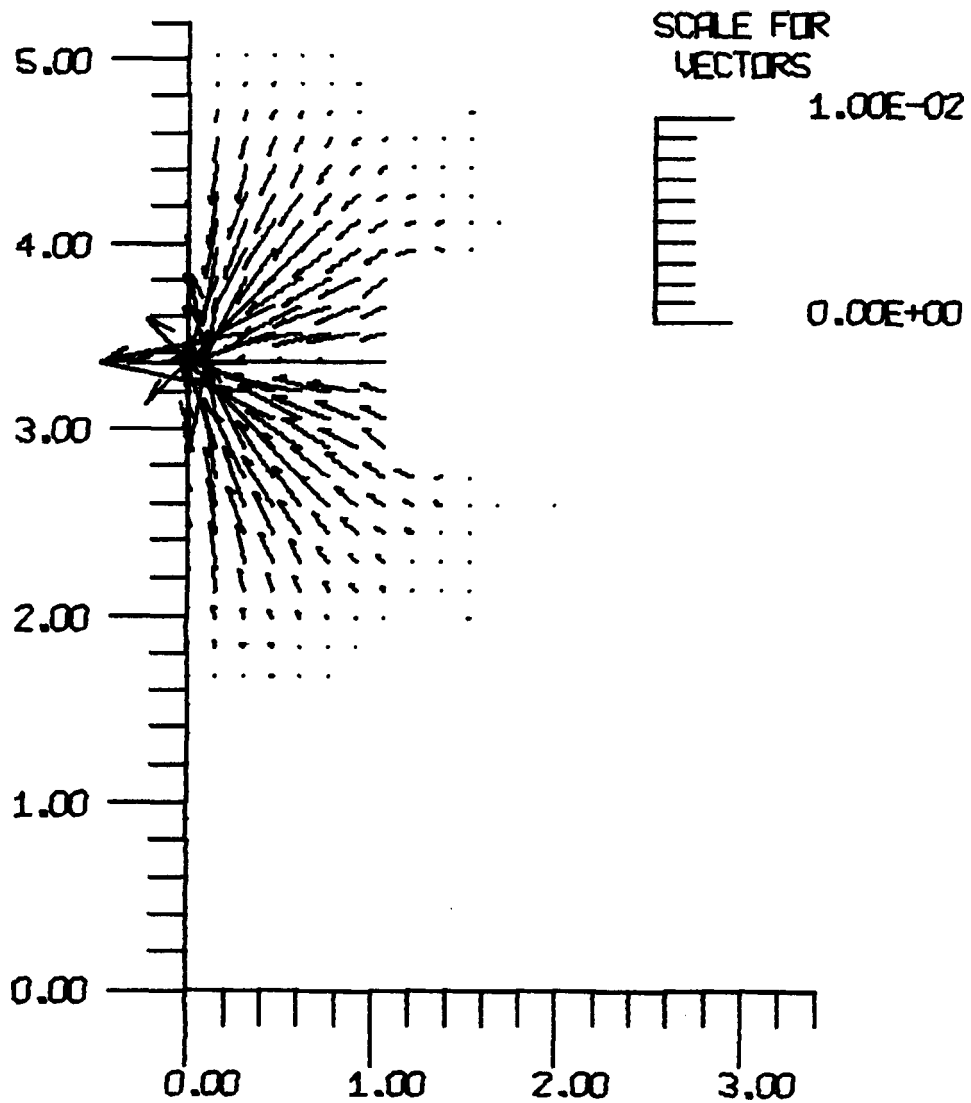


Figure 8.96. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: velocity vectors at cycle 34, time = 1.00.

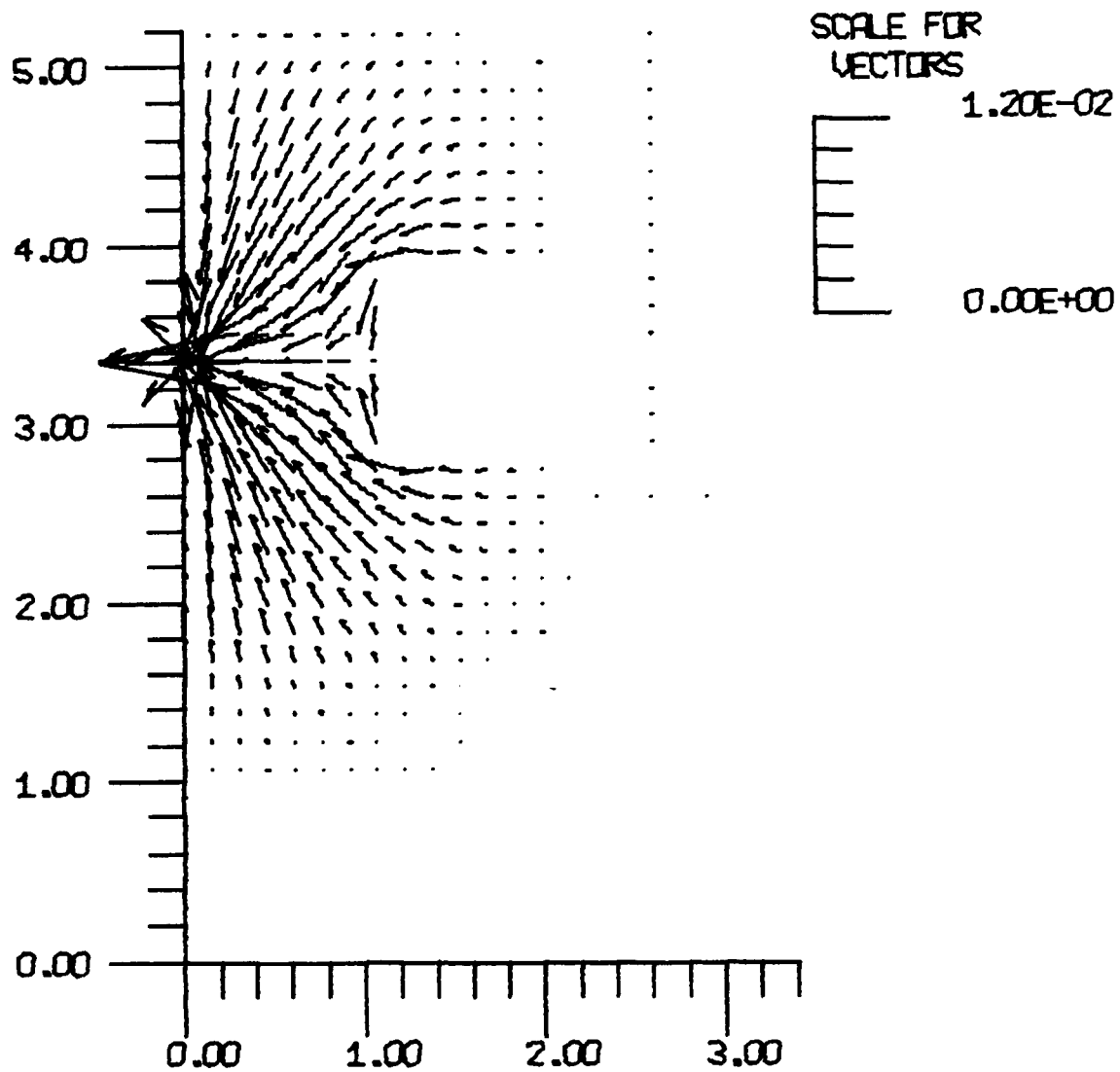


Figure 8.97. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: velocity vectors at cycle 48, time = 1.53.

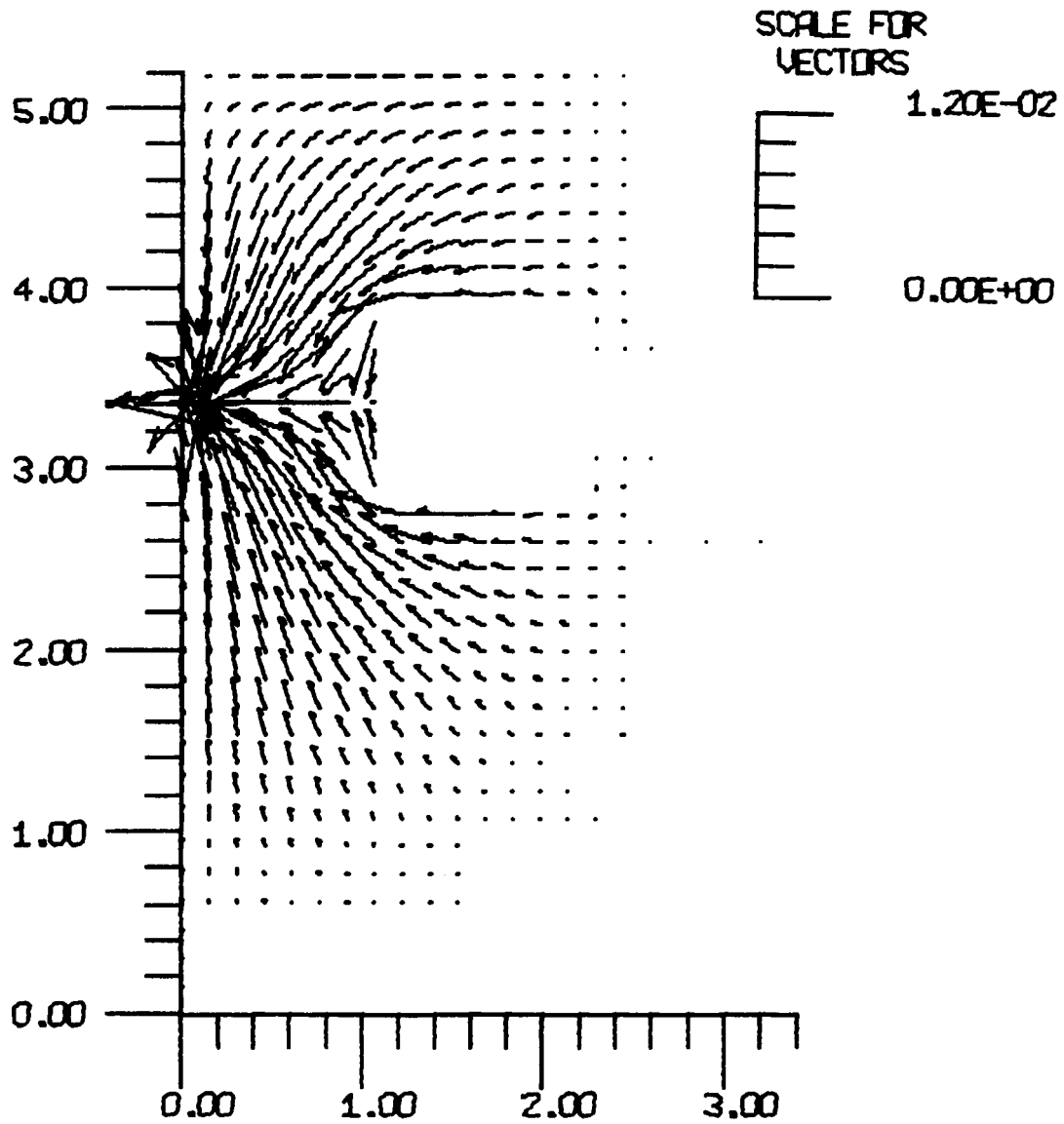


Figure 8.98. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: velocity vectors at cycle 60, time = 2.04.

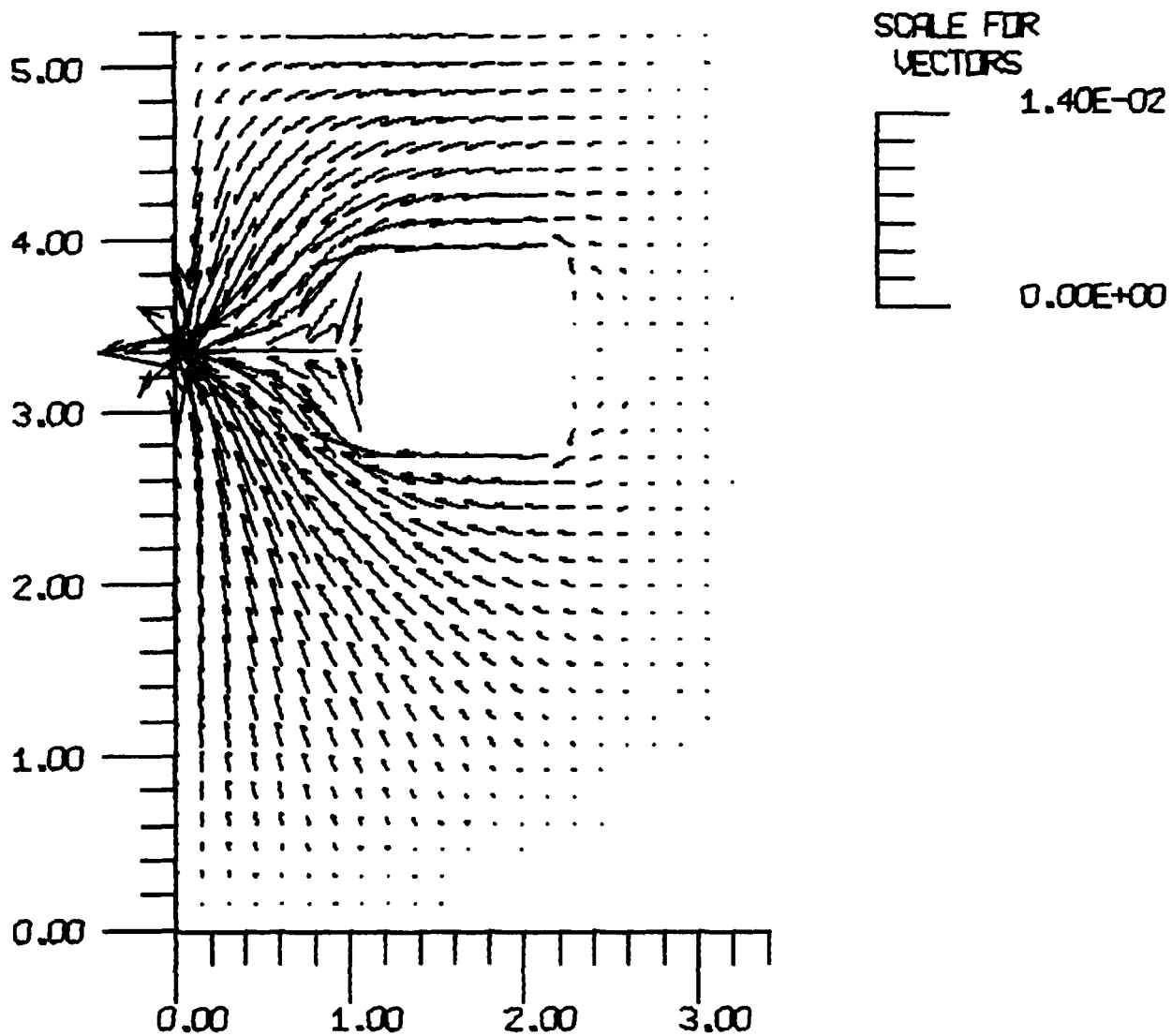


Figure 8.99. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: velocity vectors at cycle 70, time = 2.51.

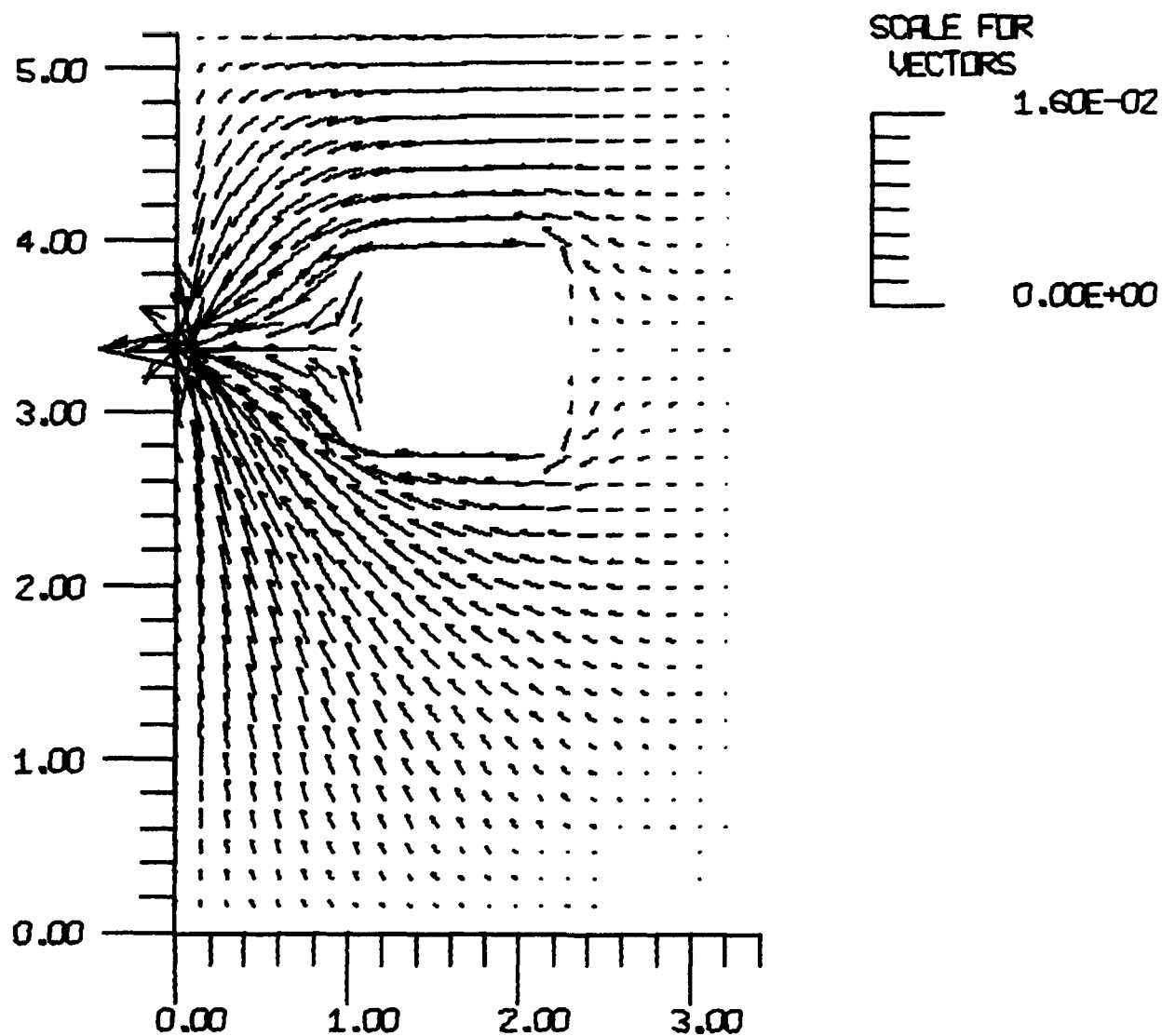


Figure 8.100. Calculation of a half section of a cylindrical rarefaction in a region with obstacles in the flow: velocity vectors at cycle 80, time = 3.04.

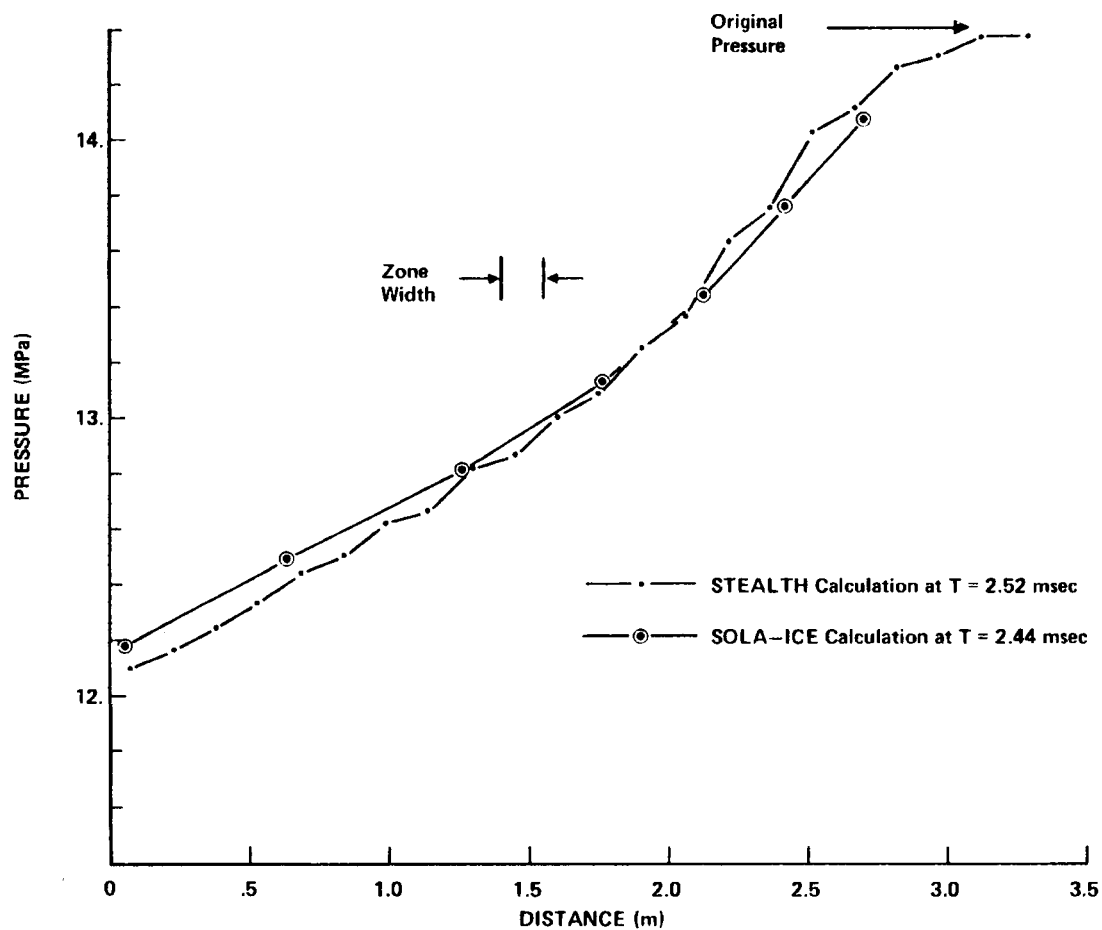


Figure 8.101. Comparison of STEALTH and SOLA-ICE calculations of a cylindrical rarefaction with obstacles in the flow: pressure profiles along a horizontal line 0.4 m below the bottom surface of the rectangular obstacle.

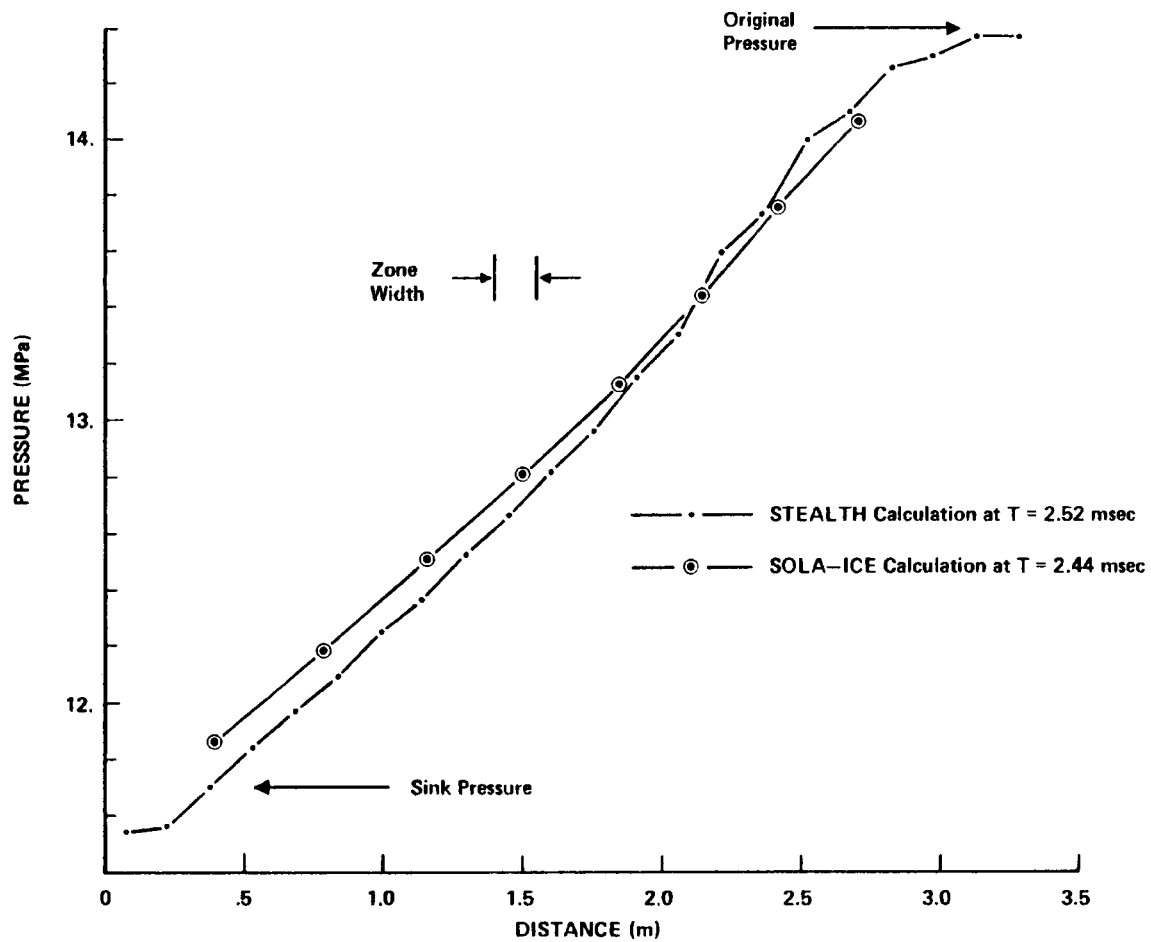


Figure 8.102. Comparison of STEALTH and SOLA-ICE calculations of a cylindrical rarefaction with obstacles in the flow: pressure profiles along a horizontal line 0.4 m above the top surface of the rectangular obstacle.

Secondly, the wave itself was not propagating along the direction of the grid lines in these regions. Because the data for the SOLA-ICE profiles was taken from contour plots which tend to average the calculated pressure, we would expect any such oscillations to be smeared out for those profiles.

Rarefaction in a Cold Leg-Downcomer Junction Geometry:

As discussed in Section 8.3.3.1, two calculations of this problem were performed. The mesh in the more coarsely zoned calculation was identical to that used in the corresponding SOLA-ICE calculation. The more finely zoned calculation was intended to provide better resolution primarily near the interior obstacles. Plots of pressure contours and velocity vectors from the more coarsely zoned calculation are provided at times of 0.55, 1.04, 1.55, 2.04, 2.55, 3.04 msec in Figures 8.103 - 8.114. The same set of plots from the more finely zoned calculation is provided in Figures 8.115 - 8.126.

The pressure contours from the more coarsely zoned calculation indicate that this zoning was not adequate for this problem. Although the contours are relatively uniform as the rarefaction propagates along the section meant to represent the cold-leg pipe, when it turns the corner and propagates along the downcomer section, particularly in the region adjacent to the obstruction, the contours become somewhat ragged. This is not surprising considering that only one row of cells on one side of the obstacle and two on the other were used. This is clearly not adequate in view of the fact that a zero velocity boundary condition was used for the interior boundaries.

The more finely zoned calculation shows at least qualitative improvement in the region near the obstruction. The pressure contours are considerably more regular, and the velocity field is much smoother. The additional zones on either side of the obstruction appear to reduce the numerical errors introduced by the boundary conditions. If substantially

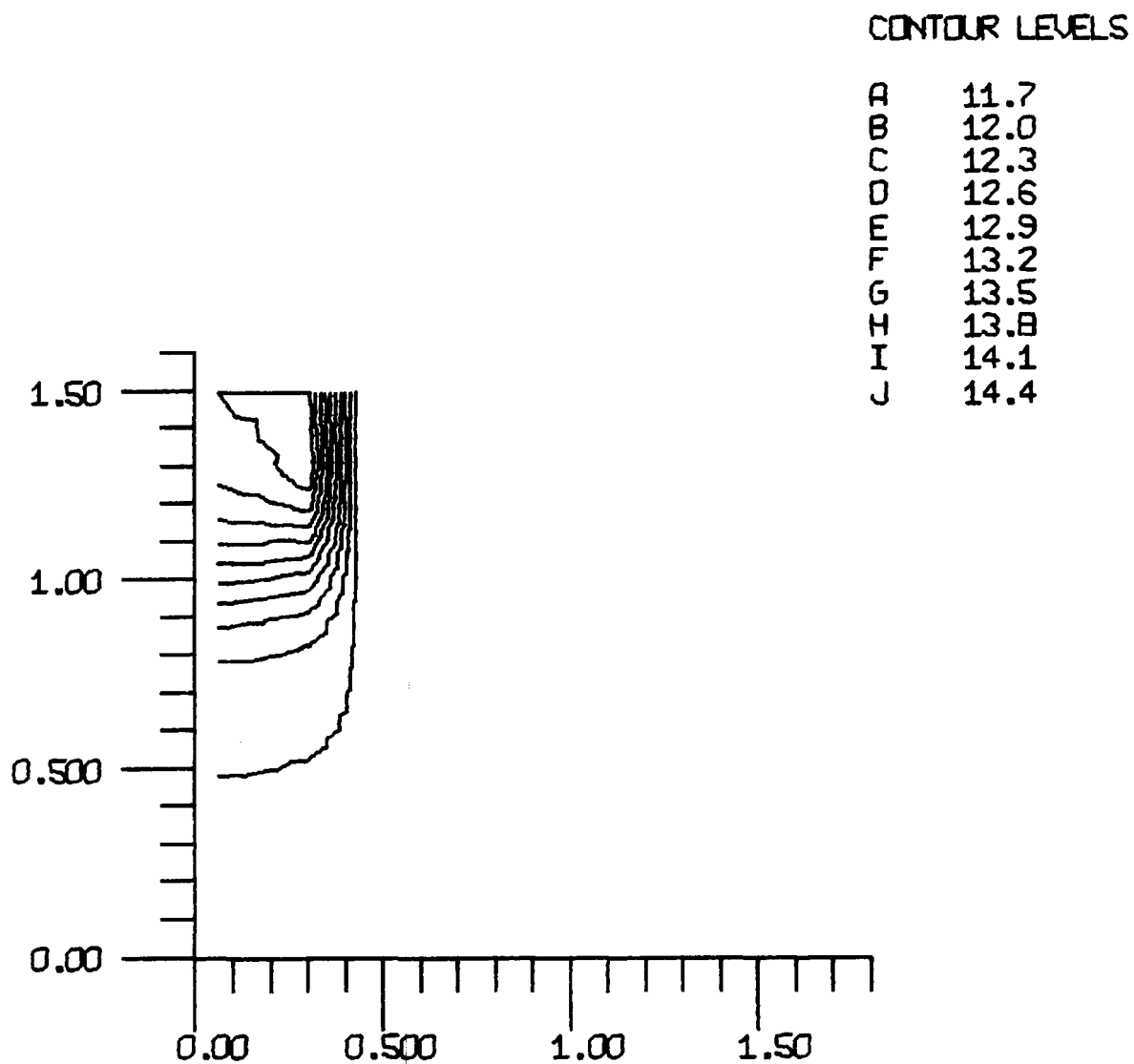


Figure 8.103. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: pressure contours at cycle 11, time = 0.55.

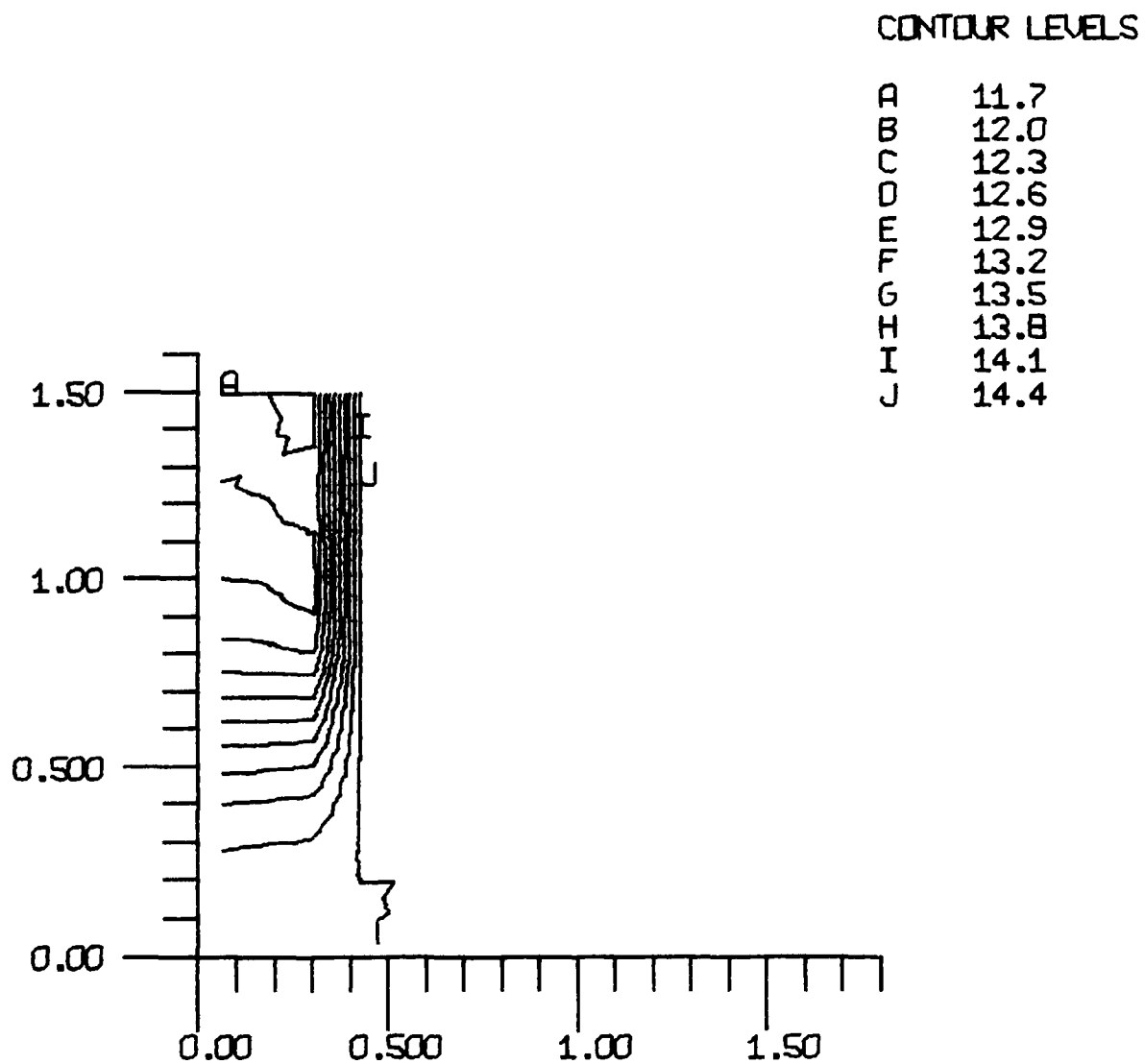


Figure 8.104. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: pressure contours at cycle 21, time = 1.05.

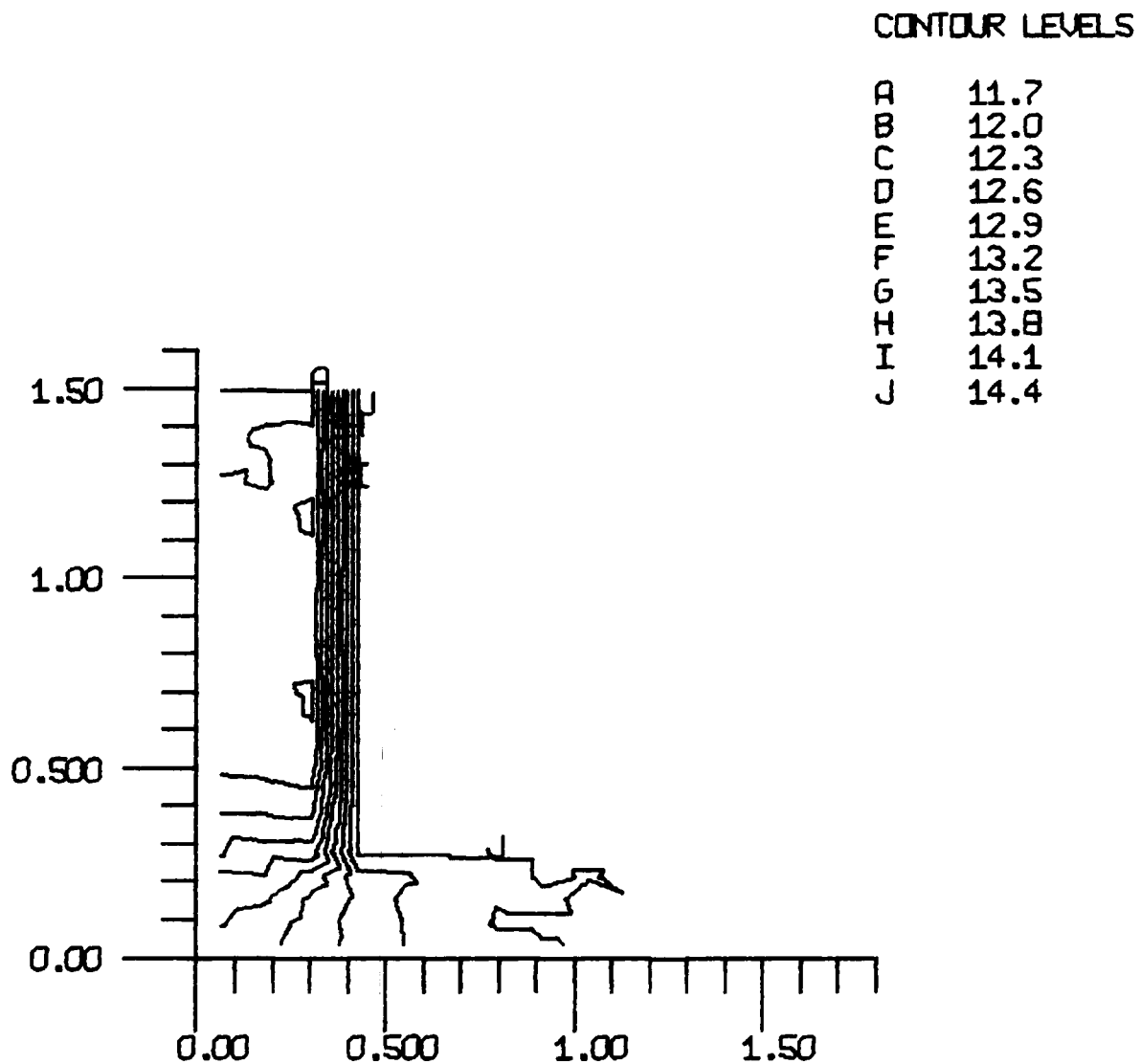


Figure 8.105. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: pressure contours at cycle 31, time = 1.55.

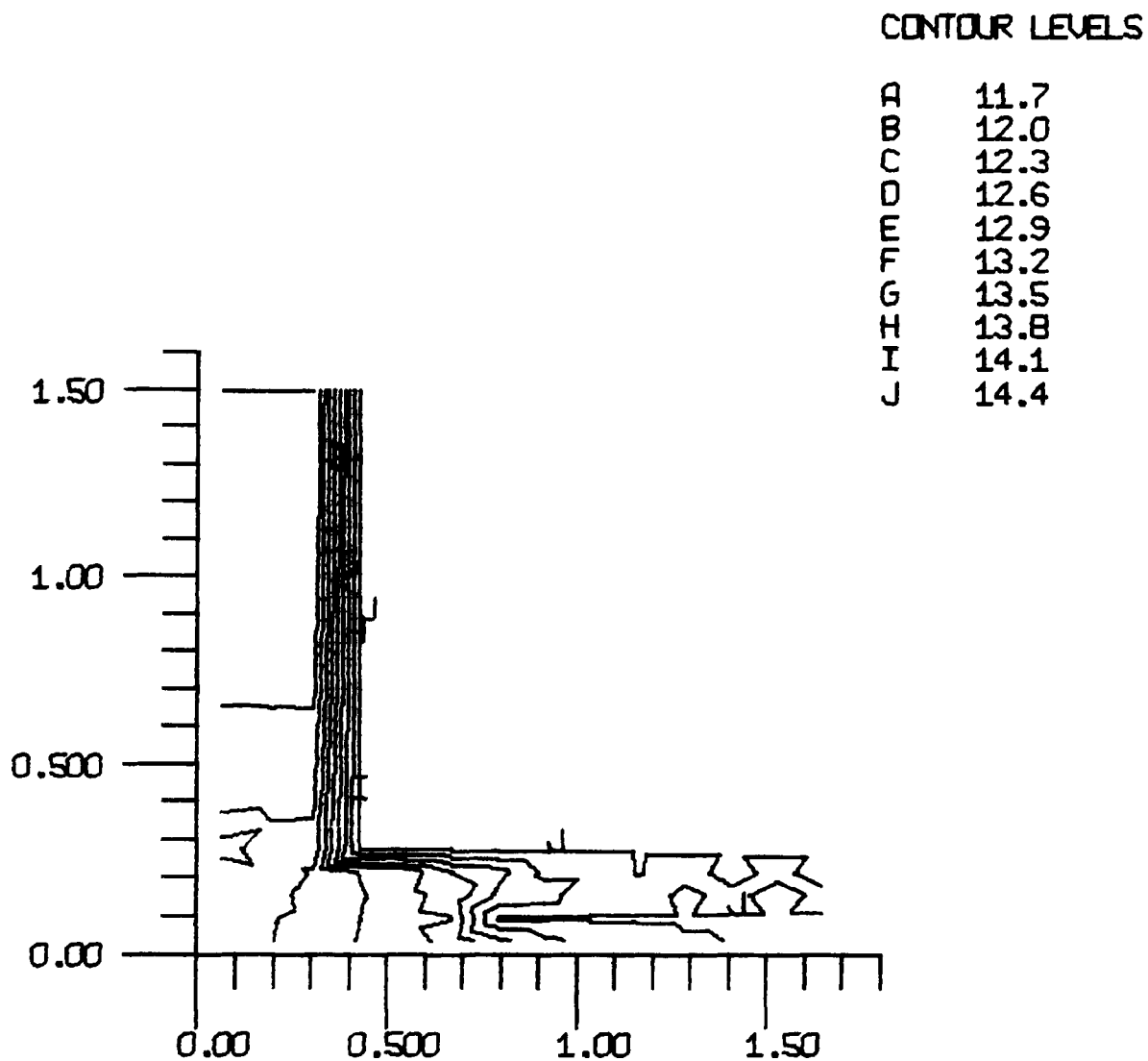


Figure 8.106. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: pressure contours at cycle 41, time = 2.05.

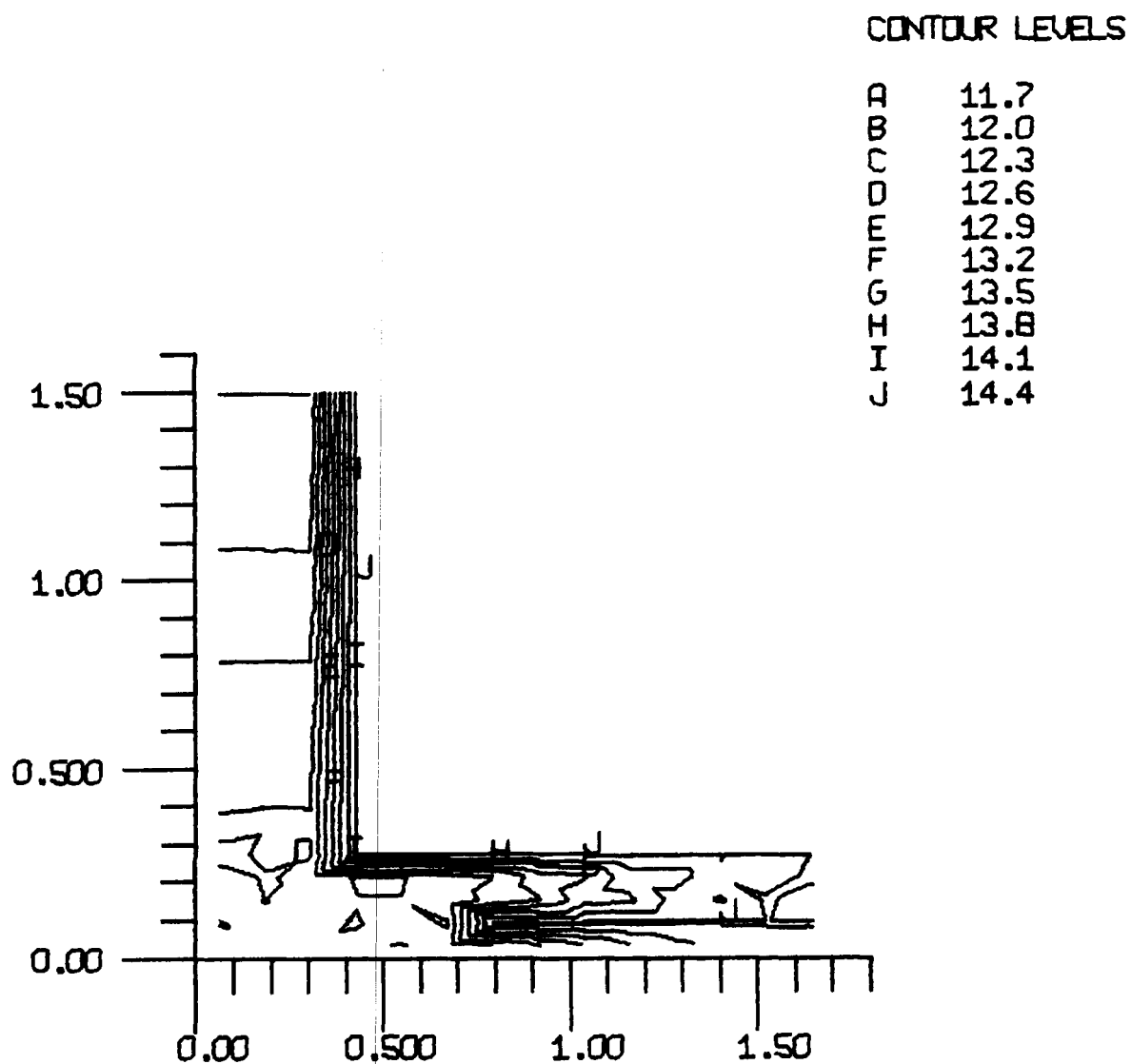


Figure 8.107. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: pressure contours at cycle 51, time = 2.55.

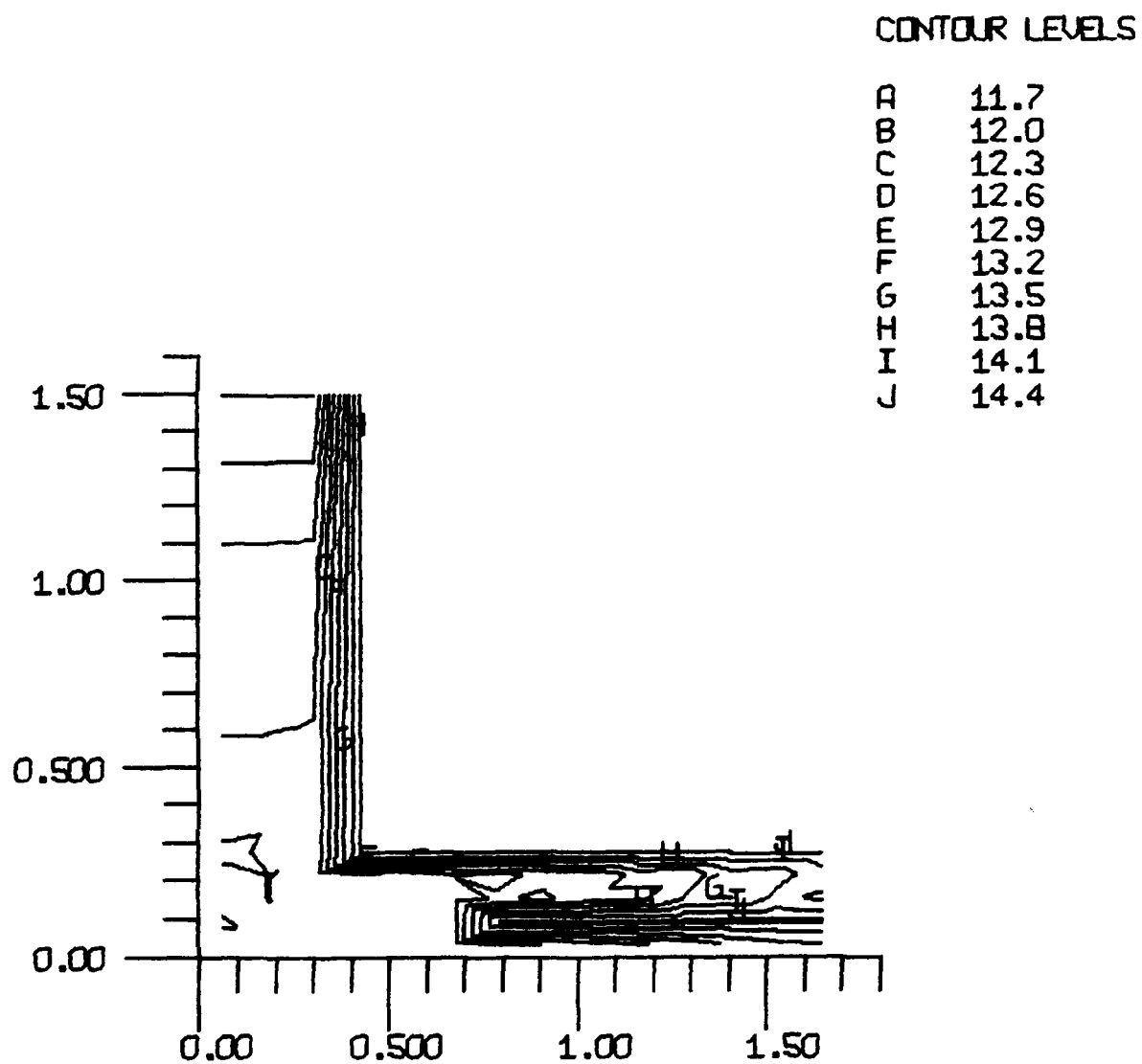


Figure 8.108. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: pressure contours at cycle 61, time = 3.05.

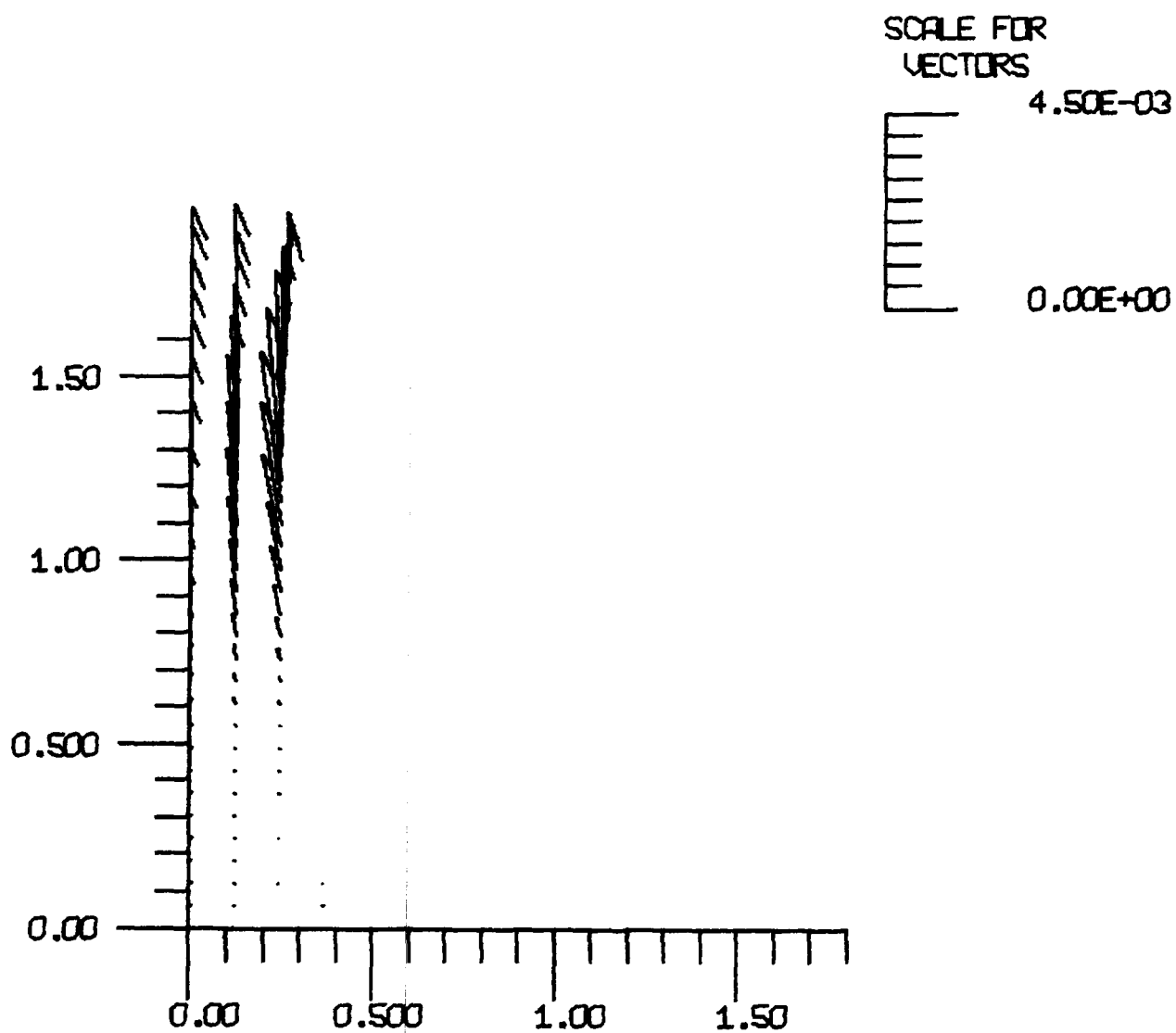


Figure 8.109. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: velocity vectors at cycle 11, time = 0.55.

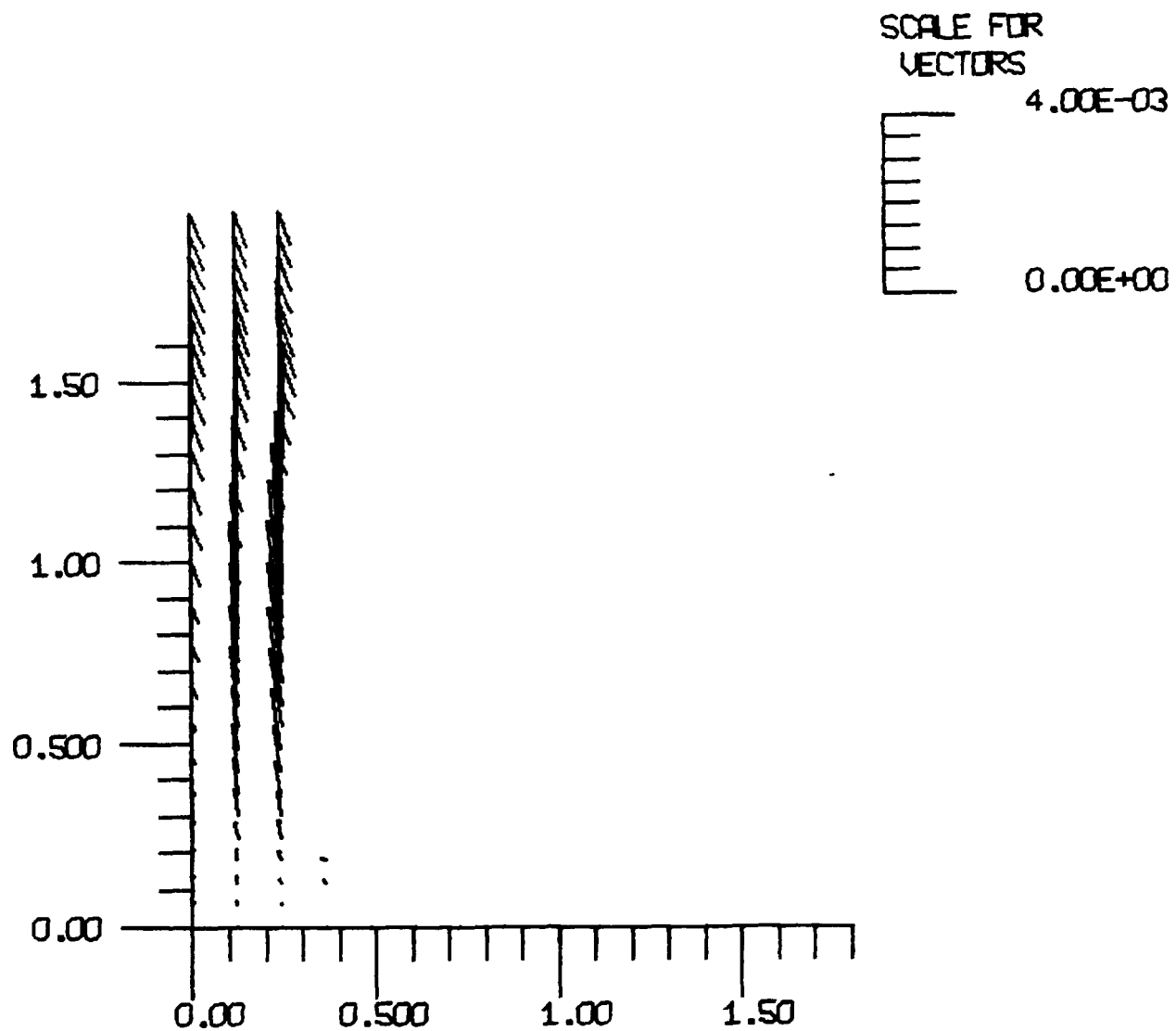


Figure 8.110. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: velocity vectors at cycle 21, time = 1.05.

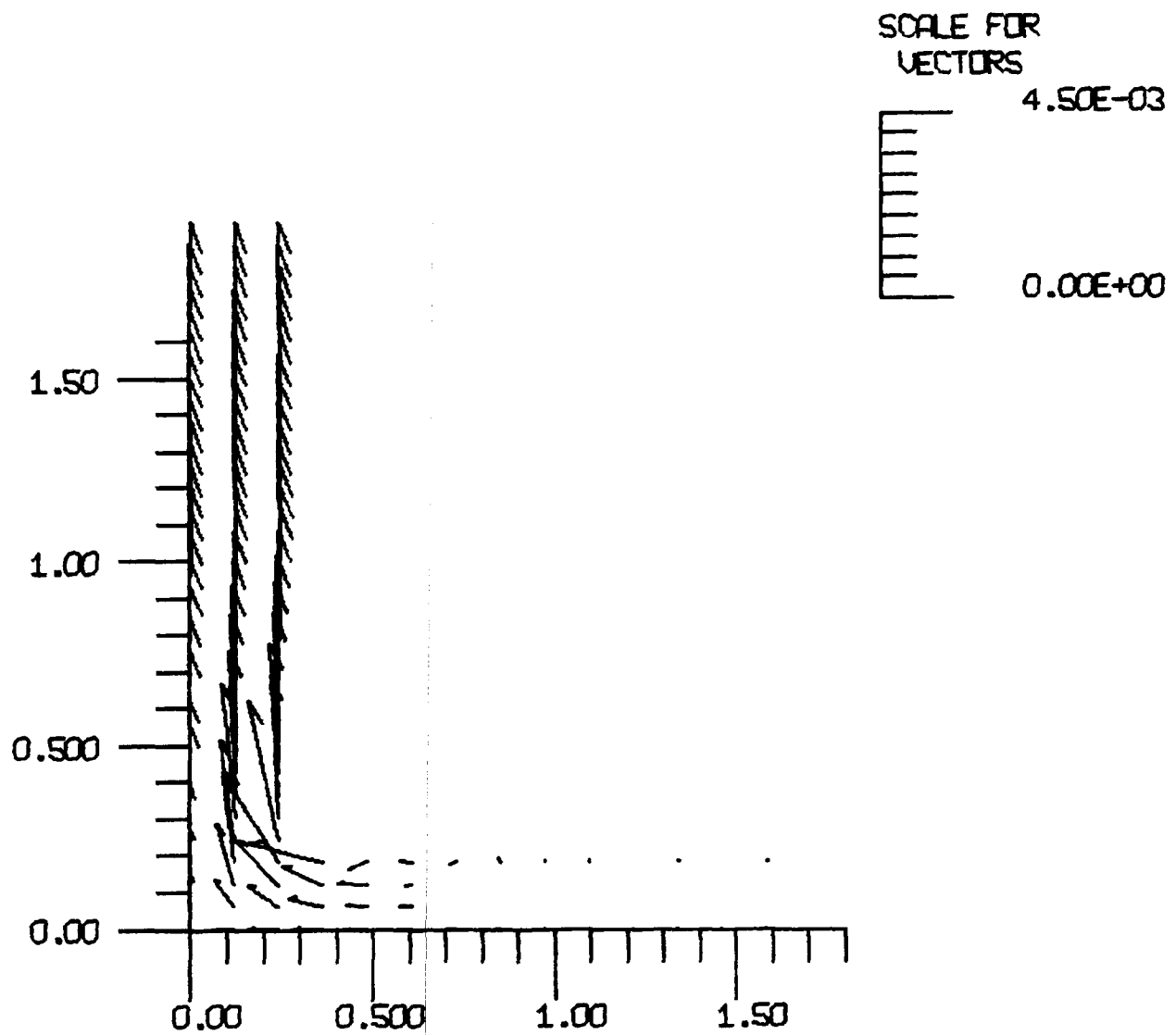


Figure 8.111. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: velocity vectors at cycle 31, time = 1.55.

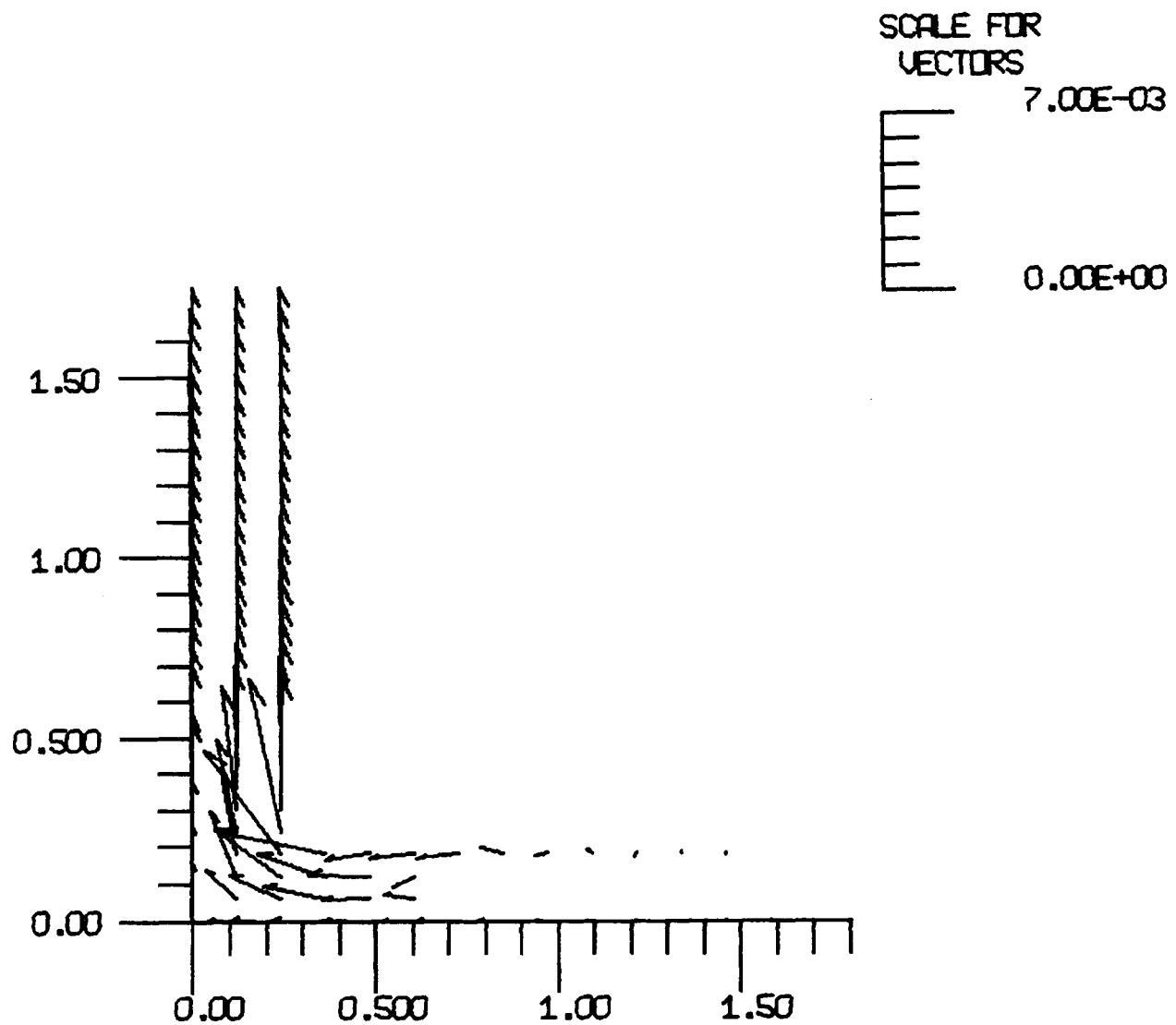


Figure 8.112. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: velocity vectors at cycle 41, time = 2.05.

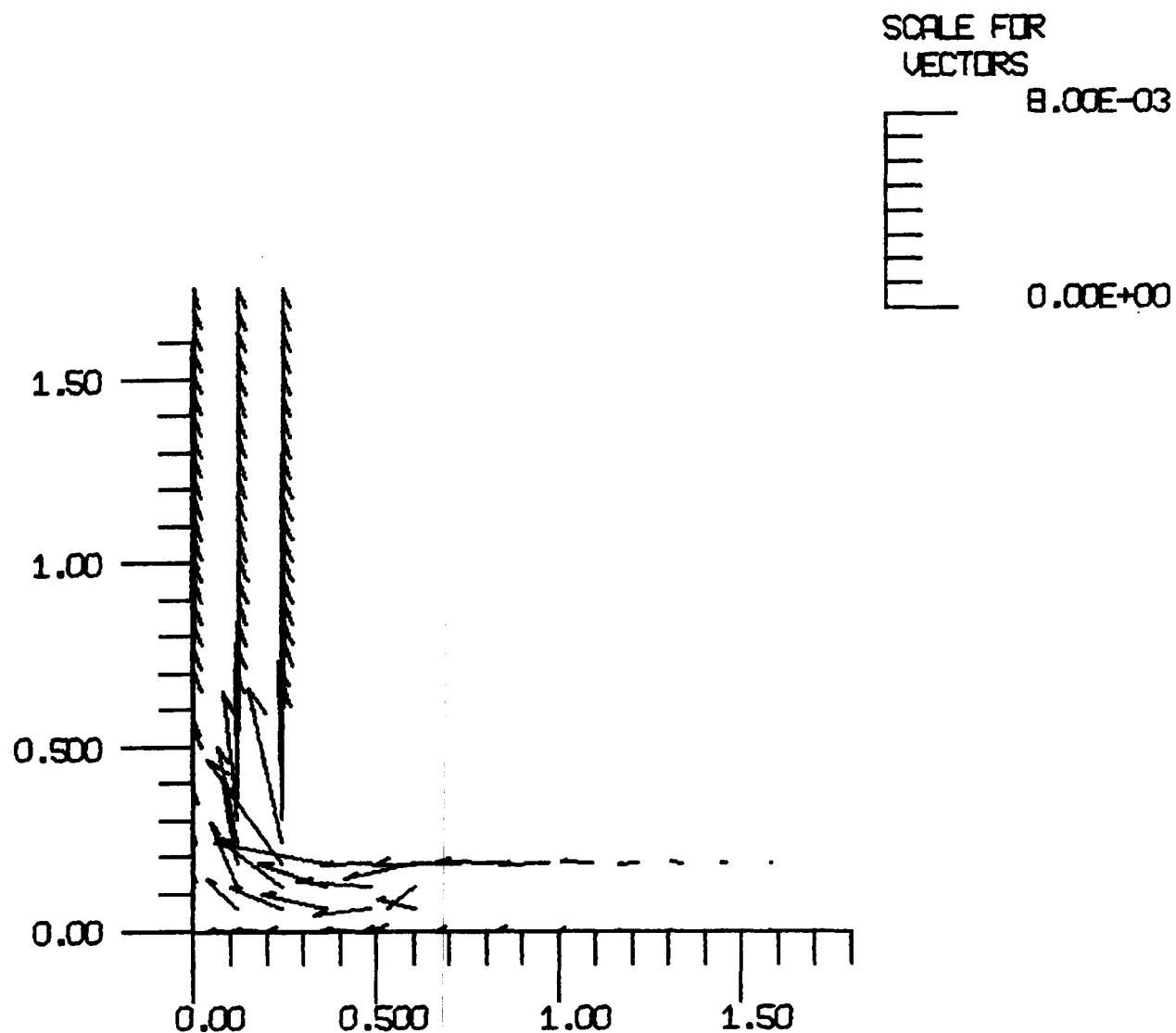


Figure 8.113. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: velocity vectors at cycle 51, time = 2.55.

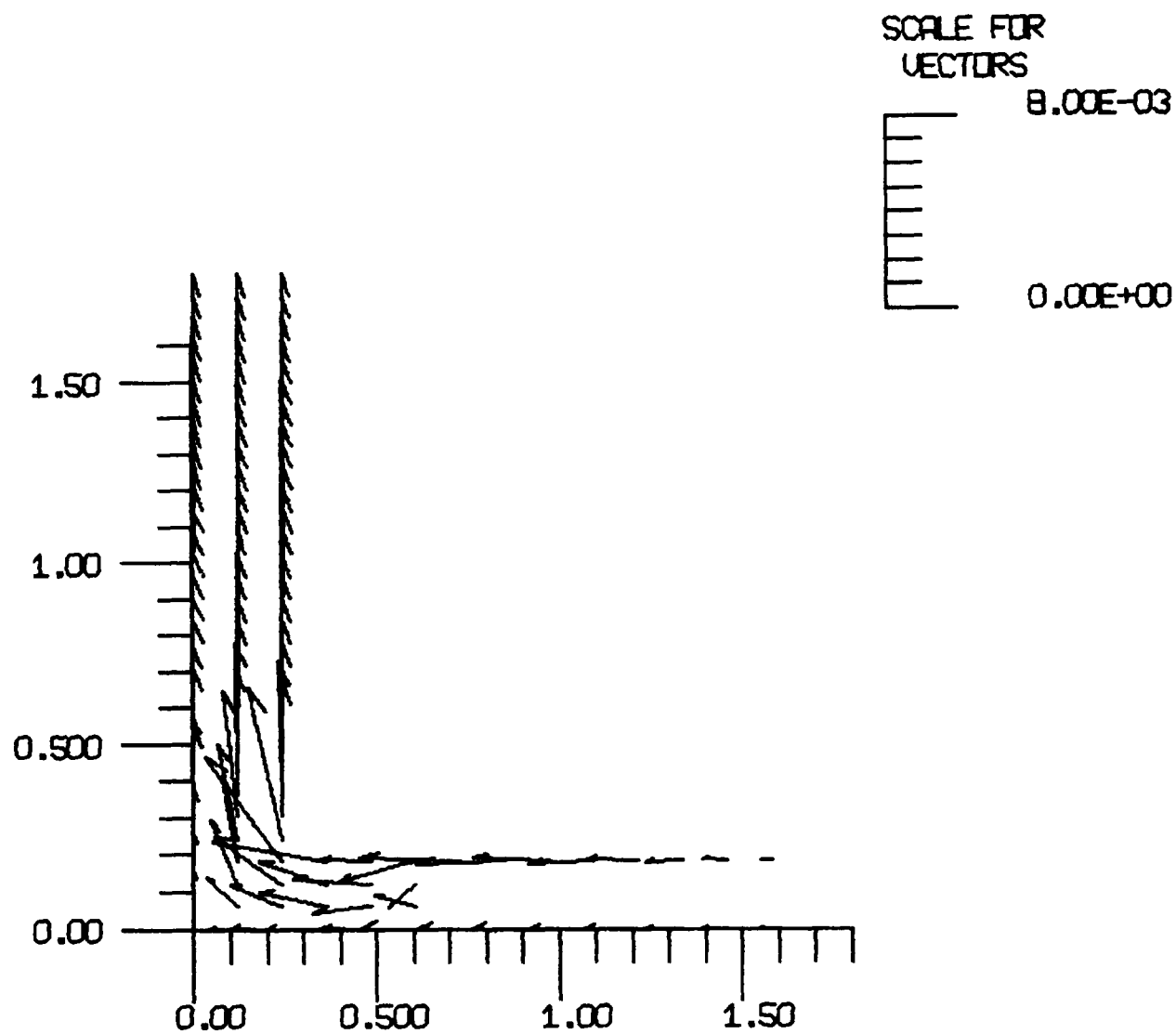


Figure 8.114. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - coarse zoning: velocity vectors at cycle 61, time = 3.05.

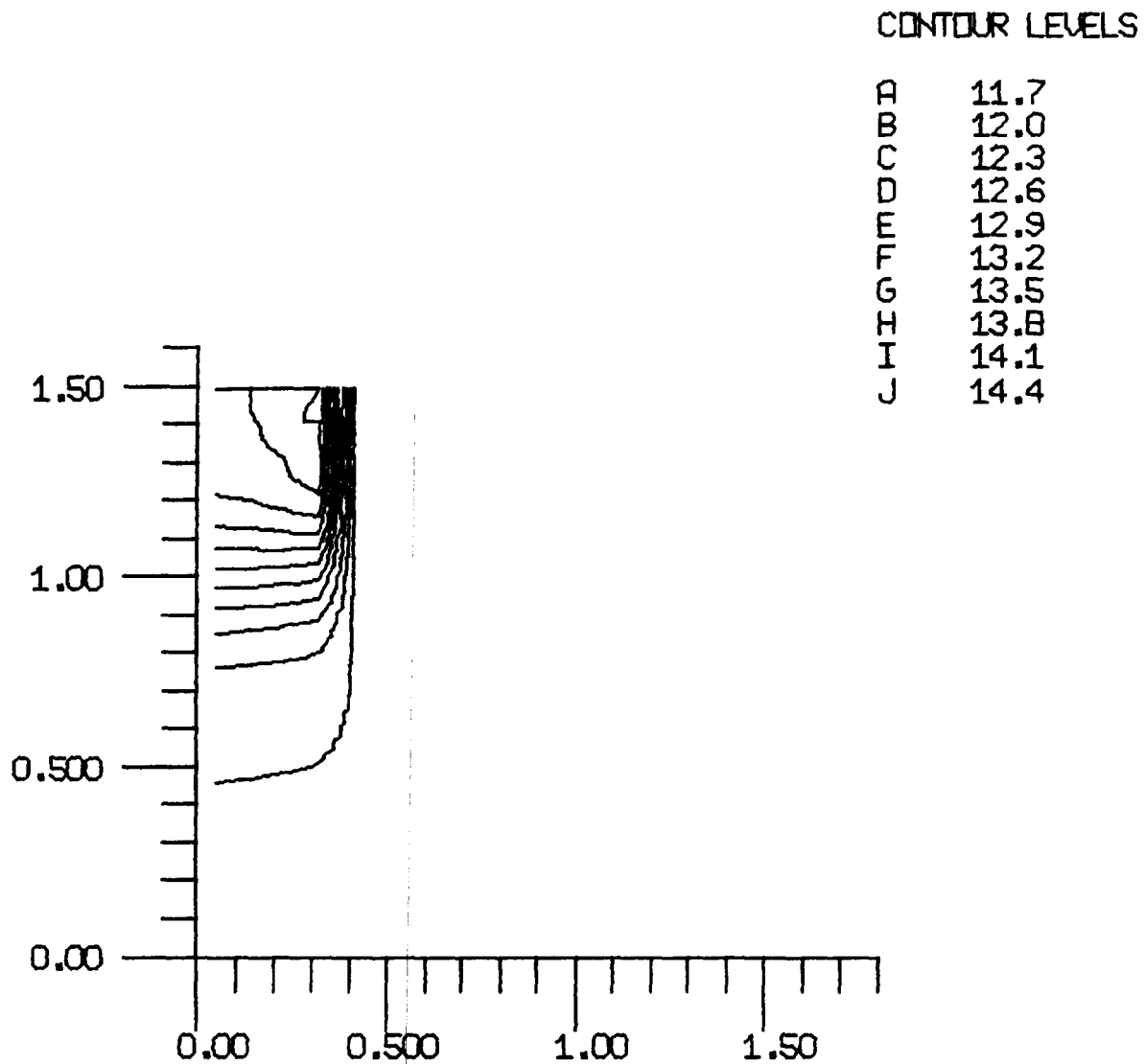


Figure 8.115. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: pressure contours at cycle 11, time = 0.55.

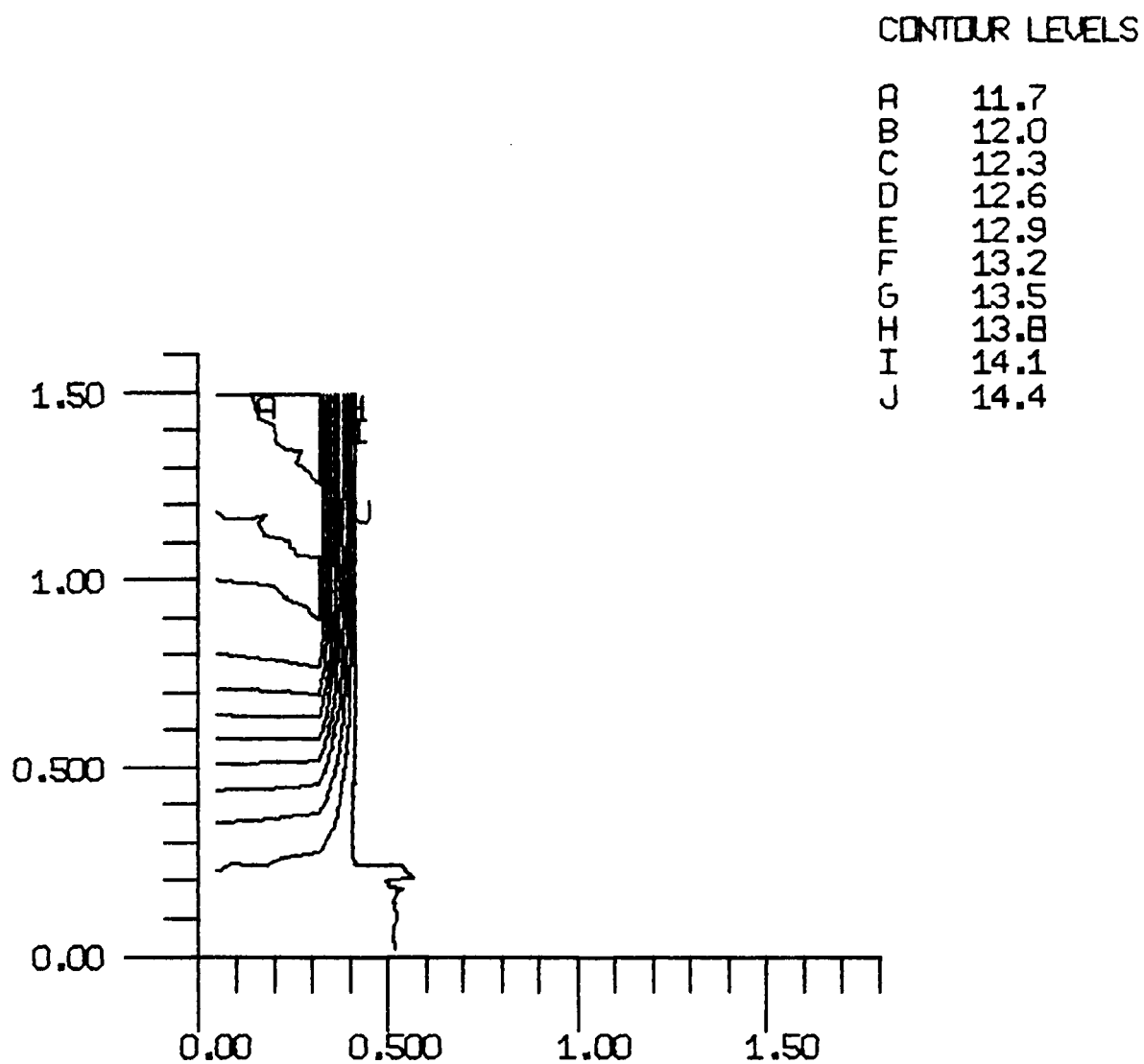


Figure 8.116. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: pressure contours at cycle 21, time = 1.05.

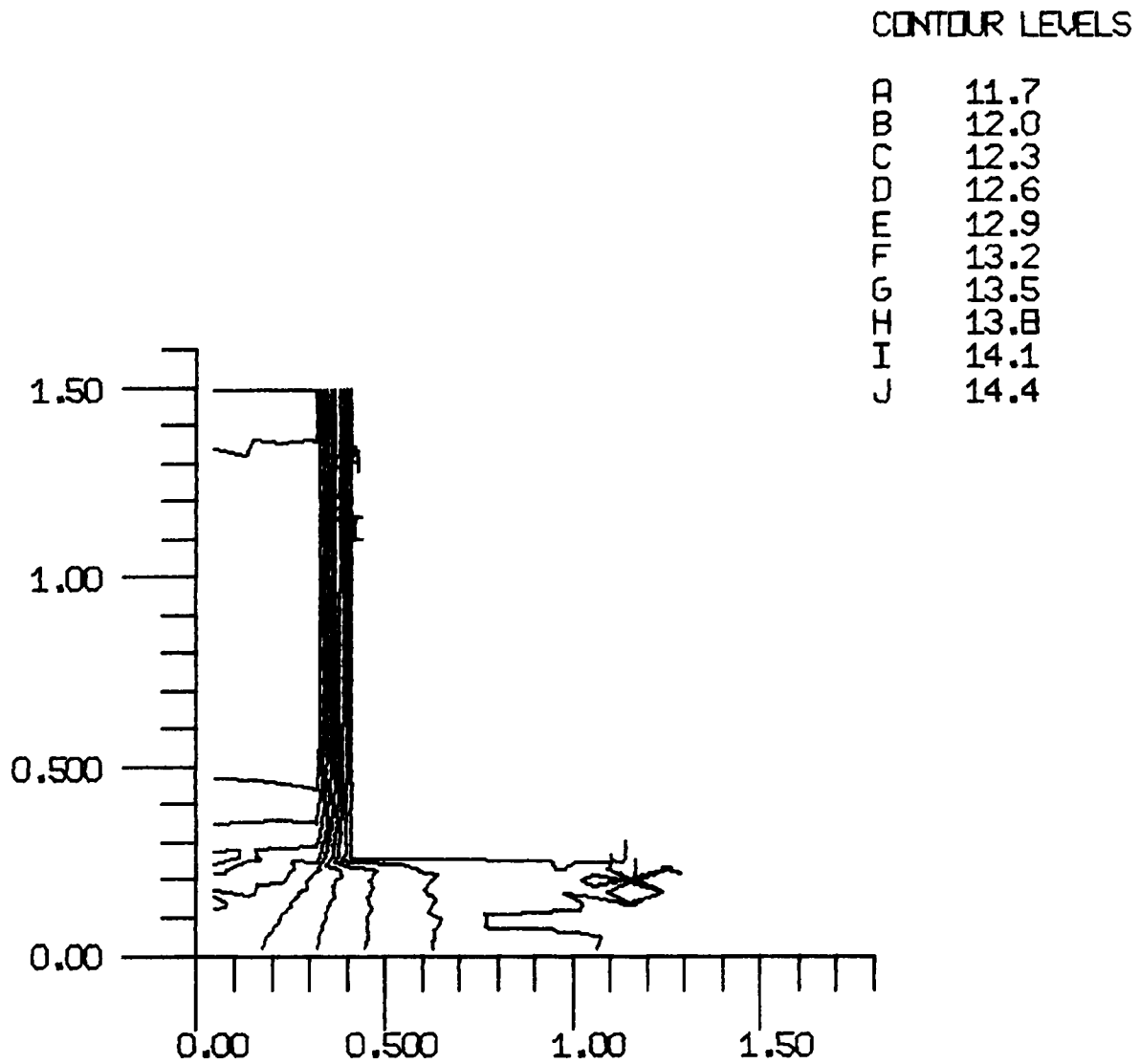


Figure 8.117. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: pressure contours at cycle 31, time = 1.44.

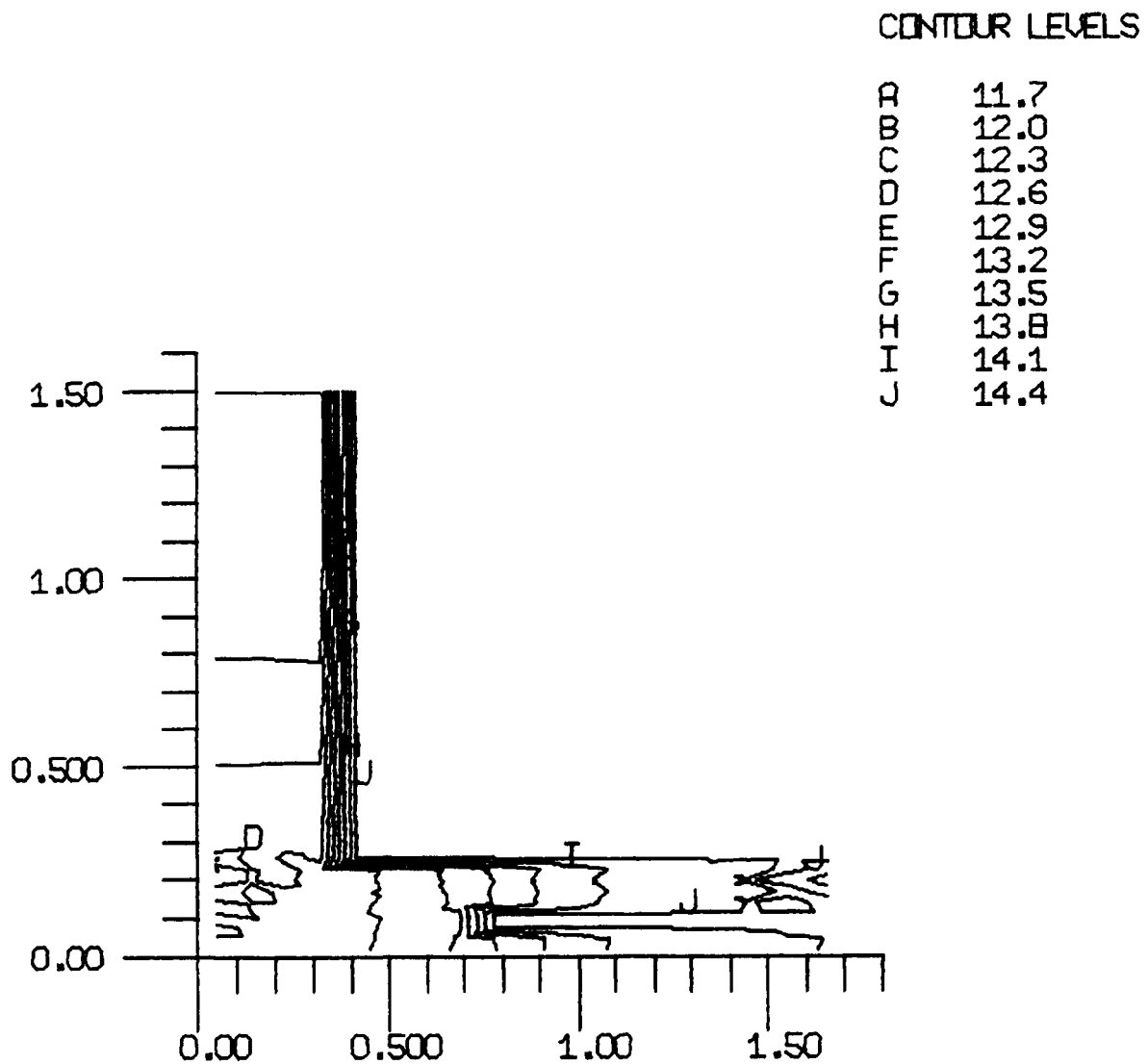


Figure 8.118. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: pressure contours at cycle 41, time = 2.05.

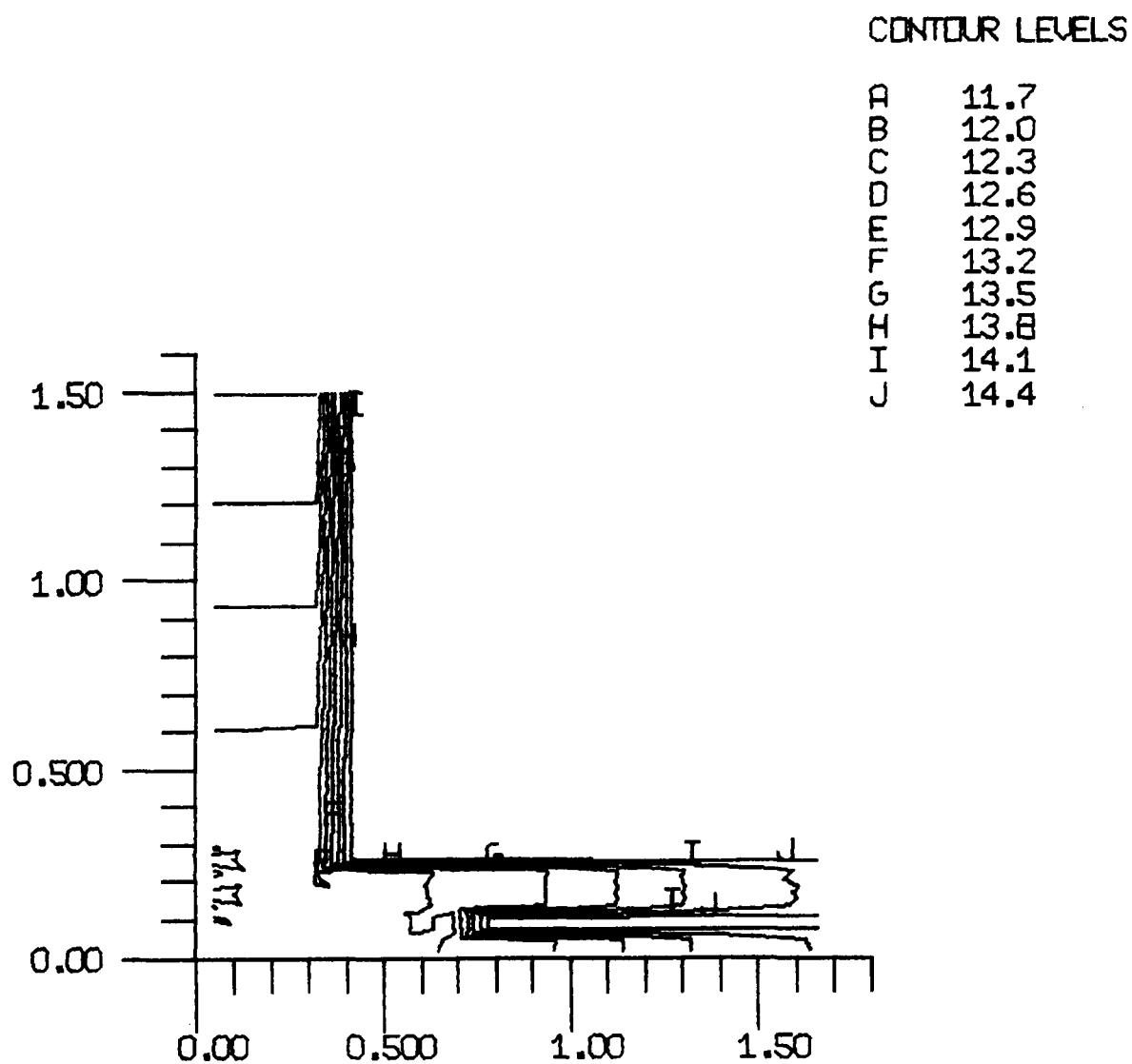


Figure 8.119. Calculation of a rarefaction in a geometry similar to a cold-leg downcomer junction - fine zoning: pressure contours at cycle 51, time = 2.55.

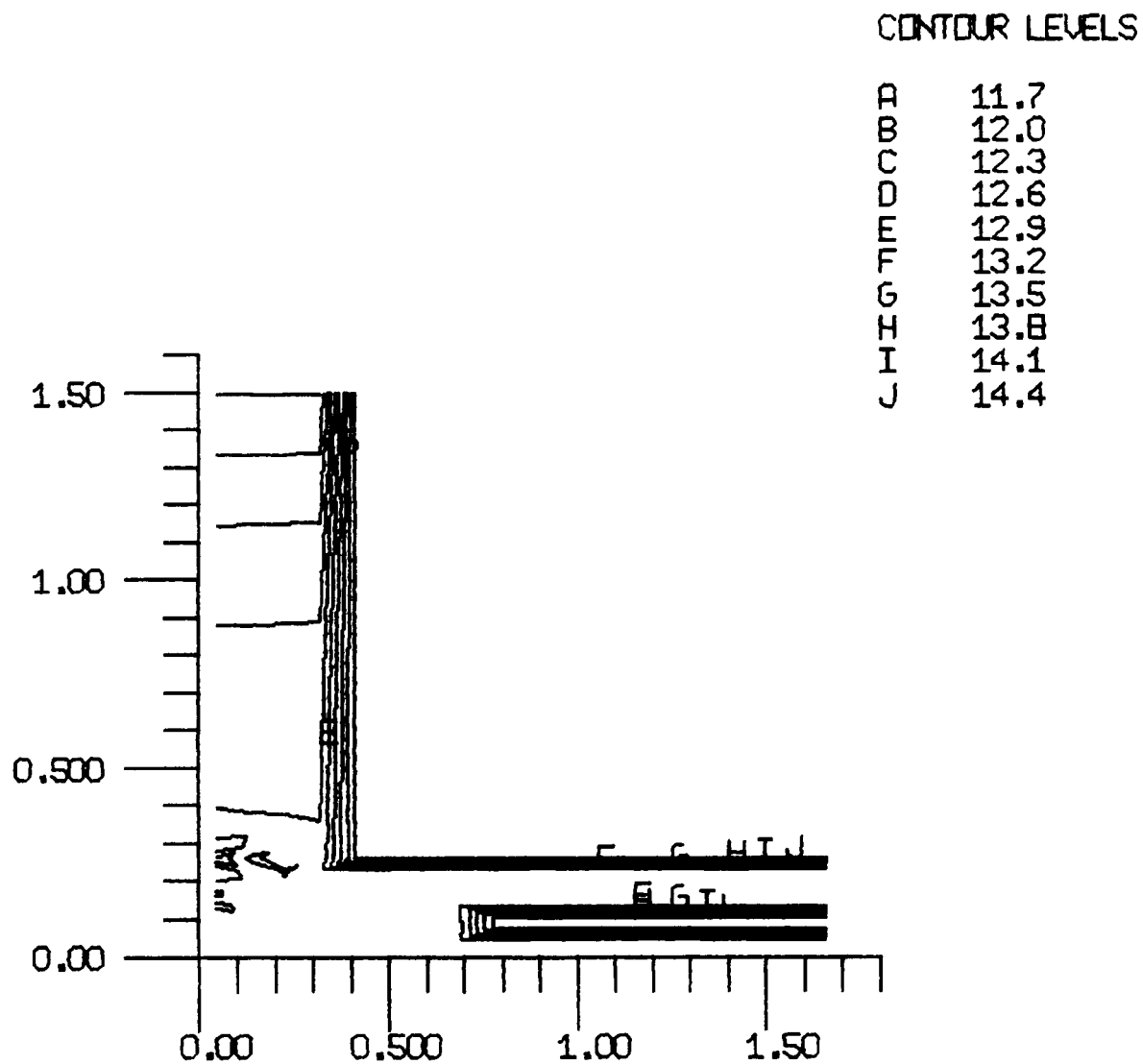


Figure 8.120. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: pressure contours at cycle 61, time = 3.05.

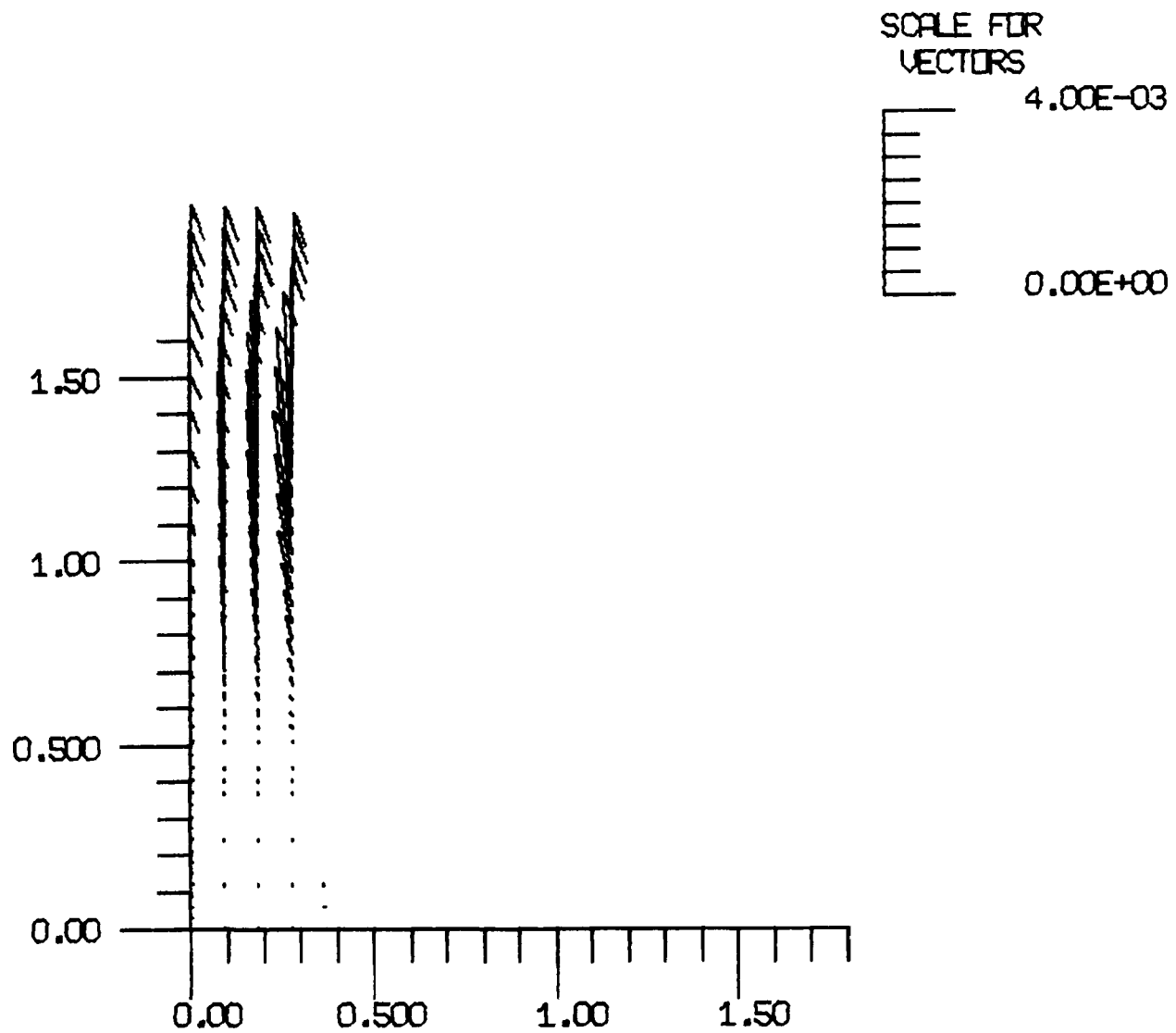


Figure 8.121. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: velocity vectors at cycle 11, time = 0.55.

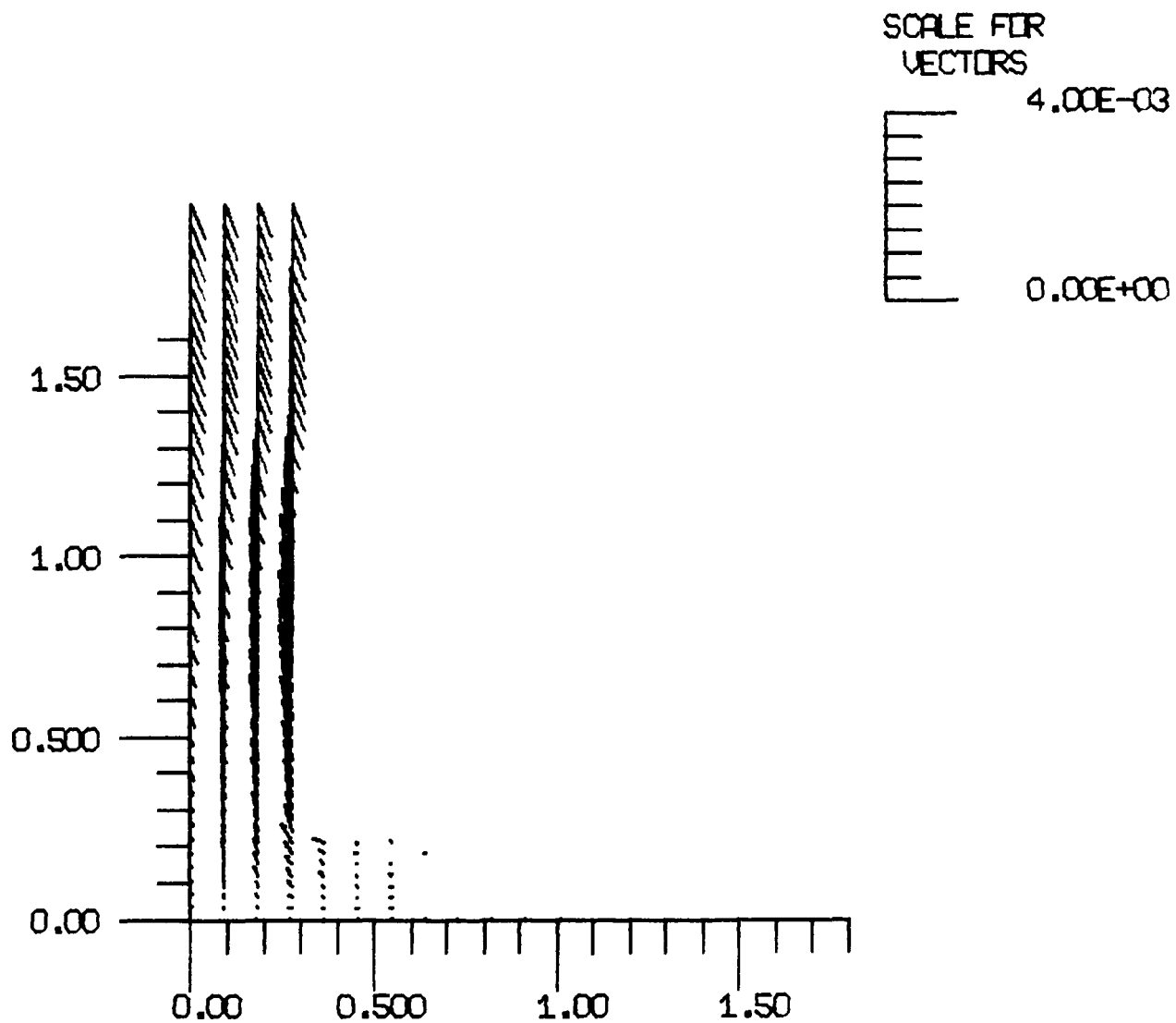


Figure 8.122. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: velocity vectors at cycle 21, time = 1.05.

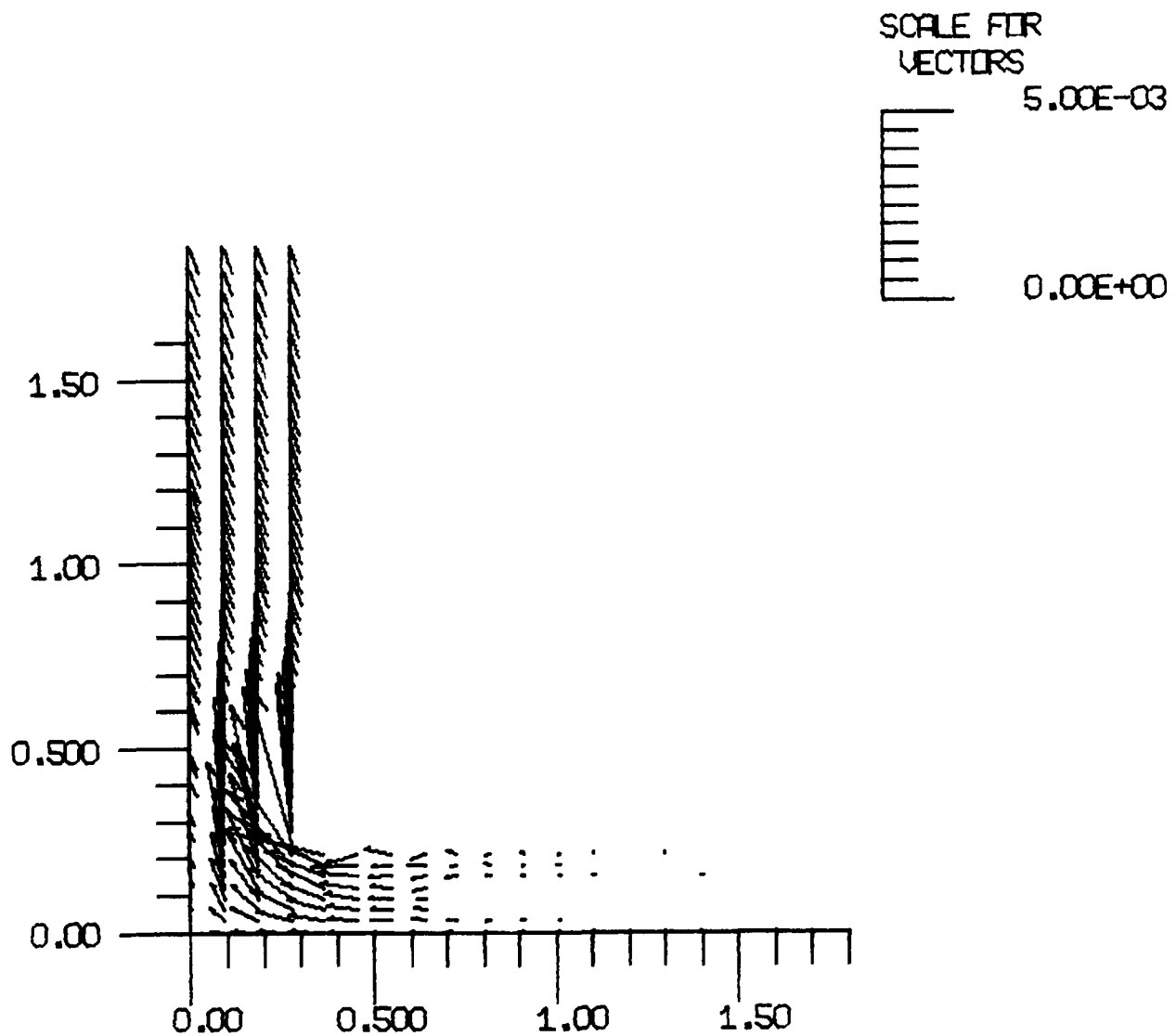


Figure 8.123. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: velocity vectors at cycle 31, time = 1.55.

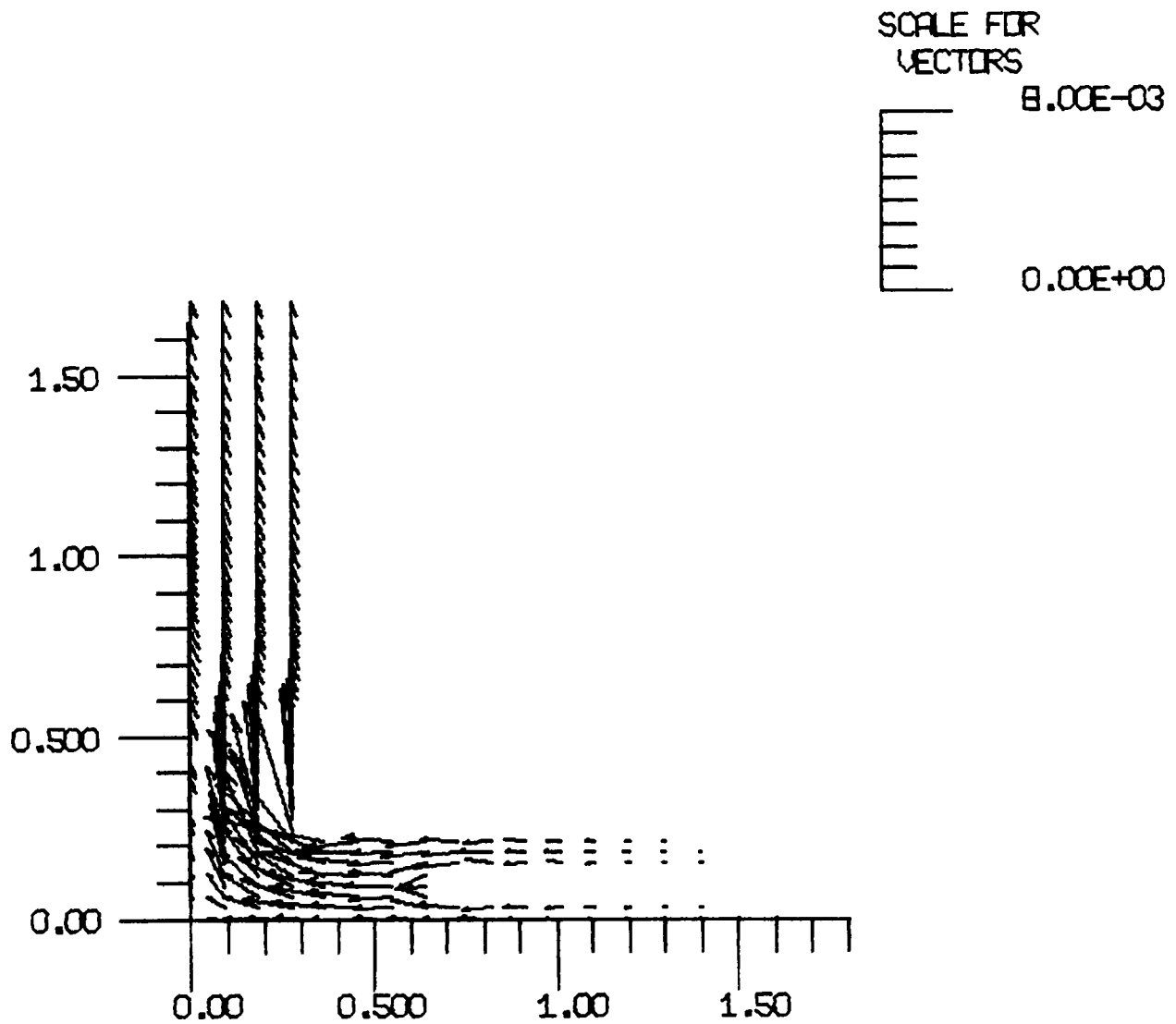


Figure 8.124. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: velocity vectors at cycle 41, time = 2.05.

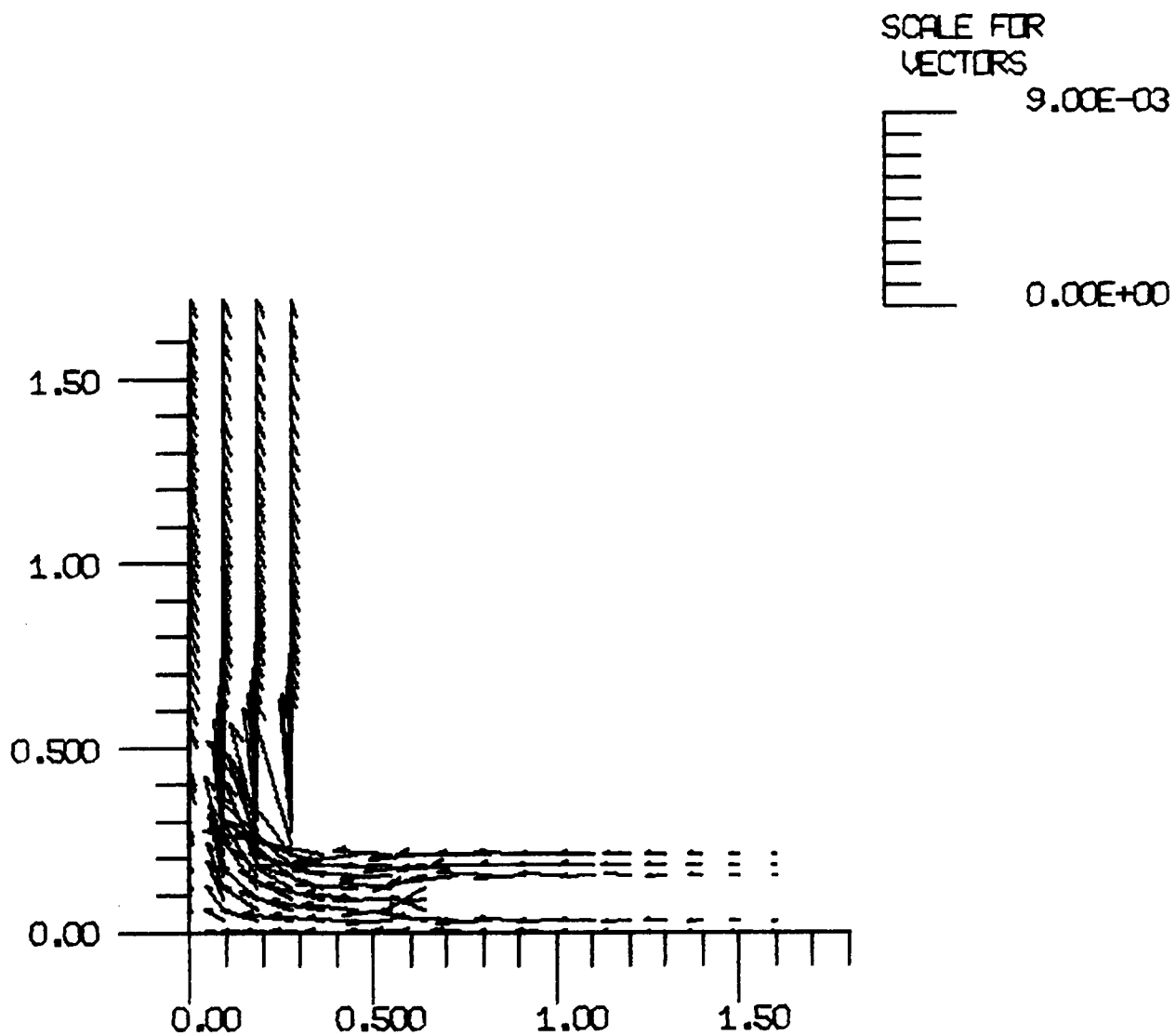


Figure 8.125. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: velocity vectors at cycle 51, time = 2.55.

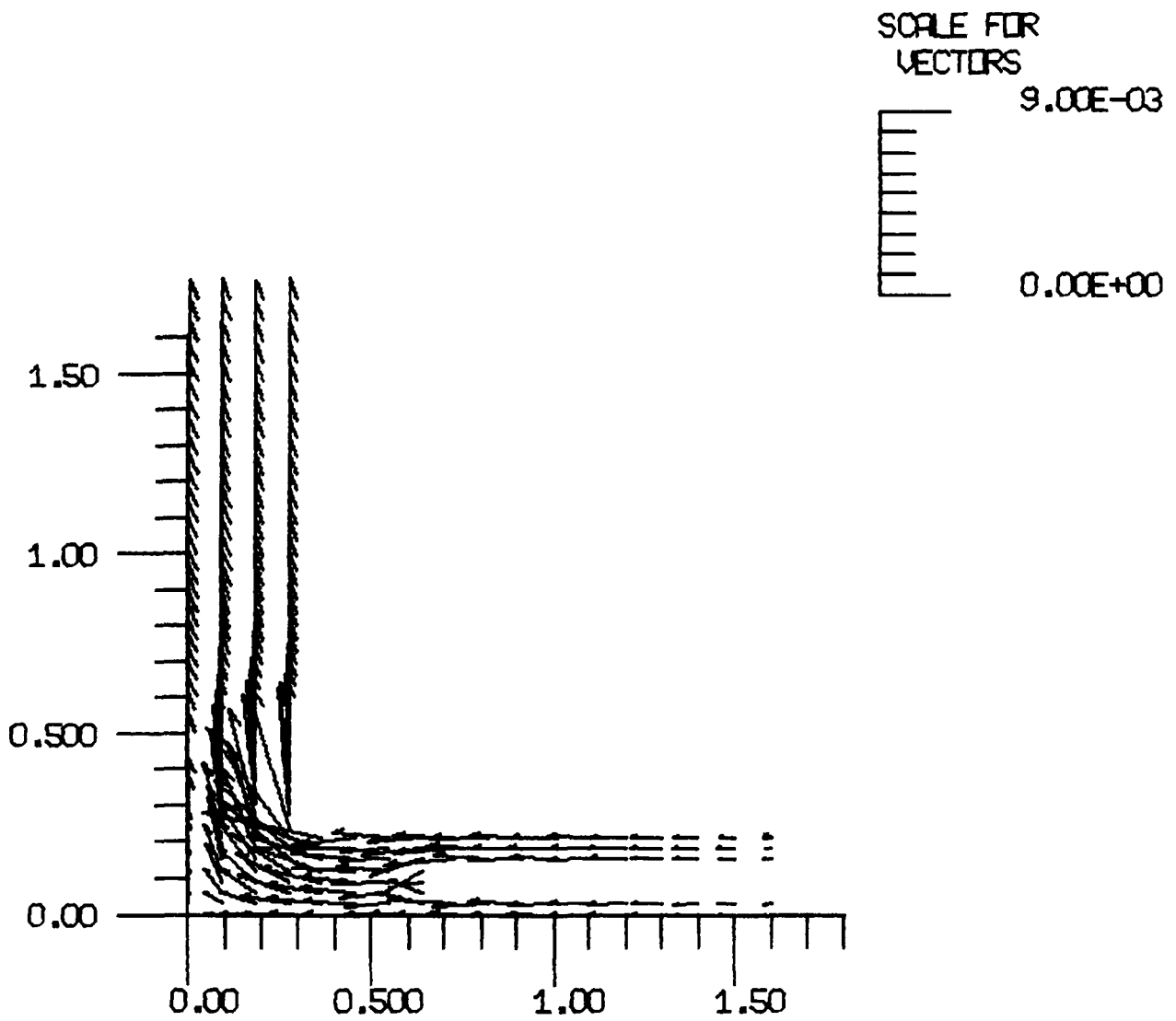


Figure 8.126. Calculation of a rarefaction in a geometry similar to a cold leg-downcomer junction - fine zoning: velocity vectors at cycle 61, time = 3.05.

finer zoning were used (i.e., on the order of 10 rows on either side of the obstacle so that the rows immediately adjacent to the boundaries make up only a small part of the width of the channels) one would expect the numerical errors to be essentially eliminated. However, a better solution would be to implement a sliding boundary condition for interior boundaries in STEALTH. This development is planned for the future.

A more quantitative evaluation of the two calculations is provided by Figure 8.127. This shows pressure profiles at a time of approximately 1 msec along a line parallel to the symmetry axis and located one half of a pipe radius to the right (i.e., down the center of the computational region representing the cold-leg pipe. A similar profile from the corresponding SOLA-ICE profile is also shown.

The rarefaction front at this time is about 500 cm from the bottom boundary of the channel or less than one pipe radius from the junction with the downcomer region. In Figure 8.127 the rarefaction is propagating to the left.

The profiles show that the rarefactions from the STEALTH calculations lag behind that calculated by SOLA-ICE by about three cell widths (taken in the direction of propagation, i.e., $3\Delta y$). Since this is a relatively simple linear problem, one would expect closer agreement. This discrepancy can be directly traced to the zero velocity boundary condition used for the right boundary of the pipe. (This is discussed further in a more detailed discussion of these calculations in Reference 18.) A similar effect is observed in comparing propagation velocities through the channels adjacent to the obstruction in the downcomer region. The effect is reduced in both regions in the more finely-zoned calculation and presumably would disappear if much finer zoning were used. However, as pointed out earlier, this problem will be taken care of when the capability for interior sliding boundaries is incorporated into STEALTH.

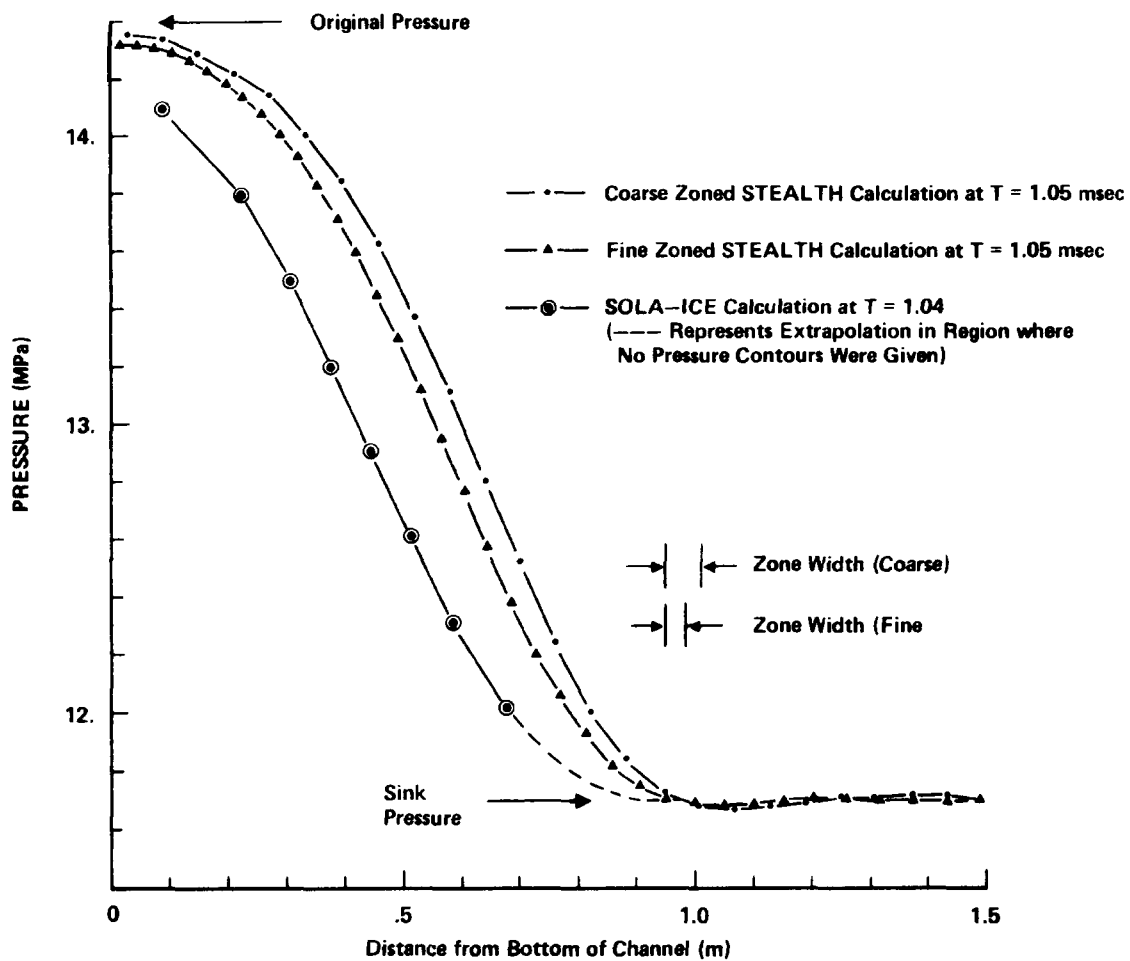


Figure 8.127. Comparison of STEALTH and SOLA-ICE calculations of a rarefaction in a cold leg-downcomer junction geometry: pressure profiles along a vertical line 0.18 m to the right of the symmetry axis ($1/2$ radius of channel).

Rarefaction in a Long, Narrow Channel Containing a Central Obstruction:

Like the previous problem, two calculations of this problem were performed. In one calculation, a mesh corresponding to that used in a similar SOLA-ICE calculation was used. In the second calculation a more finely zoned mesh was used. Pressure contour plots from the more coarsely zoned calculation are provided at 1 msec intervals from 1 to 9 msec in Figures 8.128 - 8.136. A similar set of plots at times from 1 to 7 msec for the more finely zoned calculation are provided in Figures 8.137 - 8.143.

Differences between the STEALTH and SOLA-ICE solutions for this problem were qualitatively similar to those observed for the previous problem. The STEALTH pressure contours were somewhat more irregular, and the rarefaction lagged somewhat compared to the SOLA-ICE solution. However, in general the agreement was closer than the previous problem. This can be attributed to the fact that there was somewhat better spatial resolution on both sides of the central obstruction (particularly for the more finely zoned calculation) than in the previous problem. This tended to reduce the effect of the boundary conditions used for the obstacle in the STEALTH calculations.

Figure 8.144 shows a comparison of pressure profiles along vertical lines on either side of the obstacle from the more coarsely zoned STEALTH calculation and from the SOLA-ICE calculation. In the STEALTH calculation, the rarefaction on the narrow (left) side of the obstruction lagged behind the one on the wider side. Both lagged behind those calculated by SOLA-ICE (which propagated at the same velocity on both sides). Once again, the difference in boundary conditions is the principal cause for the different propagation speeds. The fact that the rarefaction propagates more slowly on the narrower side of the obstruction is consistent with our previously stated contention that the effect of using a zero velocity boundary

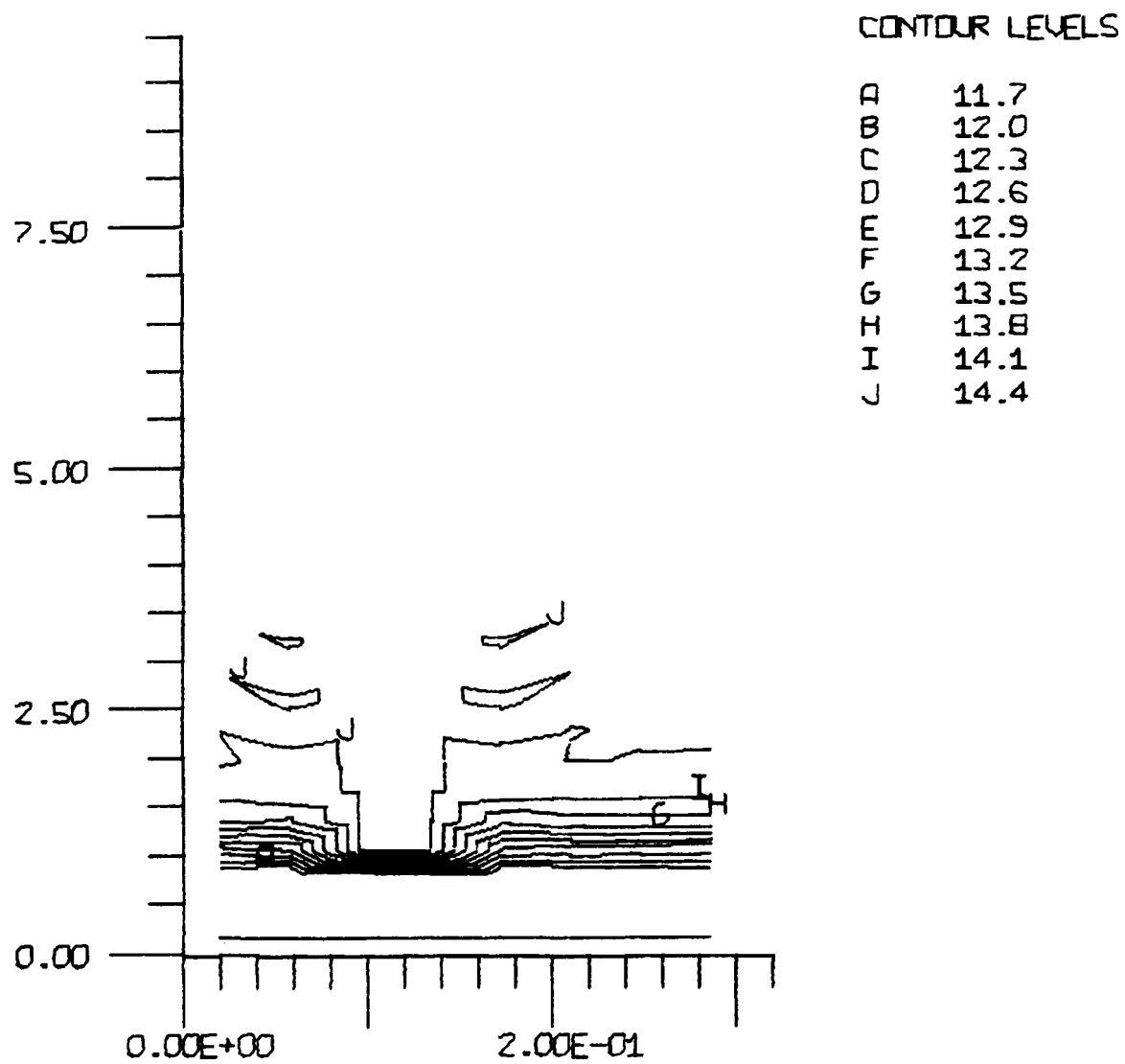


Figure 8.128. Calculation of a rarefaction in a narrow channel with a central obstruction - coarse zoning: pressure contours at cycle 26, time = 1.04.

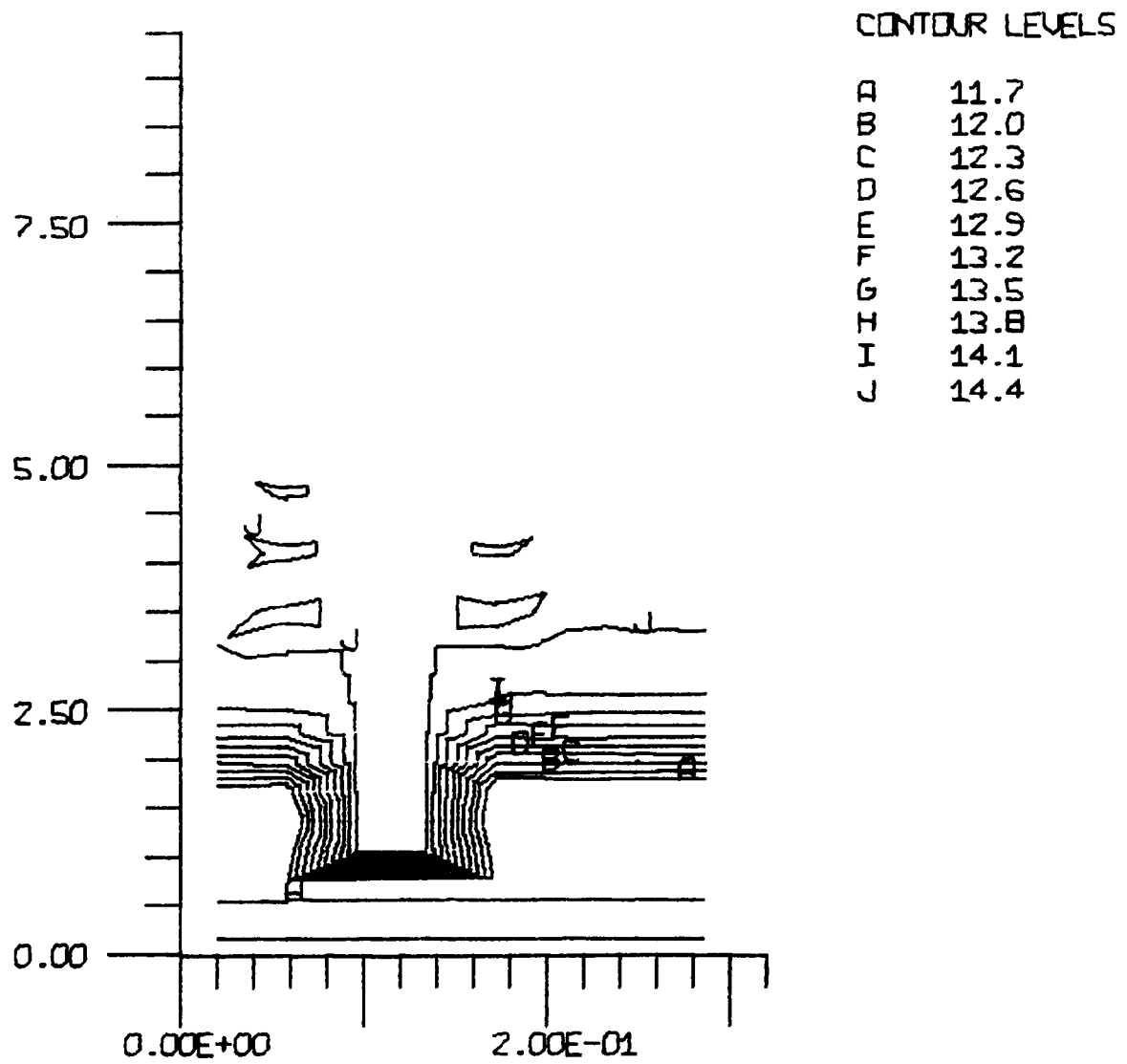


Figure 8.129. Calculation of a rarefaction in a narrow channel with a central obstruction - coarse zoning: pressure contours at cycle 51, time = 2.04.

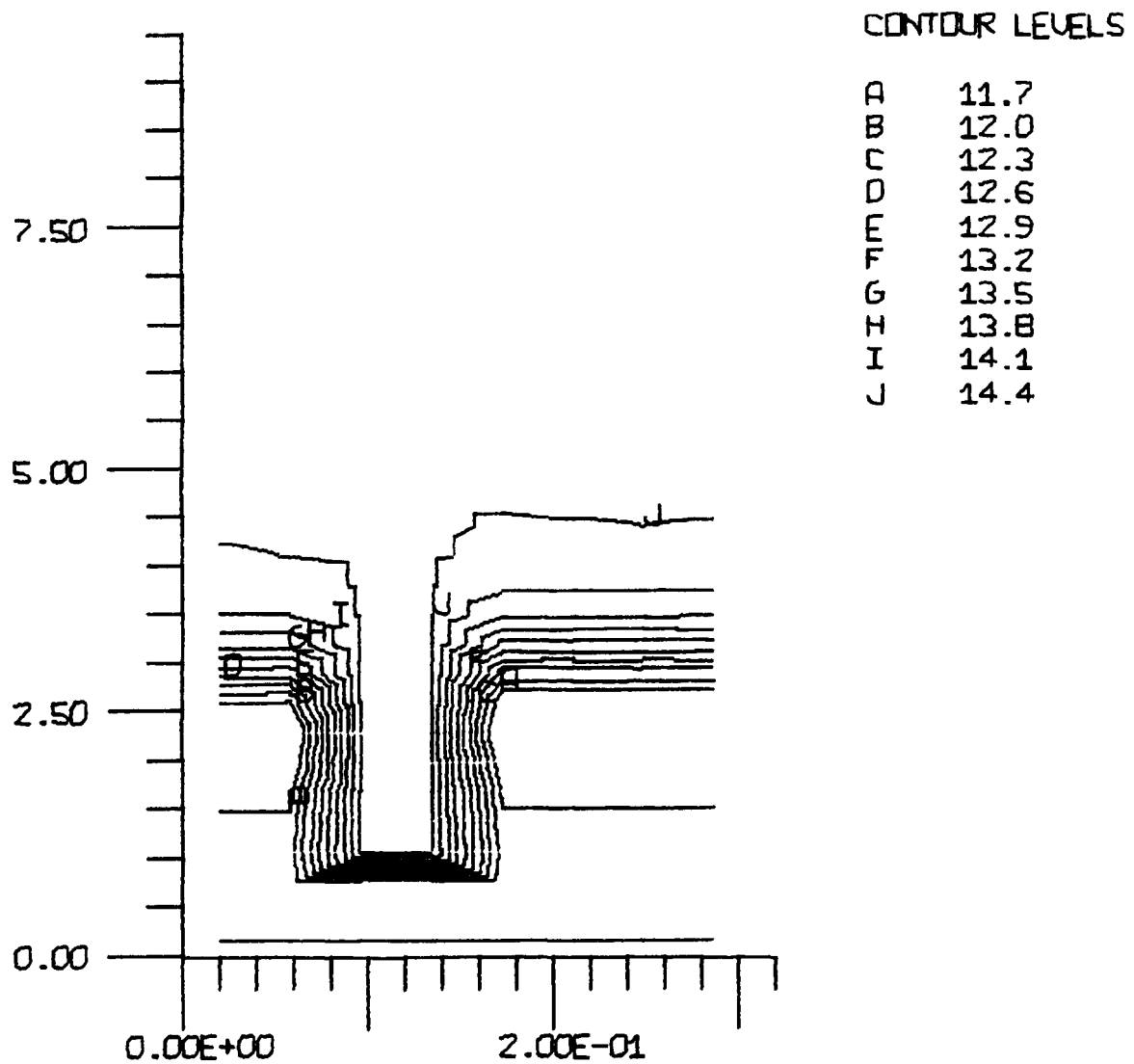


Figure 8.130. Calculation of a rarefaction in a narrow channel with a central obstruction - coarse zoning: pressure contours at cycle 76, time = 3.04.

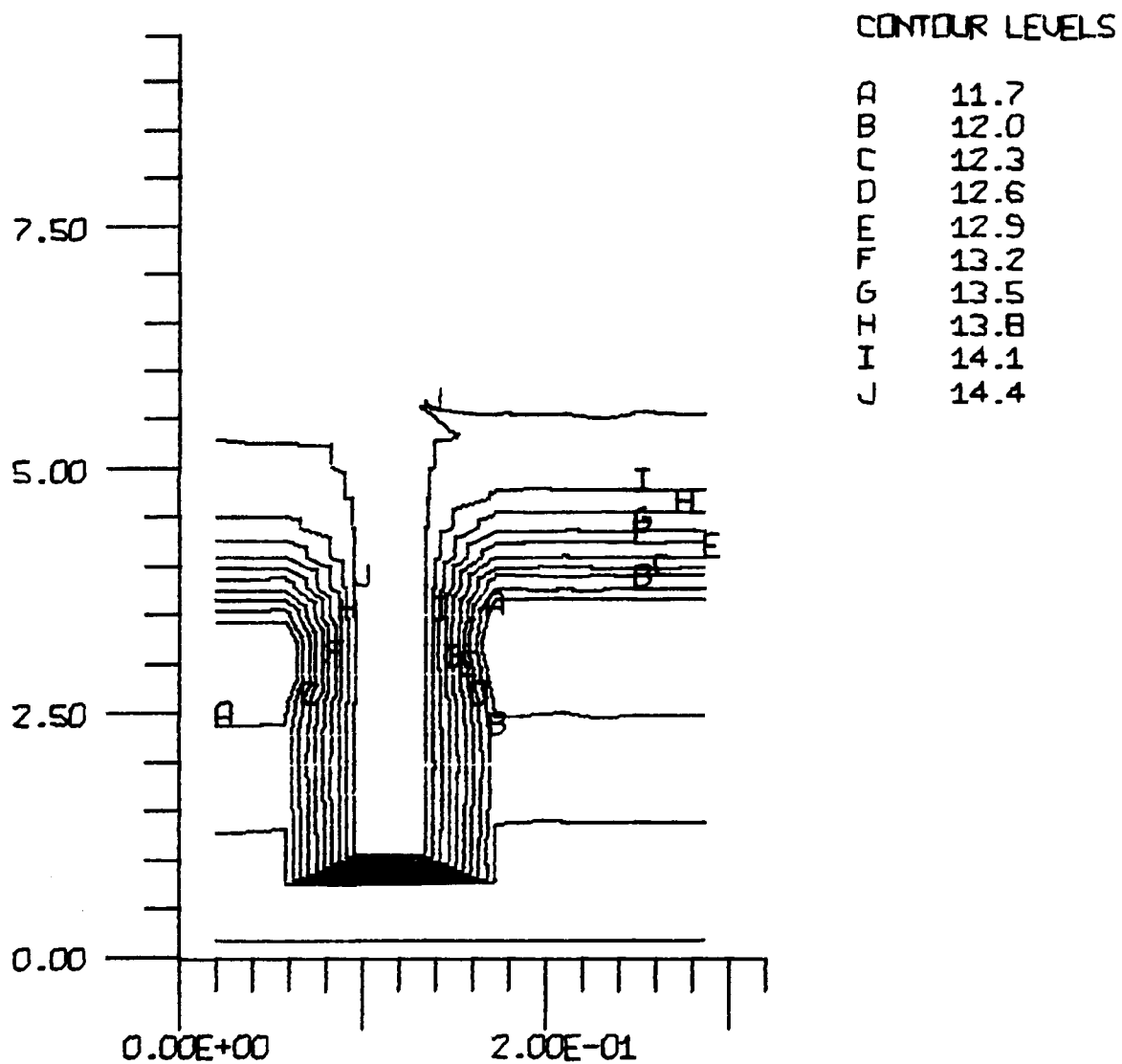


Figure 8.131. Calculation of a rarefaction in a narrow channel with a central obstruction - coarse zoning: pressure contours at cycle 101, time = 4.04.

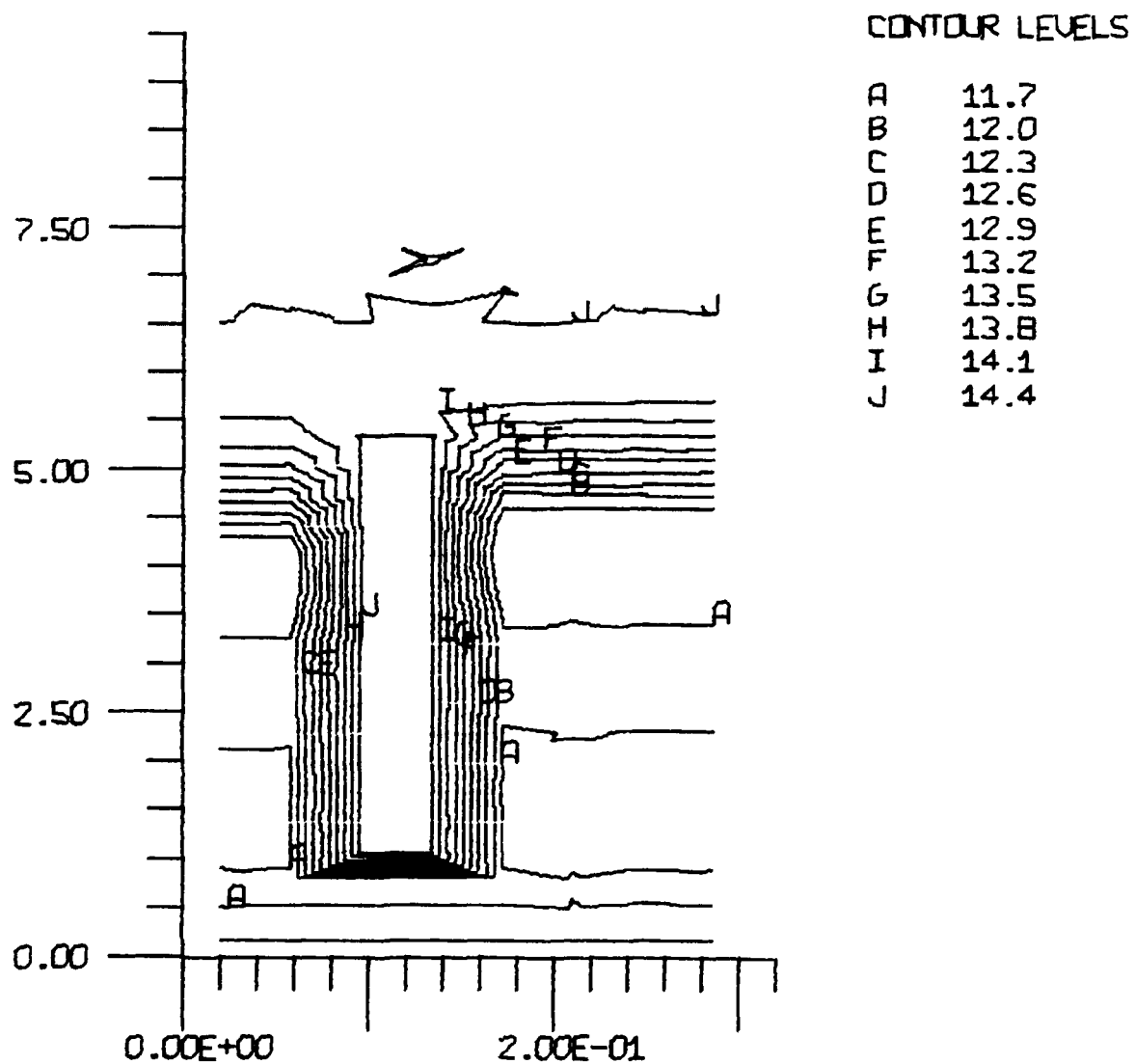


Figure 8.132. Calculation of a rarefaction in a narrow channel with a central obstruction - coarse zoning: pressure contours at cycle 126, time = 5.04.

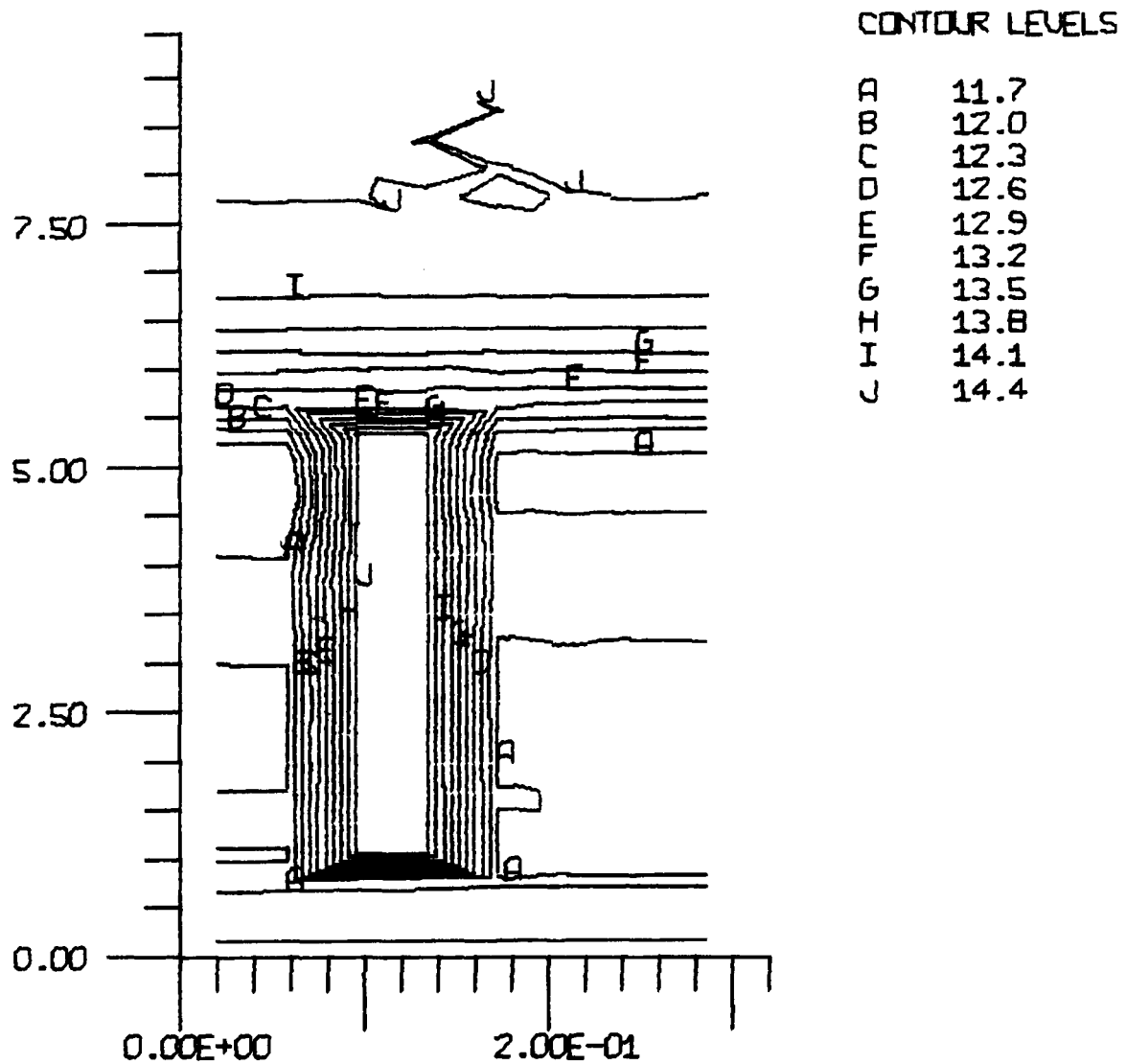


Figure 8.133. Calculation of a rarefaction in a narrow channel with a central obstruction - coarse zoning: pressure contours at cycle 151, time ≈ 6.04 .

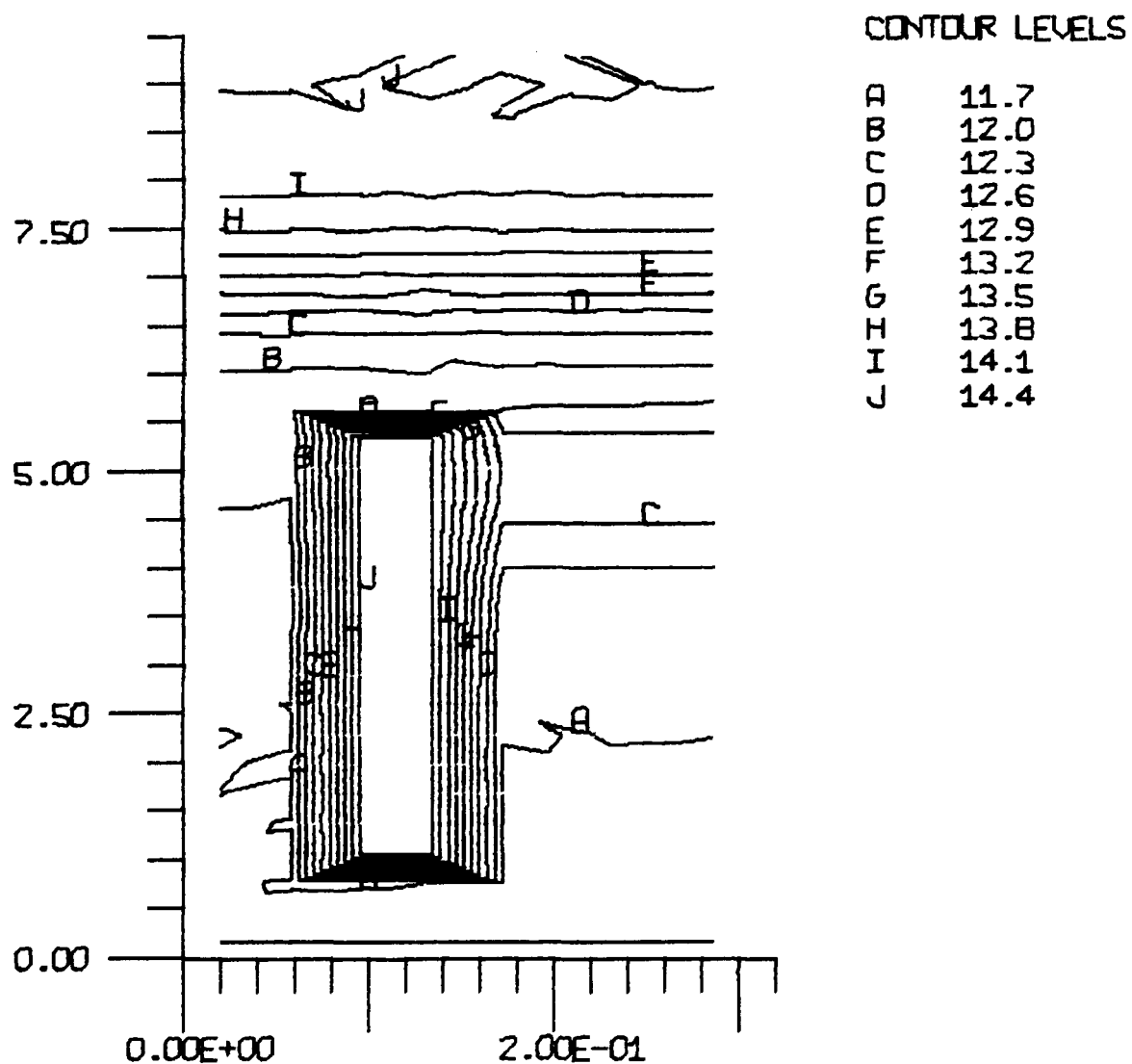


Figure 8.134. Calculation of a rarefaction in a narrow channel with a central obstruction - coarse zoning: pressure contours at cycle 176, time = 7.04.

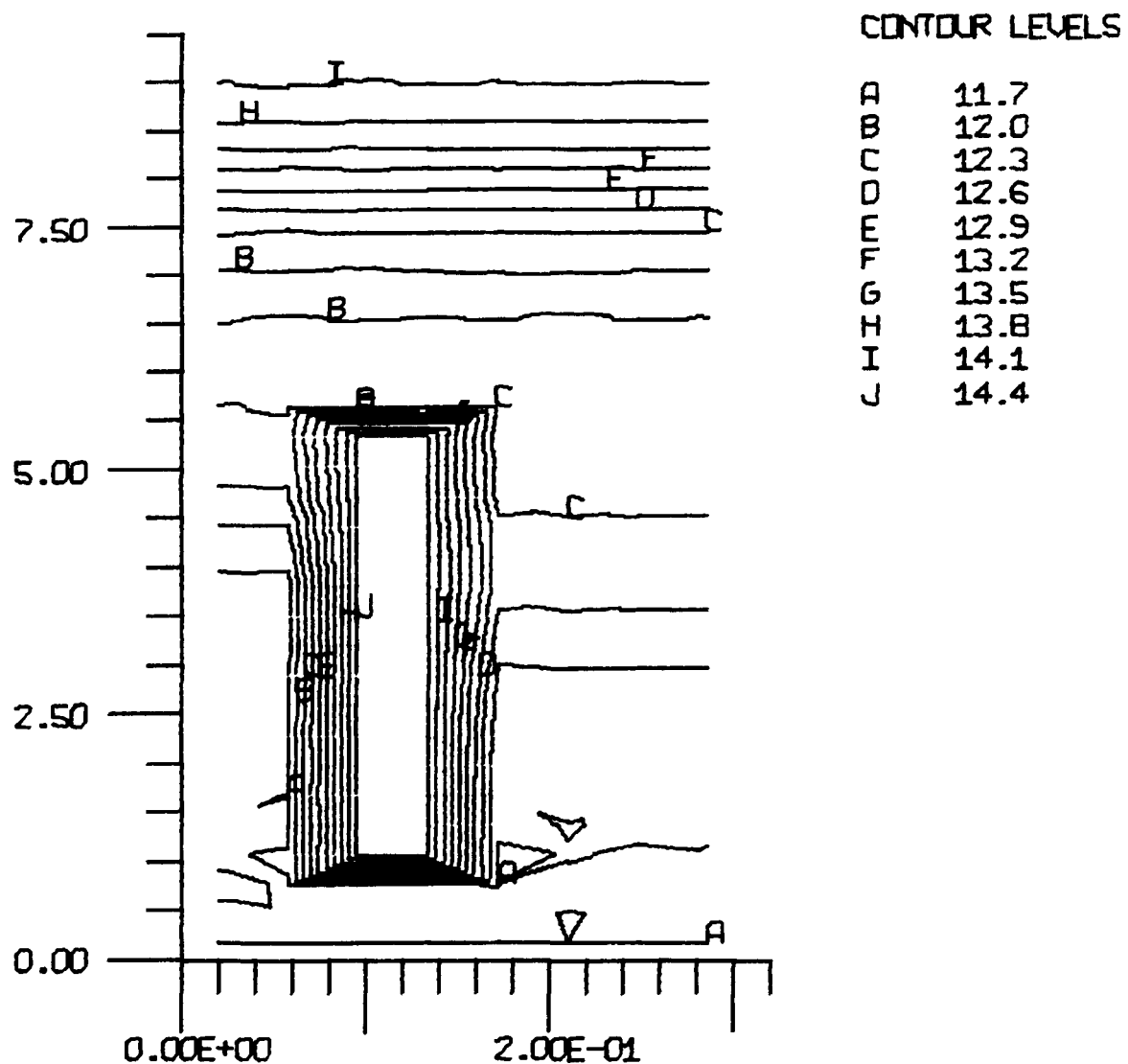


Figure 8.135. Calculation of a rarefaction in a narrow channel with a central obstruction - coarse zoning: pressure contours at cycle 201, time = 8.04.

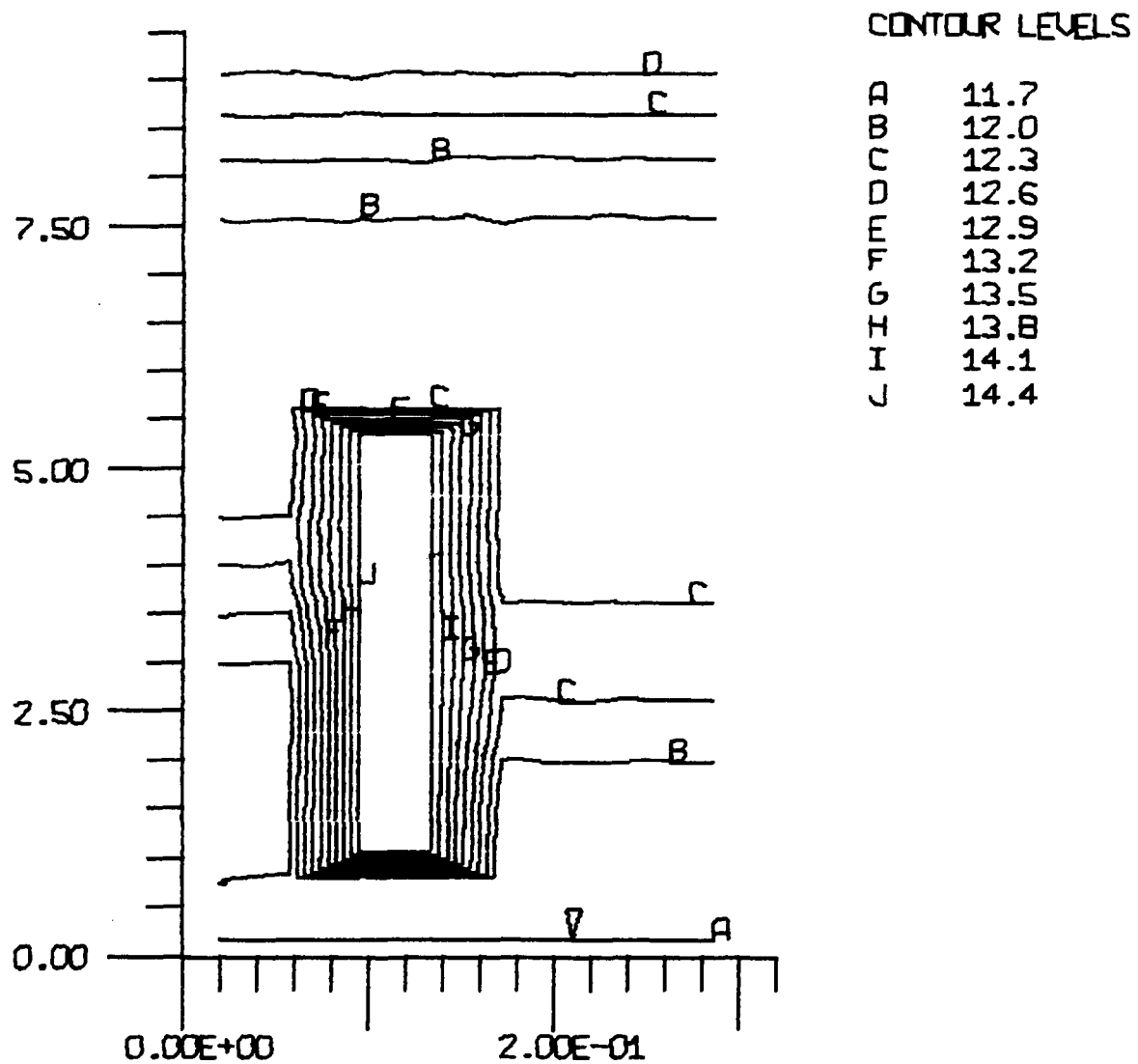


Figure 8.136. Calculation of a rarefaction in a narrow channel with a central obstruction - coarse zoning: pressure contours at cycle 226, time = 9.04.

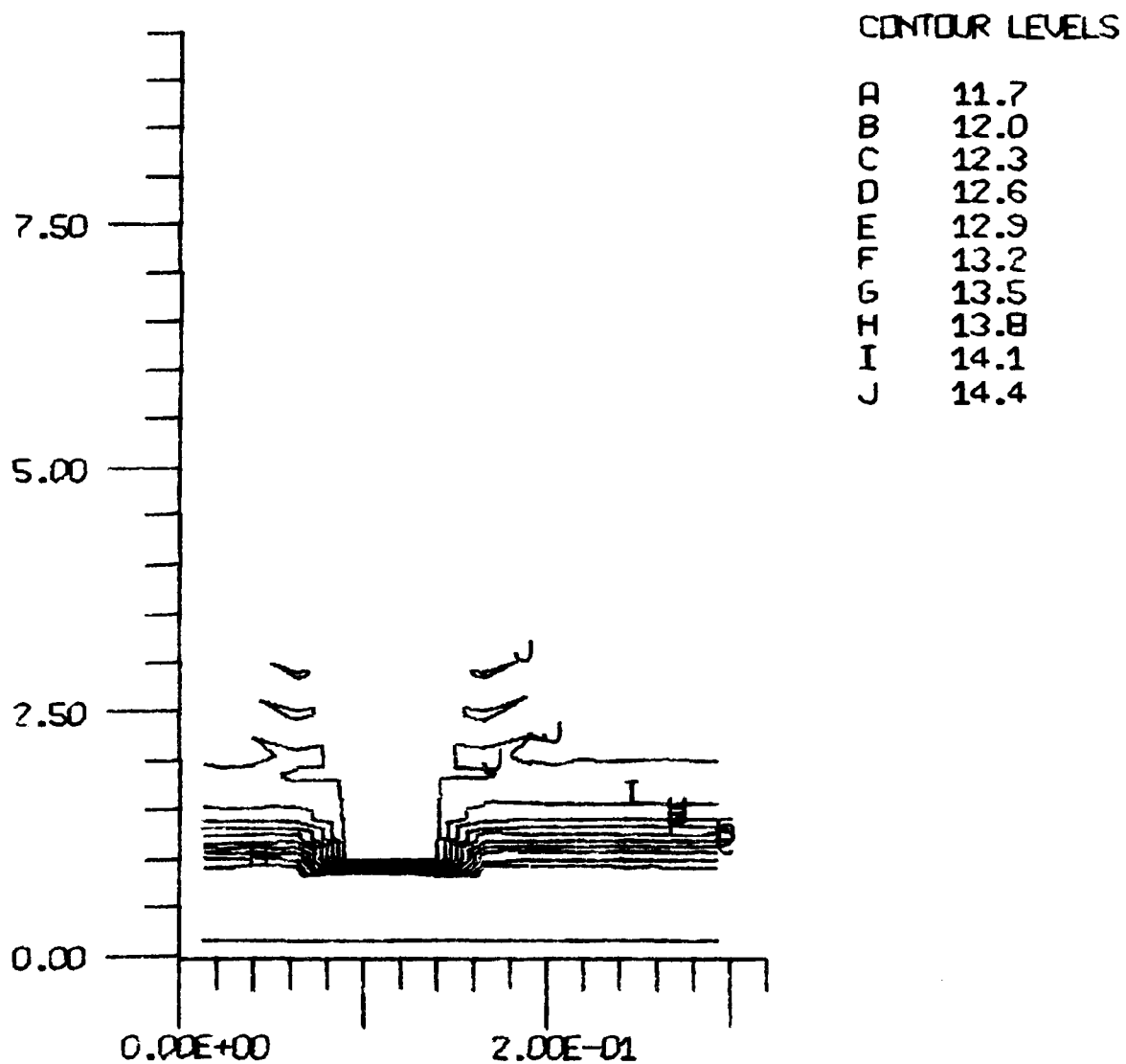


Figure 8.137. Calculation of a rarefaction in a narrow channel with a central obstruction - fine zoning: pressure contours at cycle 26, time = 1.04.

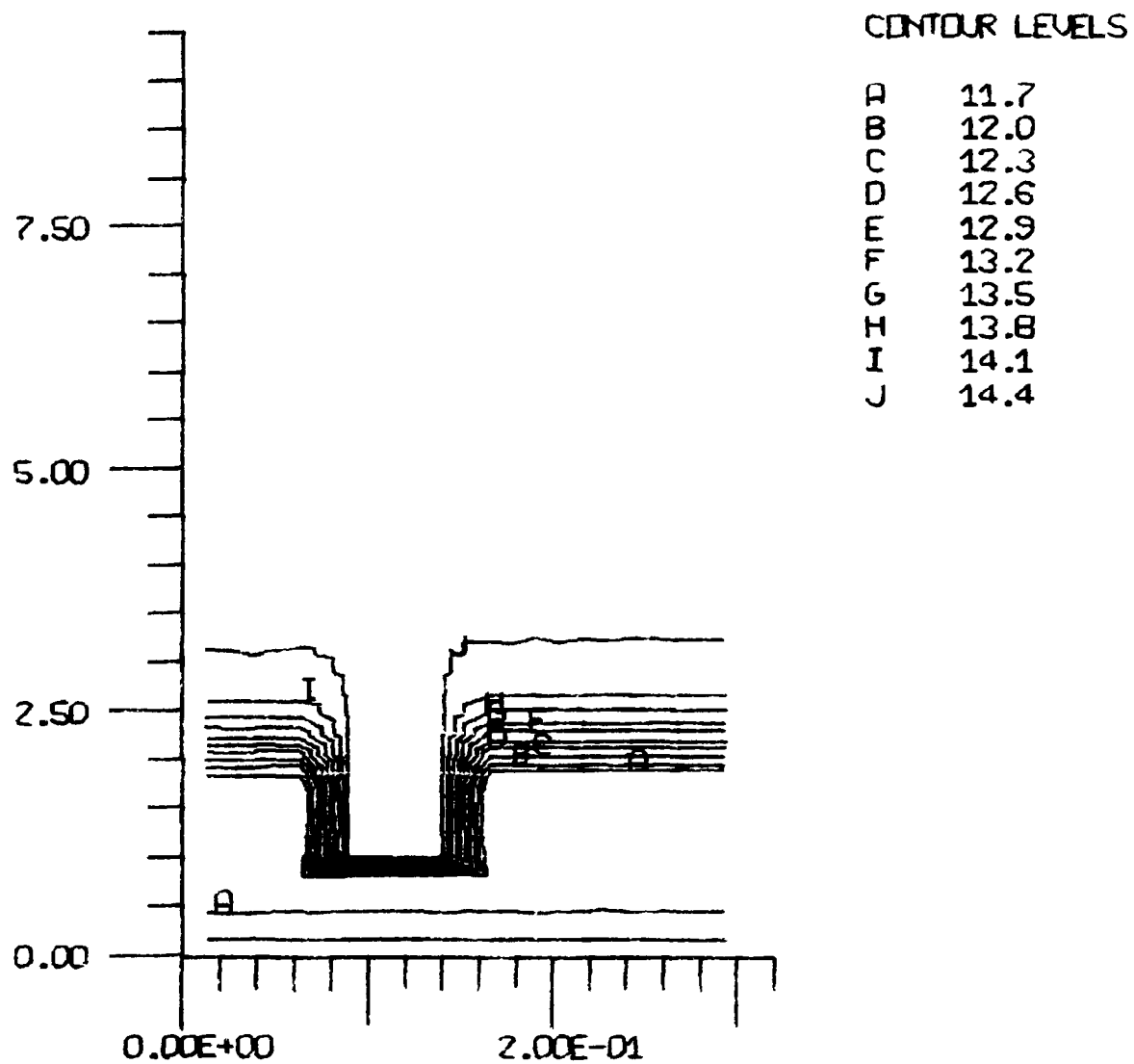


Figure 8.138. Calculation of a rarefaction in a narrow channel with a central obstruction - fine zoning: pressure contours at cycle 51, time = 2.04.

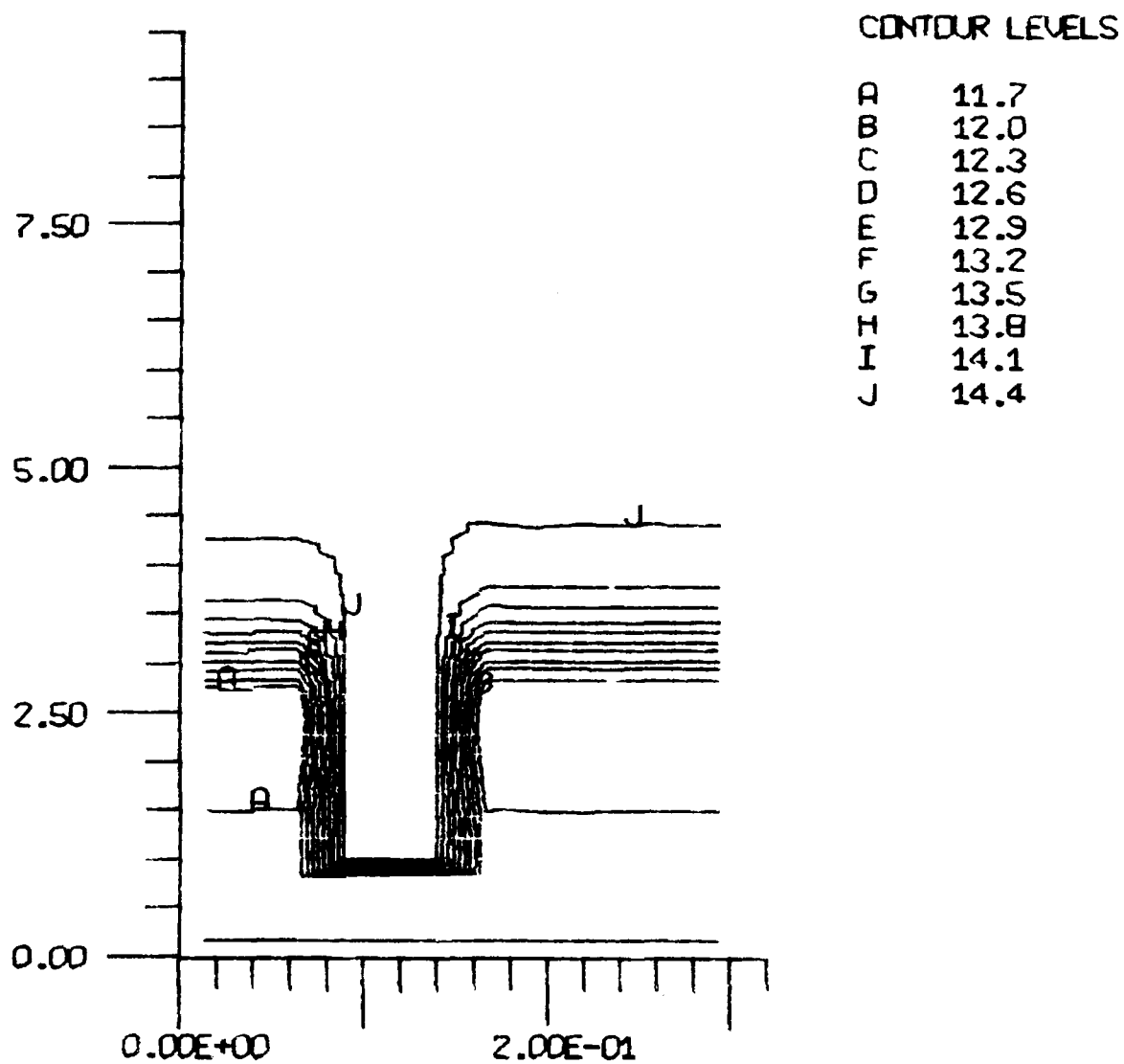


Figure 8.139. Calculation of a rarefaction in a narrow channel with a central obstruction - fine zoning: pressure contours at cycle 76, time = 3.04.

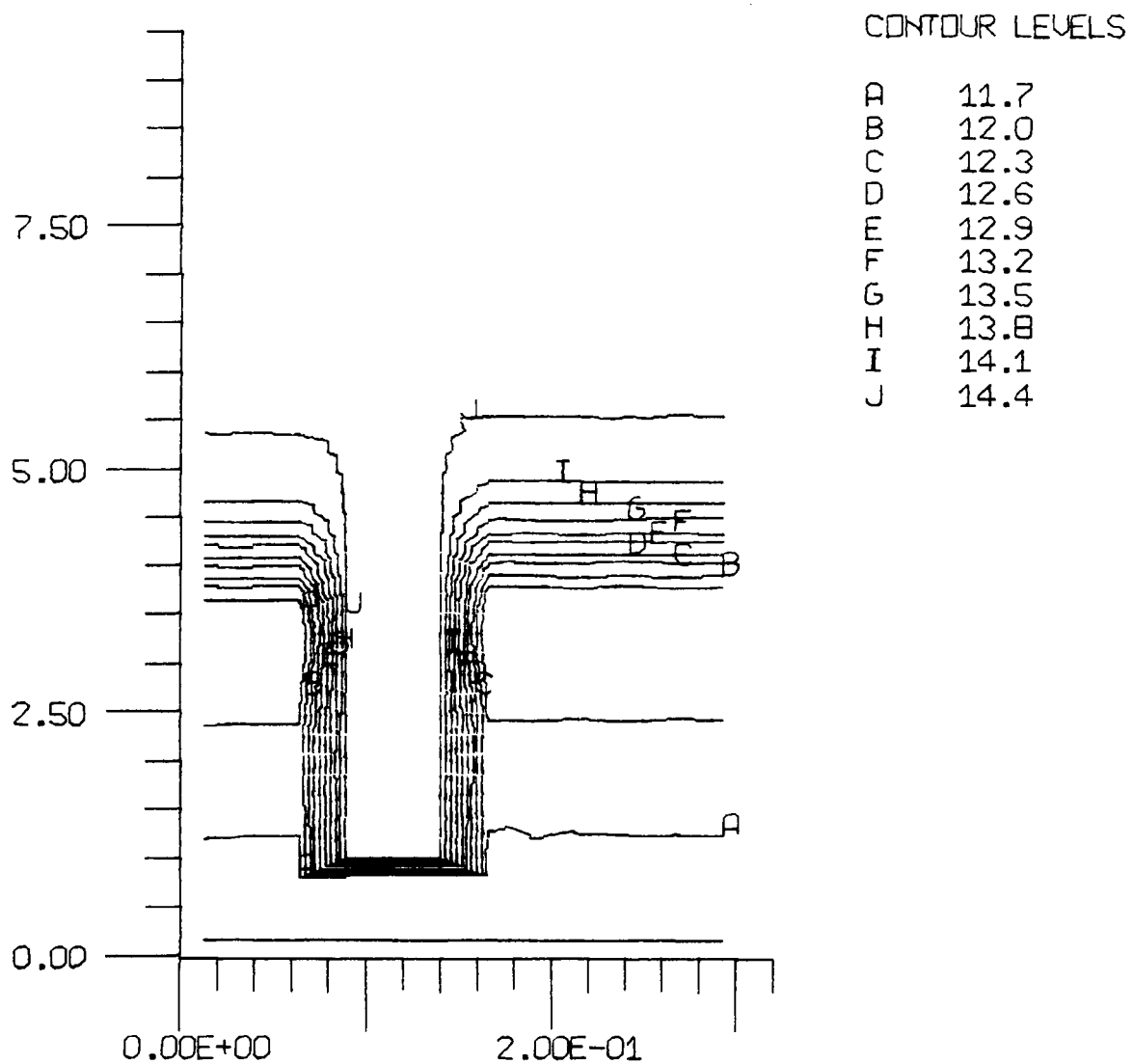


Figure 8.140. Calculation of a rarefaction in a narrow channel with a central obstruction - fine zoning: pressure contours at cycle 101, time = 4.04.

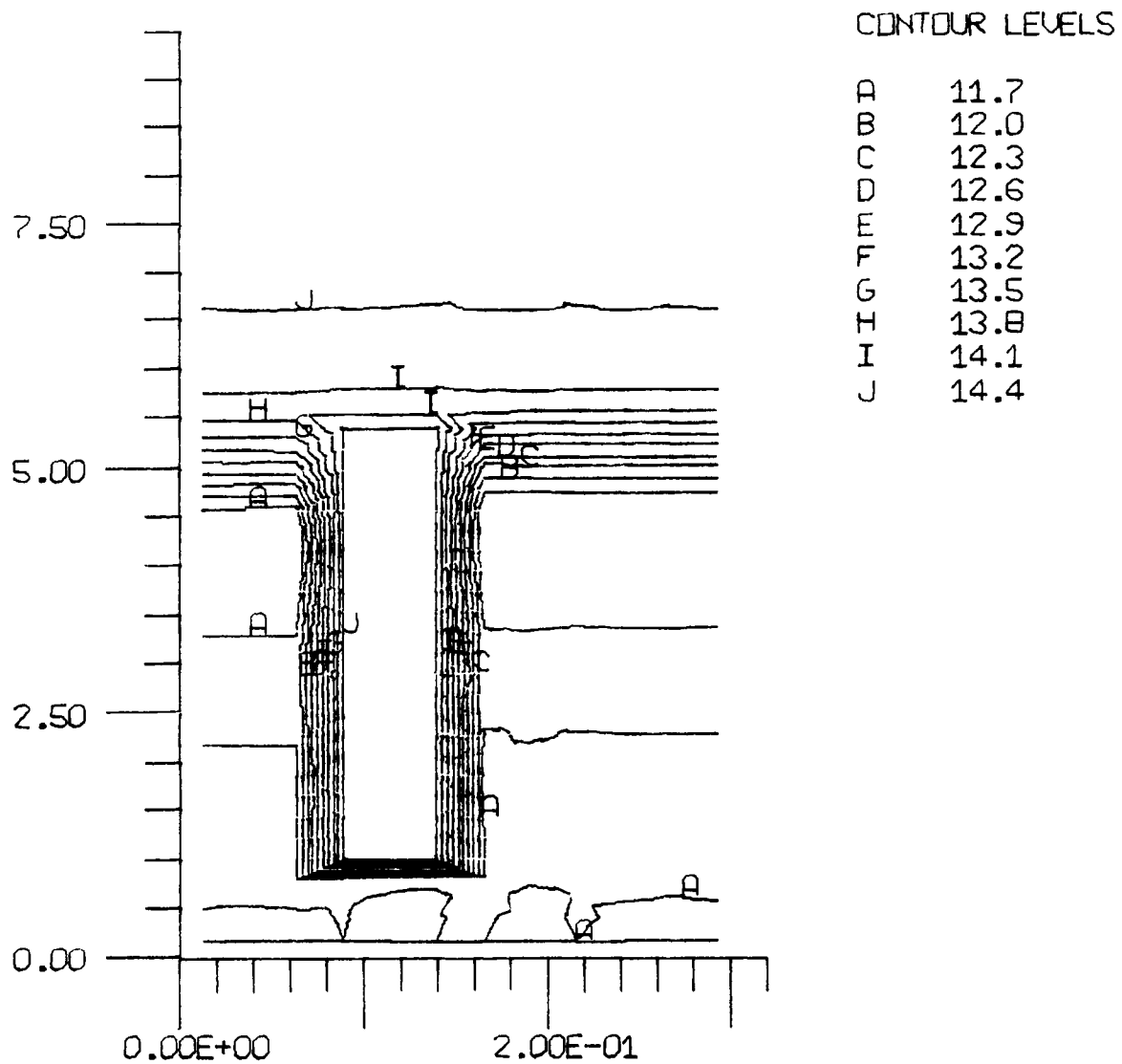


Figure 8.141. Calculation of a rarefaction in a narrow channel with a central obstruction - fine zoning: pressure contours at cycle 126, time = 5.04.

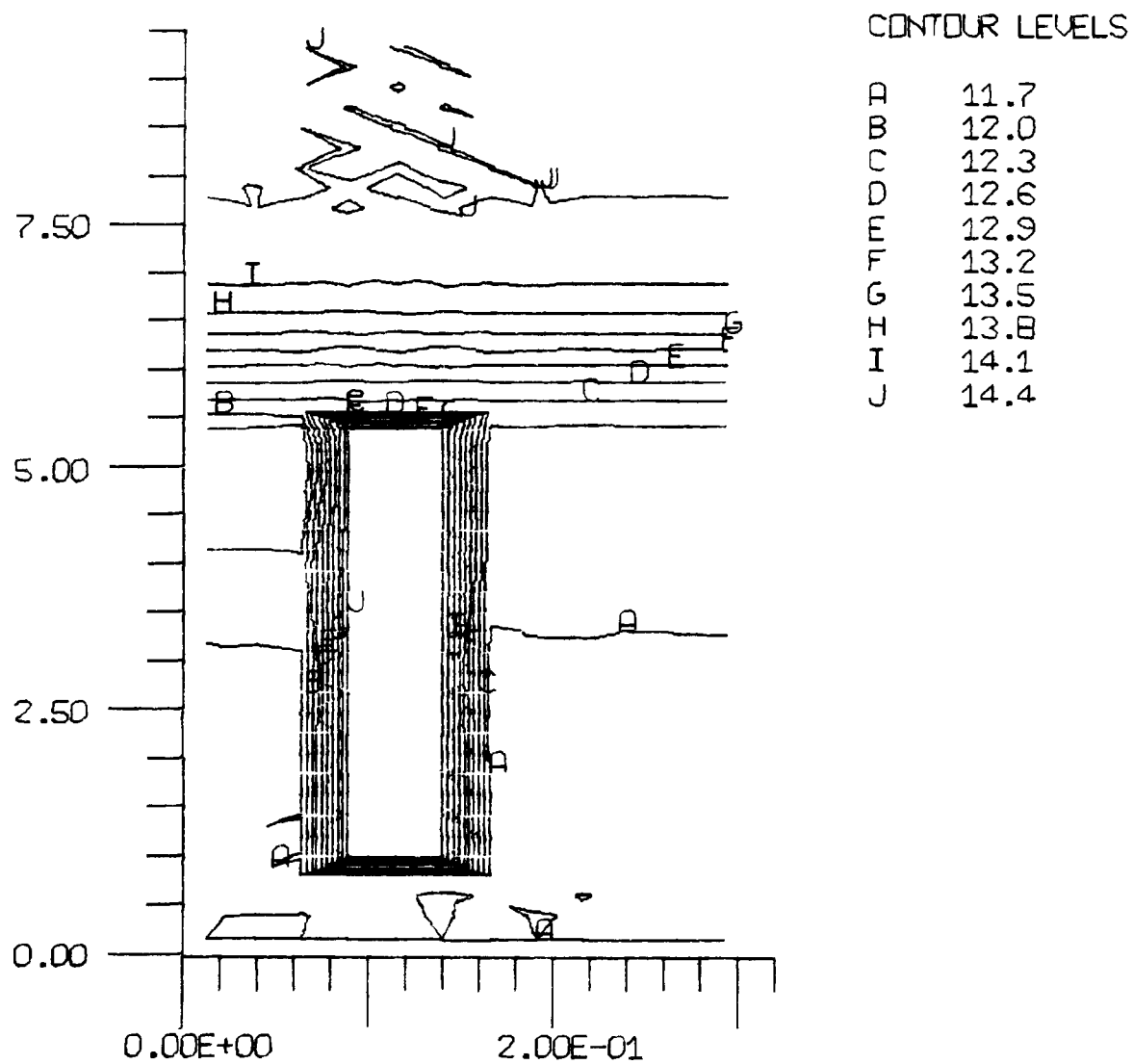


Figure 8.142. Calculation of a rarefaction in a narrow channel with a central obstruction - fine zoning: pressure contours at cycle 151, time = 6.04.

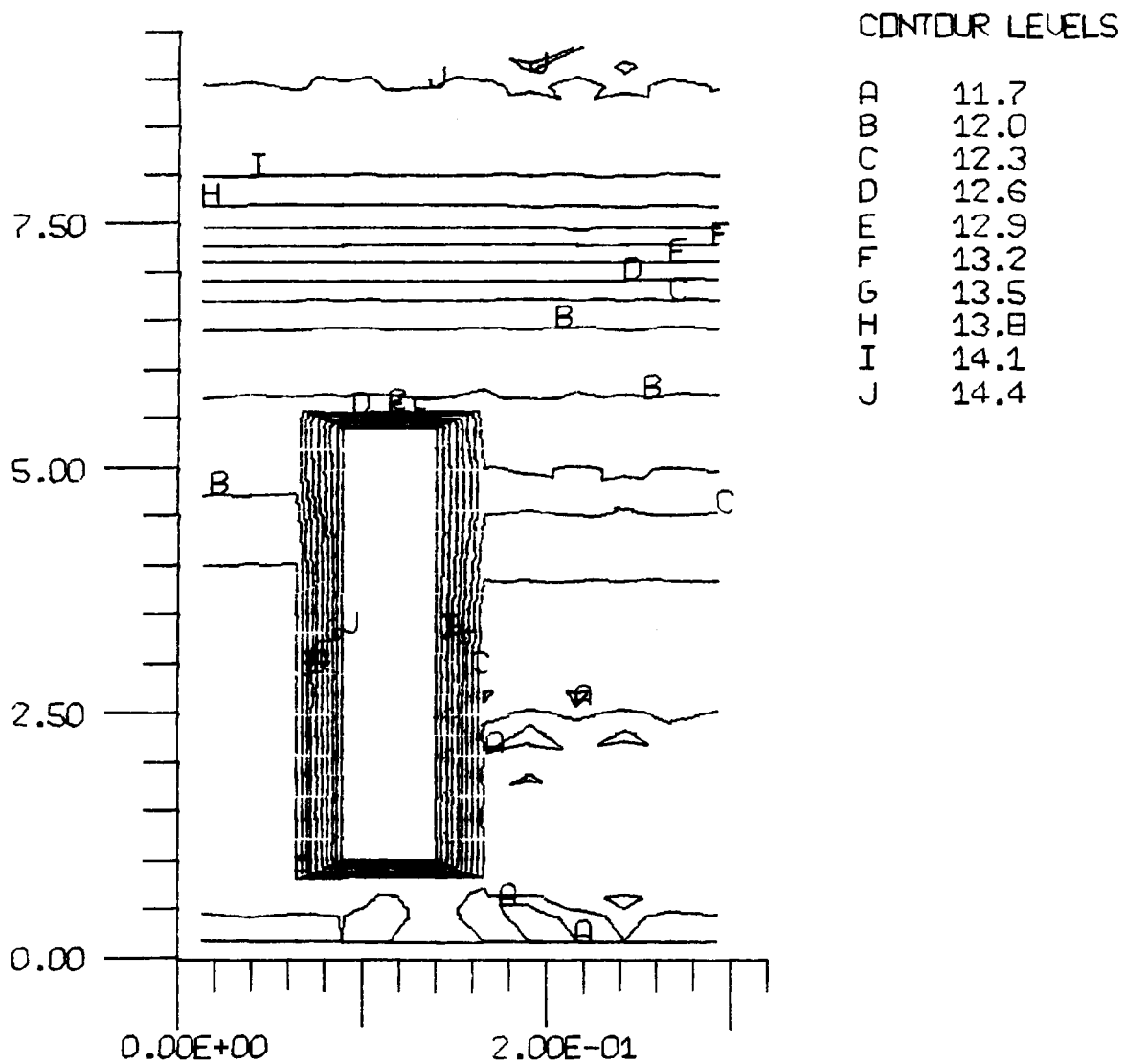


Figure 8.143. Calculation of a rarefaction in a narrow channel with a central obstruction - fine zoning: pressure contours at cycle 176, time = 7.04.

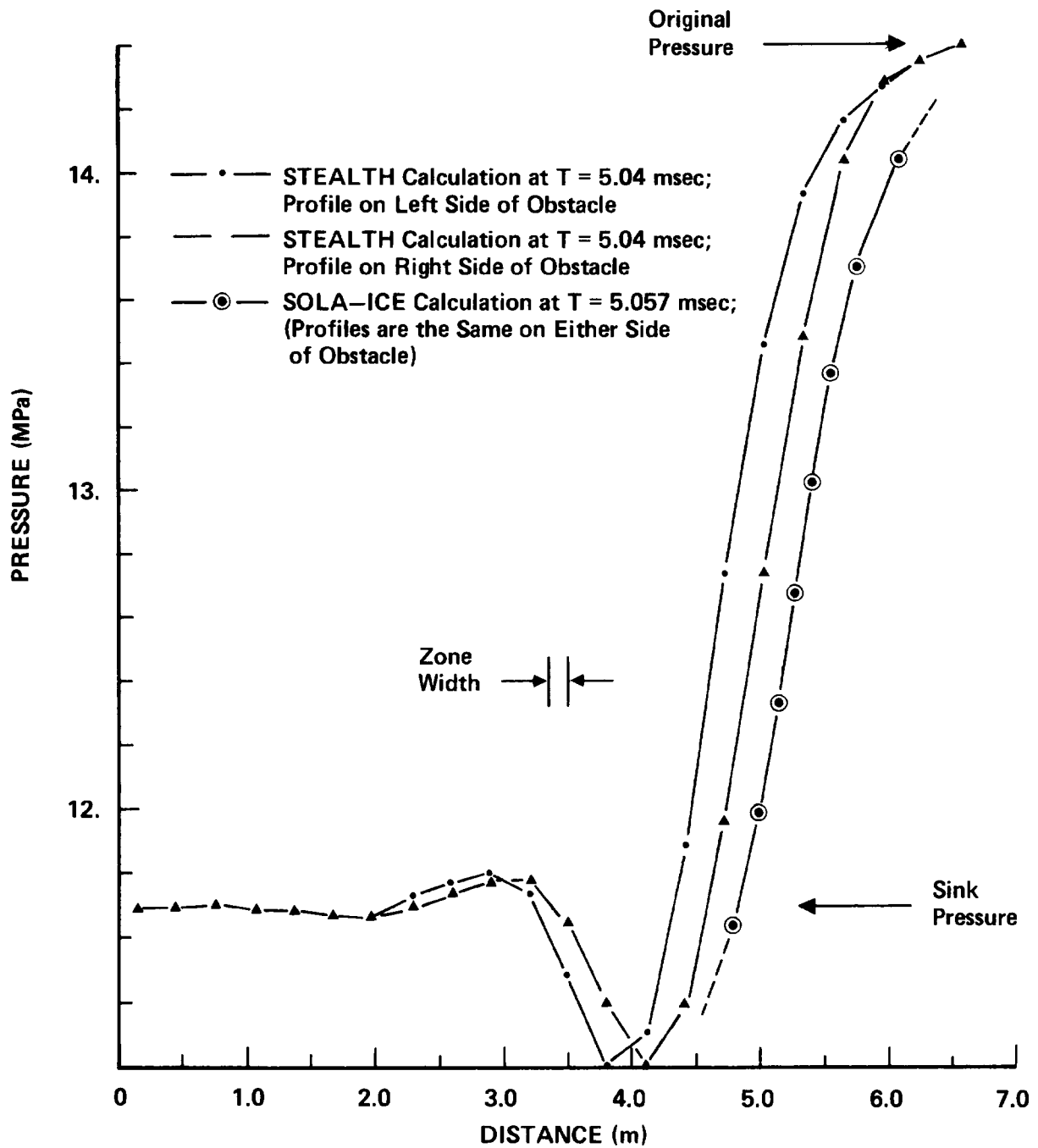


Figure 8.144. Comparison of the more coarsely zoned STEALTH calculation and the SOLA-ICE calculation of a rarefaction in a narrow channel with a central obstruction: pressure profiles along vertical lines on either side of obstacle.

condition on one side of a channel can be reduced if better spatial resolution is provided by using more zones across the width of the channel.

A similar set of pressure profiles from the more finely zoned STEALTH calculation is compared with the SOLA-ICE results in Figure 8.145. In this case the agreement is better. Although spatial differences on the order of a zone width still exist, these differences are small compared to the other characteristic distances in the problem, so we consider to be the agreement reasonably good.

8.3.3.3 Input Decks. The STEALTH input decks for the calculations of pressure release transients are provided in Tables 8.18 - 8.23.

8.3.4 Calculation of an Explosion in a Partially Water-Filled, Rigid Container

8.3.4.1 Problem Description. This calculation is one of several that were used in the APRICOT (Analysis of PRImary COntainment Transients) program (Reference 20) to validate computational methods for simulating a hypothetical core disruptive accident (HCDA) in a liquid metal fast breeder reactor (LMFBR). This particular calculation, known as APRICOT 3, was intended to simulate a set of experiments in which small high explosive charges were detonated in closed containers partially filled with water.

Because this calculation is dominated by the propagation of an explosively generated shock wave and its interaction with the container walls, it is not an ideal application of the implicit, fluid mechanics versions of STEALTH which were designed for calculating long wavelength, small strain-rate phenomena. In spite of that fact, APRICOT 3 was selected as a test calculation in order to assess how well the 2D implicit, compressible flow code can treat this flow regime and to try to determine some of the potential limitations of the code. Because this calculation has also been performed using the 2D explicit version of STEALTH

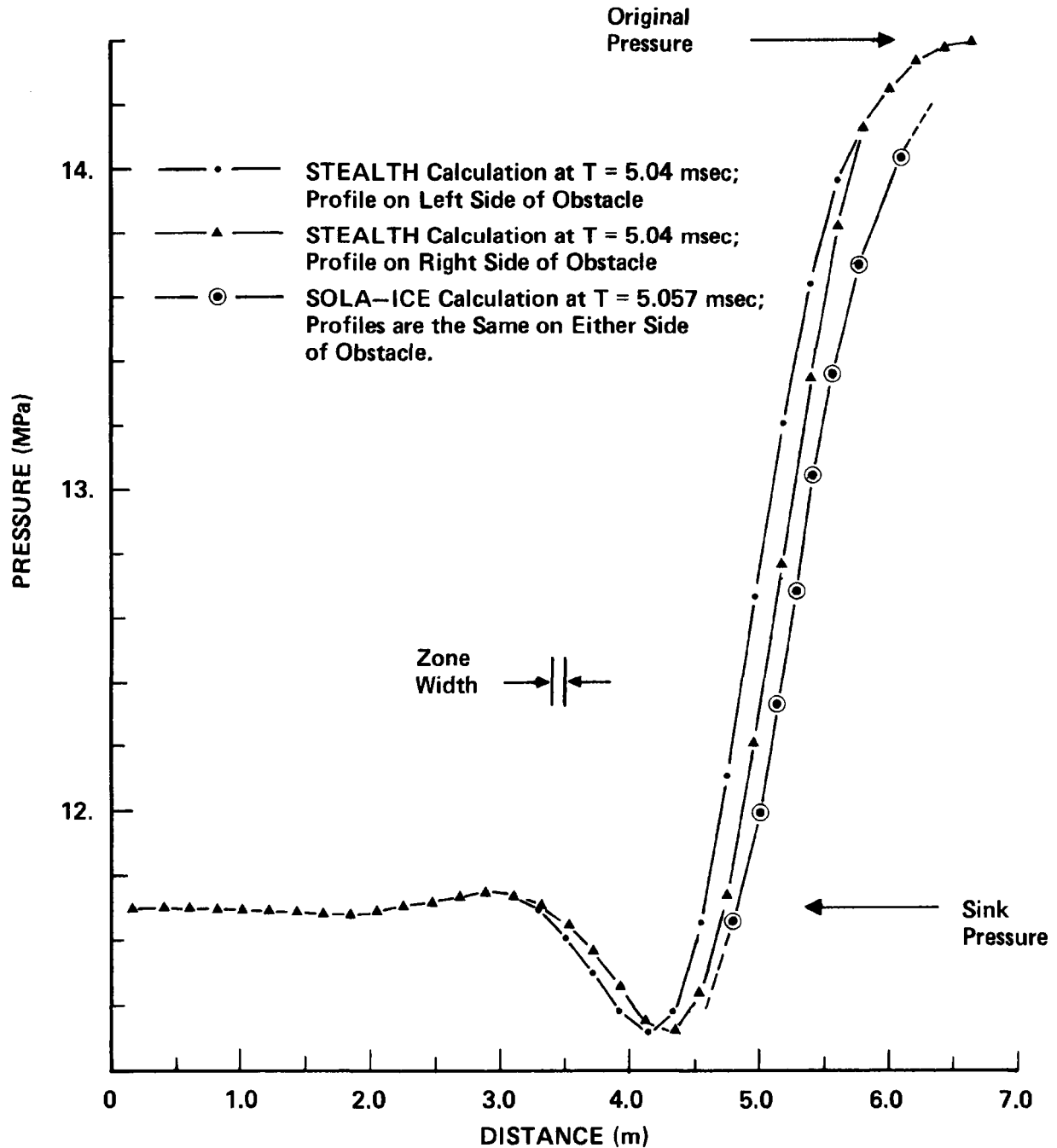


Figure 8.145. Comparison of the more finely zoned STEALTH calculation and the SOLA-ICE calculation of a rarefaction in a narrow channel with a central obstruction: pressure profiles along vertical lines on either side of obstacle.

TABLE 8.18

DATA DECK FOR THE CALCULATION
OF A CYLINDRICAL RAREFACTION

TTL	CYLINDRICAL RAREFACTION				
PRB					2.0
PRO	2.0				
MIN					.015
GRD	1.0		21.	21.	
ITR	200.	.001	1.0		
ALE	2.0	1.0	1.0		
END					
MAT					2.0
111	1.0	1.0			
121	1.0	741.525			
122	1.0	1.0	6.897	833.2	
111	2.0	1.0			
121	2.0	741.525			
122	2.0	1.0	11.7		
END					
GPT				2.0	2.0
211	1.0	1.0	1.0	0.0	0.0
212	1.0	0.0	3.5	2.0	
212	2.0	0.0	0.0	1.0	
212	3.0	3.5	0.0	3.0	
221	1.0	1.0	21.	1.0	21.
247	1.0	0.0	3.048	0.0	3.048
END					
ZON					2.0
311	1.0	1.0	21.	1.0	21.
321	1.0	1.0			
322	1.0	.991052			
311	2.0	1.0	2.0	1.0	2.0
321	2.0	2.0			
322	2.0	1.0			
END					
BDY					2.0
411	1.0	1.0	21.	1.0	1.0
412	1.0	1.0	6.0	5.0	2.0
411	2.0	1.0	1.0	20.	1.0
412	2.0	1.0	6.0	5.0	3.0
411	3.0	20.	1.0	21.	1.0
412	3.0	1.0	5.0	5.0	
411	4.0	21.	1.0	21.	21.
412	4.0	1.0	5.0	5.0	
411	5.0	21.	21.	1.0	21.
412	5.0	1.0	5.0	5.0	
481	1.0	1.0	3.0		
482	1.0	1.0	5.0	5.0	
END					
TIM					2.0
511	.05				
512	.01	.05			
513	1.02	.25	1.0		
521	3.0	100.			
END					

(Continued on next page)

TABLE 8.18 (continued)

EDT					2.0	
621	1.0	0.0	3.0	1.0		
622	1.0	21.	1.0	21.		
623	1.0	12.				
623	2.0	15.				
623	3.0	42.				
623	4.0	45.				
623	5.0	47.				
623	6.0	51.				
623	7.0	64.				
623	8.0	66.				
631	1.0	0.0	3.0	1.0		
632	1.0	1.0	21.	1.0	21.	
632	2.0	1.0	2.0	1.0	2.0	
671	1.0	0.0	10.	.025		
675	1.0	4.0	64.			.01
675	2.0	5.0				.01
675	3.0	4.0	64.			0.5
675	4.0	5.0				0.5
675	5.0	4.0	64.			1.0
675	6.0	5.0				1.0
675	7.0	4.0	64.			1.5
675	8.0	5.0				1.5
675	9.0	4.0	64.			2.0
675	10.	5.0				2.0
675	11.	4.0	64.			2.5
675	12.	5.0				2.5
675	13.	4.0	64.			3.0
675	14.	5.0				3.0
674	15.	1.0	64.	1.0	6002.	
674	16.	1.0	64.	1.0	2006.	
674	17.	1.0	64.	1.0	4004.	
674	18.	1.0	64.	1.0	11002.	
674	19.	1.0	64.	1.0	2011.	
674	20.	1.0	64.	1.0	8008.	
674	21.	1.0	64.	1.0	16002.	
674	22.	1.0	64.	1.0	2016.	
674	23.	1.0	64.	1.0	12012.	
674	24.	1.0	64.	1.0	16016.	
END						
END						

TABLE 8.19

DATA DECK FOR THE CALCULATION OF A CYLINDRICAL
RAREFACTION WITH OBSTACLES IN THE FLOW

CYLINDRICAL RAREFACTION WITH OBSTACLES					
TTL					
PRB					2.0
PRO	2.0				
MIN					.015
GRD	1.0		23.	35.	
ITR	200.	.001	1.0		
ALE	2.0	1.0	1.0		
END					
MAT					2.0
111	1.0	1.0			
121	1.0	741.525			
122	1.0	1.0	6.897	833.2	
111	2.0	1.0			
121	2.0	741.525			
122	2.0	1.0	11.7		
END					
GPT				2.0	2.0
211	1.0	1.0	1.0	0.0	0.0
212	1.0	3.36	5.1816	2.0	
212	2.0	0.0	5.1816	1.0	
212	3.0	0.0	-.01	3.0	
221	1.0	1.0	23.	1.0	35.
247	1.0	0.0	3.3528	0.0	5.1816
END					
ZON					2.0
311	1.0	1.0	23.	1.0	35.
321	1.0	1.0			
322	1.0	.991052			
311	2.0	1.0	3.0	21.	25.
321	2.0	2.0			
322	2.0	1.0			
311	3.0	9.0	15.	20.	26.
321	3.0	1.0			
322	3.0	.991052			
END					
BDY					2.0
411	1.0	1.0	1.0	23.	1.0
412	1.0	1.0	5.0	5.0	
411	2.0	23.	1.0	23.	35.
412	2.0	1.0	5.0	5.0	
411	3.0	23.	35.	1.0	35.
412	3.0	1.0	6.0	5.0	2.0
411	4.0	1.0	35.	1.0	2.0
412	4.0	1.0	6.0	5.0	3.0
411	5.0	1.0	2.0	1.0	1.0
412	5.0	1.0	5.0	5.0	
411	6.0	9.0	20.	15.	20.
412	6.0	1.0	5.0	5.0	
411	7.0	15.	20.	15.	26.
412	7.0	1.0	5.0	5.0	
411	8.0	15.	26.	9.0	26.
412	8.0	1.0	5.0	5.0	
411	9.0	9.0	26.	9.0	20.
412	9.0	1.0	5.0	5.0	
481	1.0	1.0	3.0		
482	1.0	1.0	5.0	5.0	
END					

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TABLE 8.19 (continued)

TIM					2.0	
511	.025					
512	.01	0.1				
513	1.01	.25	0.0			
521	3.0	100.				
END						
EDT					2.0	
621	1.0	0.0	3.0	1.0		
622	1.0	23.	1.0	35.		
623	1.0	12.				
623	2.0	15.				
623	3.0	42.				
623	4.0	45.				
623	5.0	47.				
623	6.0	51.				
623	7.0	64.				
623	8.0	66.				
631	1.0	0.0	3.0	1.0		
632	1.0	1.0	23.	1.0	35.	
632	2.0	1.0	3.0	21.	25.	
671	1.0	0.0	10.	.025		
675	1.0	4.0	64.			.01
675	2.0	5.0				.01
675	3.0	4.0	64.			0.5
675	4.0	5.0				0.5
675	5.0	4.0	64.			1.0
675	6.0	5.0				1.0
675	7.0	4.0	64.			1.5
675	8.0	5.0				1.5
675	9.0	4.0	64.			2.0
675	10.	5.0				2.0
675	11.	4.0	64.			2.5
675	12.	5.0				2.5
675	13.	4.0	64.			3.0
675	14.	5.0				3.0
END						
END						

TABLE 8.20

DATA DECK FOR THE MORE COARSELY ZONED CALCULATION OF A
RAREFACTION IN A COLD LEG-DOWNCOMER JUNCTION GEOMETRY

TTL	RAREFACTION IN DOWNCOMER JUNCTION GEOMETRY				
PRB					2.0
PRO	2.0				
SYM	2.0				
MIN					.01
GRD	1.0		15.	26.	
ITR	50.	.001	1.5		
ALE	2.0	1.0	1.0		
END					
MAT					2.0
111	1.0	1.0			
121	1.0	741.525			
122	1.0	1.0	6.897	833.2	
111	2.0	1.0			
121	2.0	741.525			
122	2.0	1.0	11.7		
END					
GPT				2.0	2.0
211	1.0	1.0	1.0	0.0	0.0
212	1.0	0.0	1.525	2.0	
212	2.0	0.0	0.0	1.0	
212	3.0	1.707	0.0	3.0	
221	1.0	1.0	15.	1.0	26.
247	1.0	0.0	1.70688	0.0	1.524
END					
ZON					2.0
311	1.0	1.0	15.	1.0	26.
321	1.0	1.0			
322	1.0	.991052			
311	2.0	1.0	4.0	25.	26.
321	2.0	2.0			
322	2.0	1.0			
311	3.0	4.0	15.	5.0	26.
321	3.0	1.0			
322	3.0	.991052			
311	4.0	7.0	15.	2.0	3.0
321	4.0	1.0			
322	4.0	.991052			
END					
BDY					2.0
411	1.0	15.	1.0	15.	26.
412	1.0	1.0	5.0	5.0	
411	2.0	15.	26.	1.0	26.
412	2.0	1.0	5.0	5.0	
411	3.0	1.0	26.	1.0	1.0
412	3.0	1.0	6.0	5.0	2.0
411	4.0	1.0	1.0	14.	1.0
412	4.0	1.0	6.0	5.0	3.0
411	5.0	14.	1.0	15.	1.0
412	5.0	1.0	5.0	5.0	
411	6.0	4.0	26.	4.0	5.0
412	6.0	1.0	5.0	5.0	
411	7.0	4.0	5.0	15.	5.0
412	7.0	1.0	5.0	5.0	
411	8.0	15.	3.0	7.0	3.0
412	8.0	1.0	5.0	5.0	
411	9.0	7.0	3.0	7.0	2.0
412	9.0	1.0	5.0	5.0	
411	10.	7.0	2.0	15.	2.0
412	10.	1.0	5.0	5.0	
481	1.0	1.0	3.0		
482	1.0	1.0	5.0	5.0	
END					

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TABLE 8.20 (continued)

TIM					2.0
511	.05				
512	.01	.05			
513	1.05	.25	0.0		
521	3.0	100.			
END					
EDT					2.0
621	1.0	0.0	3.0	0.5	
622	1.0	15.	1.0	26.	
623	1.0	12.			
623	2.0	15.			
623	3.0	42.			
623	4.0	45.			
623	5.0	47.			
623	6.0	51.			
623	7.0	64.			
623	8.0	66.			
671	1.0	0.0	10.	.025	
675	1.0	4.0	64.		.01
675	2.0	5.0			.01
675	3.0	4.0	64.		0.5
675	4.0	5.0			0.5
675	5.0	4.0	64.		1.0
675	6.0	5.0			1.0
675	7.0	4.0	64.		1.5
675	8.0	5.0			1.5
675	9.0	4.0	64.		2.0
675	10.	5.0			2.0
675	11.	4.0	64.		2.5
675	12.	5.0			2.5
675	13.	4.0	64.		3.0
675	14.	5.0			3.0
END					
END					

TABLE 8.21

DATA DECK FOR THE MORE FINELY ZONED CALCULATION OF A
RAREFACTION IN A COLD LEG-DOWNCOMER JUNCTION GEMOETRY

TTL	RAREFACTION IN DOWNCOMER JUNCTION GEOMETRY - FINE ZONING							
PRB	2.0							
PRO	2.0							
SYM	2.0							
MIN						.01		
GRD	1.0		19.	38.				
ITR	50.	.001	1.5					
ALE	2.0	1.0	1.0					
END								
MAT	2.0							
111	1.0	1.0						
121	1.0	741.525						
122	1.0	1.0	6.897	833.2				
111	2.0	1.0						
121	2.0	741.525						
122	2.0	1.0	11.7					
END								
GPT	2.0 2.0							
211	1.0	1.0	1.0	0.0	0.0			
212	1.0	0.0	1.525	2.0				
212	2.0	0.0	0.0	1.0				
212	3.0	1.707	0.0	3.0				
221	1.0	1.0	9.0	1.0	9.0			
247	1.0	0.0	.73152	0.0	.24384	1.0	1.0	
221	2.0	9.0	19.	1.0	9.0			
247	2.0	.73152	.97536	0.0	.24384	1.0143	1.0	
221	3.0	1.0	9.0	9.0	37.			
247	3.0	0.0	.73152	.24384	1.2192	1.0	1.0253828	
221	4.0	9.0	19.	9.0	37.			
247	4.0	.73152	.97536	.24384	1.2192	1.0143	1.0253828	
221	5.0	1.0	9.0	37.	38.			
247	5.0	0.0	.73152	1.46304	.06096	1.0	1.0	
221	6.0	9.0	19.	37.	38.			
247	6.0	.73152	.97536	1.46304	.06096	1.0143	1.0	
END								
ZON	2.0							
311	1.0	1.0	19.	1.0	38.			
321	1.0	1.0						
322	1.0	.991052						
311	2.0	1.0	5.0	37.	38.			
321	2.0	2.0						
322	2.0	1.0						
311	3.0	5.0	19.	9.0	38.			
321	3.0	1.0						
322	3.0	.991052						
311	4.0	9.0	19.	3.0	5.0			
321	4.0	1.0						
322	4.0	.991052						
END								

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TABLE 8.21 (continued)

BDY					2.0
411	1.0	19.	1.0	19.	38.
412	1.0	1.0	5.0	5.0	
411	2.0	19.	38.	1.0	38.
412	2.0	1.0	5.0	5.0	
411	3.0	1.0	38.	1.0	1.0
412	3.0	1.0	6.0	5.0	2.0
411	4.0	1.0	1.0	18.	1.0
412	4.0	1.0	6.0	5.0	3.0
411	5.0	18.	1.0	19.	1.0
412	5.0	1.0	5.0	5.0	
411	6.0	5.0	38.	5.0	9.0
412	6.0	1.0	5.0	5.0	
411	7.0	5.0	9.0	19.	9.0
412	7.0	1.0	5.0	5.0	
411	8.0	19.	5.0	9.0	5.0
412	8.0	1.0	5.0	5.0	
411	9.0	9.0	5.0	9.0	3.0
412	9.0	1.0	5.0	5.0	
411	10.	9.0	3.0	19.	3.0
412	10.	1.0	5.0	5.0	
481	1.0	1.0	3.0		
482	1.0	1.0	5.0	5.0	
END					
TIM					2.0
511	.05				
512	.01	.05			
513	1.05	.25	0.0		
521	3.0	100.			
END					
EDT					2.0
621	1.0	0.0	3.0	0.5	
622	1.0	19.	1.0	38.	
623	1.0	12.			
623	2.0	15.			
623	3.0	42.			
623	4.0	45.			
623	5.0	47.			
623	6.0	51.			
623	7.0	64.			
623	8.0	66.			
671	1.0	0.0	10.	.025	
675	1.0	4.0	64.		.01
675	2.0	5.0			.01
675	3.0	4.0	64.		0.5
675	4.0	5.0			0.5
675	5.0	4.0	64.		1.0
675	6.0	5.0			1.0
675	7.0	4.0	64.		1.5
675	8.0	5.0			1.5
675	9.0	4.0	64.		2.0
675	10.	5.0			2.0
675	11.	4.0	64.		2.5
675	12.	5.0			2.5
675	13.	4.0	64.		3.0
675	14.	5.0			3.0
END					
END					

TABLE 8.22

DATA DECK FOR THE MORE COARSELY ZONED CALCULATION OF A RAREFACTION
IN A NARROW CHANNEL CONTAINING A CENTRAL OBSTRUCTION

TTL	RAREFACTION IN A NARROW CHANNEL				
PRB					2.0
PRD	2.0				
MIN					.01
GRD	1.0		9.0	32.	
ITR	50.	.001	1.5		
ALE	2.0	1.0	1.0		
END					
MAT					2.0
111	1.0	1.0			
121	1.0	741.525			
122	1.0	1.0	6.897	833.2	
111	2.0	1.0			
121	2.0	741.525			
122	2.0	1.0	11.7		
END					
GPT				2.0	2.0
211	1.0	1.0	1.0	0.0	0.0
212	1.0	0.0	9.45	2.0	
212	2.0	0.0	0.0	3.0	
212	3.0	.3048	0.0	2.0	
212	4.0	.3048	9.45	3.0	
221	1.0	1.0	9.0	1.0	32.
247	1.0	0.0	.3048	0.0	9.4488
END					
ZON					2.0
311	1.0	1.0	9.0	1.0	32.
321	1.0	1.0			
322	1.0	.991052			
311	2.0	1.0	9.0	1.0	2.0
321	2.0	2.0			
322	2.0	1.0			
311	3.0	3.0	5.0	4.0	19.
321	3.0	1.0			
322	3.0	.991052			
END					
BDY					2.0
411	1.0	1.0	1.0	9.0	1.0
412	1.0	1.0	5.0	5.0	
411	2.0	9.0	1.0	9.0	31.
412	2.0	1.0	6.0	5.0	4.0
411	3.0	9.0	31.	9.0	32.
412	3.0	1.0	5.0	5.0	
411	4.0	9.0	32.	1.0	32.
412	4.0	1.0	5.0	5.0	
411	5.0	1.0	32.	1.0	2.0
412	5.0	1.0	6.0	5.0	2.0
411	6.0	1.0	2.0	1.0	1.0
412	6.0	1.0	5.0	5.0	
411	7.0	3.0	4.0	5.0	4.0
412	7.0	1.0	5.0	5.0	
411	8.0	5.0	4.0	5.0	19.
412	8.0	1.0	5.0	5.0	
411	9.0	5.0	19.	3.0	19.
412	9.0	1.0	5.0	5.0	
411	10.	3.0	19.	3.0	4.0
412	10.	1.0	5.0	5.0	
481	1.0	1.0	2.0		
482	1.0	1.0	5.0	5.0	
481	2.0	3.0	4.0		
482	2.0	1.0	5.0	5.0	
END					

TABLE 8.22 (continued)

TIM					2.0	
511	.04					
512	.01	.04				
513	1.01	.25	0.0			
521	10.	250.				
END						
EDT					2.0	
621	1.0	0.0	10.	1.0		
622	1.0	9.0	1.0	32.		
623	1.0	12.				
623	2.0	15.				
623	3.0	42.				
623	4.0	45.				
623	5.0	47.				
623	6.0	51.				
623	7.0	64.				
623	8.0	66.				
671	1.0	0.0	10.	.025		
675	1.0	4.0	64.			.01
675	2.0	5.0				.01
675	3.0	4.0	64.			1.0
675	4.0	5.0				1.0
675	5.0	4.0	64.			2.0
675	6.0	5.0				2.0
675	7.0	4.0	64.			3.0
675	8.0	5.0				3.0
675	9.0	4.0	64.			4.0
675	10.	5.0				4.0
675	11.	4.0	64.			5.0
675	12.	5.0				5.0
675	13.	4.0	64.			6.0
675	14.	5.0				6.0
675	15.	4.0	64.			7.0
675	16.	5.0				7.0
675	17.	4.0	64.			8.0
675	18.	5.0				8.0
675	19.	4.0	64.			9.0
675	20.	5.0				9.0
675	21.	4.0	64.			10.
675	22.	5.0				10.
END						
END						

TABLE 8.23

DATA DECK FOR THE MORE FINELY ZONED CALCULATION OF A RAREFACTION
IN A NARROW CHANNEL CONTAINING A CENTRAL OBSTRUCTION

TTL	RAREFACTION IN A NARROW CHANNEL - FINE ZONING				
PRB	2.0				
PRO	2.0				
MIN	.01				
GRD	1.0		13.	46.	
ITR	50.	.001	1.5		
ALE	2.0	1.0	1.0		
END					
MAT	2.0				
111	1.0	1.0			
121	1.0	741.525			
122	1.0	1.0	6.897	833.2	
111	2.0	1.0			
121	2.0	741.525			
122	2.0	1.0	11.7		
END					
GPT				2.0	2.0
211	1.0	1.0	1.0	0.0	0.0
212	1.0	0.0	9.45	2.0	
212	2.0	0.0	0.0	3.0	
212	3.0	.3048	0.0	2.0	
212	4.0	.3048	9.45	3.0	
221	1.0	1.0	13.	1.0	2.0
247	1.0	0.0	.3048	0.0	.3048
221	2.0	1.0	13.	2.0	5.0
247	2.0	0.0	.3048	.3048	.6096
221	3.0	1.0	13.	5.0	46.
247	3.0	0.0	.3048	.9144	8.52062
END					
ZON					2.0
311	1.0	1.0	13.	1.0	46.
321	1.0	1.0			
322	1.0	.991052			
311	2.0	1.0	13.	1.0	2.0
321	2.0	2.0			
322	2.0	1.0			
311	3.0	4.0	7.0	5.0	27.
321	3.0	1.0			
322	3.0	.991052			
END					
BDY					2.0
411	1.0	1.0	1.0	13.	1.0
412	1.0	1.0	5.0	5.0	
411	2.0	13.	1.0	13.	45.
412	2.0	1.0	6.0	5.0	4.0
411	3.0	13.	45.	13.	46.
412	3.0	1.0	5.0	5.0	
411	4.0	13.	46.	1.0	46.
412	4.0	1.0	5.0	5.0	
411	5.0	1.0	46.	1.0	2.0
412	5.0	1.0	6.0	5.0	2.0
411	6.0	1.0	2.0	1.0	1.0
412	6.0	1.0	5.0	5.0	
411	7.0	4.0	5.0	7.0	5.0
412	7.0	1.0	5.0	5.0	
411	8.0	7.0	5.0	7.0	27.
412	8.0	1.0	5.0	5.0	
411	9.0	7.0	27.	4.0	27.
412	9.0	1.0	5.0	5.0	
411	10.	4.0	27.	4.0	5.0
412	10.	1.0	5.0	5.0	

(Continued on next page)

TABLE 8.23 (continued)

481	1.0	1.0	2.0		
482	1.0	1.0	5.0	5.0	
481	2.0	3.0	4.0		
482	2.0	1.0	5.0	5.0	
END					
TIM					2.0
511	.04				
512	.01	.04			
513	1.01	.25	0.0		
521	8.0	200.			
END					
EDT					2.0
621	1.0	0.0	10.	1.0	
622	1.0	13.	1.0	46.	
623	1.0	12.			
623	2.0	15.			
623	3.0	42.			
623	4.0	45.			
623	5.0	47.			
623	6.0	51.			
623	7.0	64.			
623	8.0	66.			
671	1.0	0.0	10.	.025	
675	1.0	4.0	64.		.01
675	2.0	5.0			.01
675	3.0	4.0	64.		1.0
675	4.0	5.0			1.0
675	5.0	4.0	64.		2.0
675	6.0	5.0			2.0
675	7.0	4.0	64.		3.0
675	8.0	5.0			3.0
675	9.0	4.0	64.		4.0
675	10.	5.0			4.0
675	11.	4.0	64.		5.0
675	12.	5.0			5.0
675	13.	4.0	64.		6.0
675	14.	5.0			6.0
675	15.	4.0	64.		7.0
675	16.	5.0			7.0
675	17.	4.0	64.		8.0
675	18.	5.0			8.0
675	19.	4.0	64.		9.0
675	20.	5.0			9.0
675	21.	4.0	64.		10.
675	22.	5.0			10.
END					
END					

(Reference 21), it provides a good comparison of the two time integration methods.

This calculation is not recommended for use as a sample calculation by new users for several reasons. First, it was a fairly difficult and costly calculation. Second, it required the use of special features that are not available in standard versions of the codes (e.g., a special ALE mesh rezoner, special equations of state, etc.). Third, as discussed above, this calculation is not an ideal application of the implicit codes; the explicit versions are probably better suited for problems of this type, i.e., shock wave problems.

The experiments which this calculation was designed to model are known as the COVA 1 experiments (References 22 and 23). In these experiments, a 1 oz. spherical charge of RDX/TNT is detonated in an essentially rigid, cylindrical container which is nearly filled with water (at room temperature and atmospheric pressure). The interior dimensions of the cylinder, which rests on one of its ends, are 70 cm (diameter) by 56 cm (height). The water level is 2.5 cm below the top end of the cylinder. The charge is located 22 cm above the bottom of the cylinder on the centerline. Figure 8.146 shows a schematic of the experimental configuration.

8.3.4.2 Problem Set-Up. The initial mesh configuration used for this calculation is shown in Figure 8.147. The explosive charge is contained in two cells (shown shaded) adjacent to the axis of symmetry on the left. The cell sizes, which are indicated on the figure, are nearly uniform throughout the mesh. The radial cell dimensions, except for the column containing the charge, are 1.40 cm while the axial dimensions vary between about 1.37 cm and 1.40 cm. This gives a mesh of $25 \times 39 = 975$ cells or $26 \times 40 = 1040$ grid points.

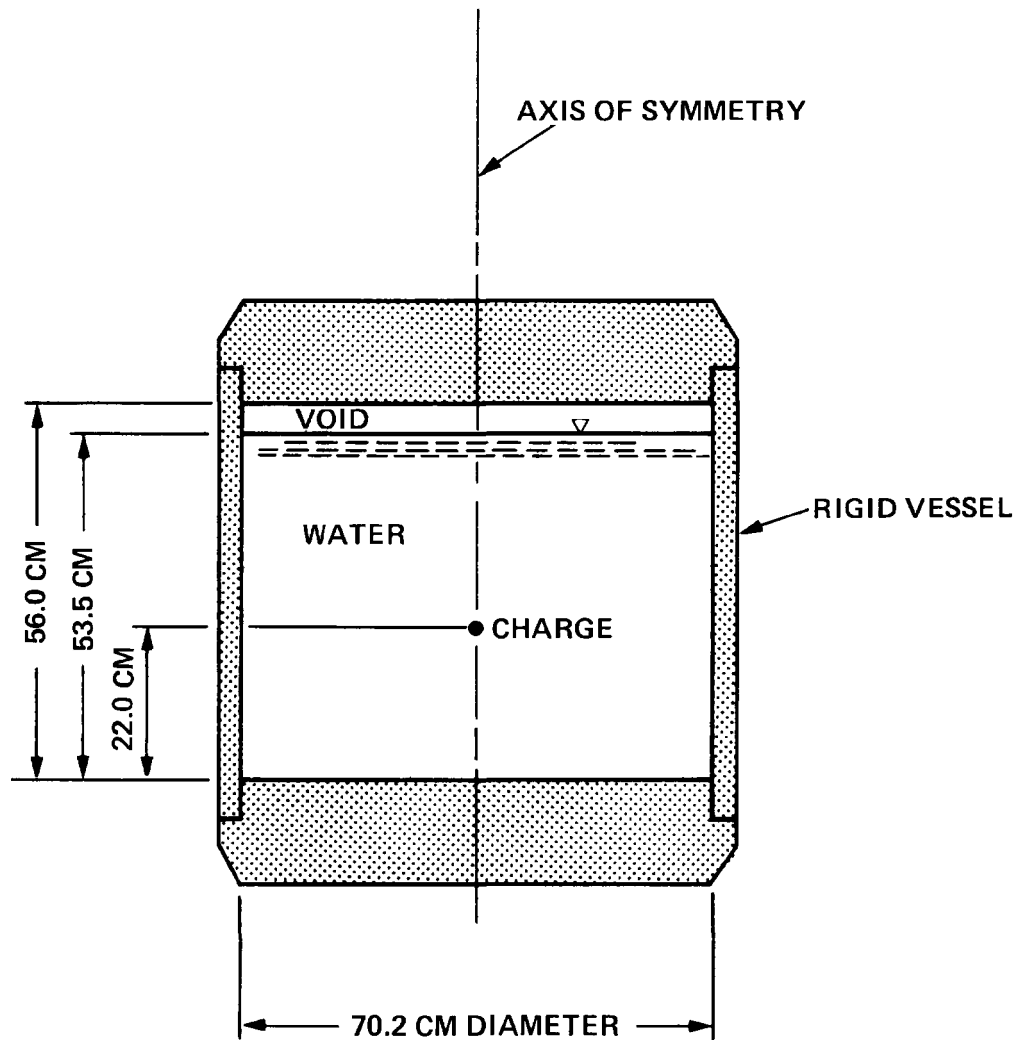


Figure 8.146. COVA 1 experiment configuration.

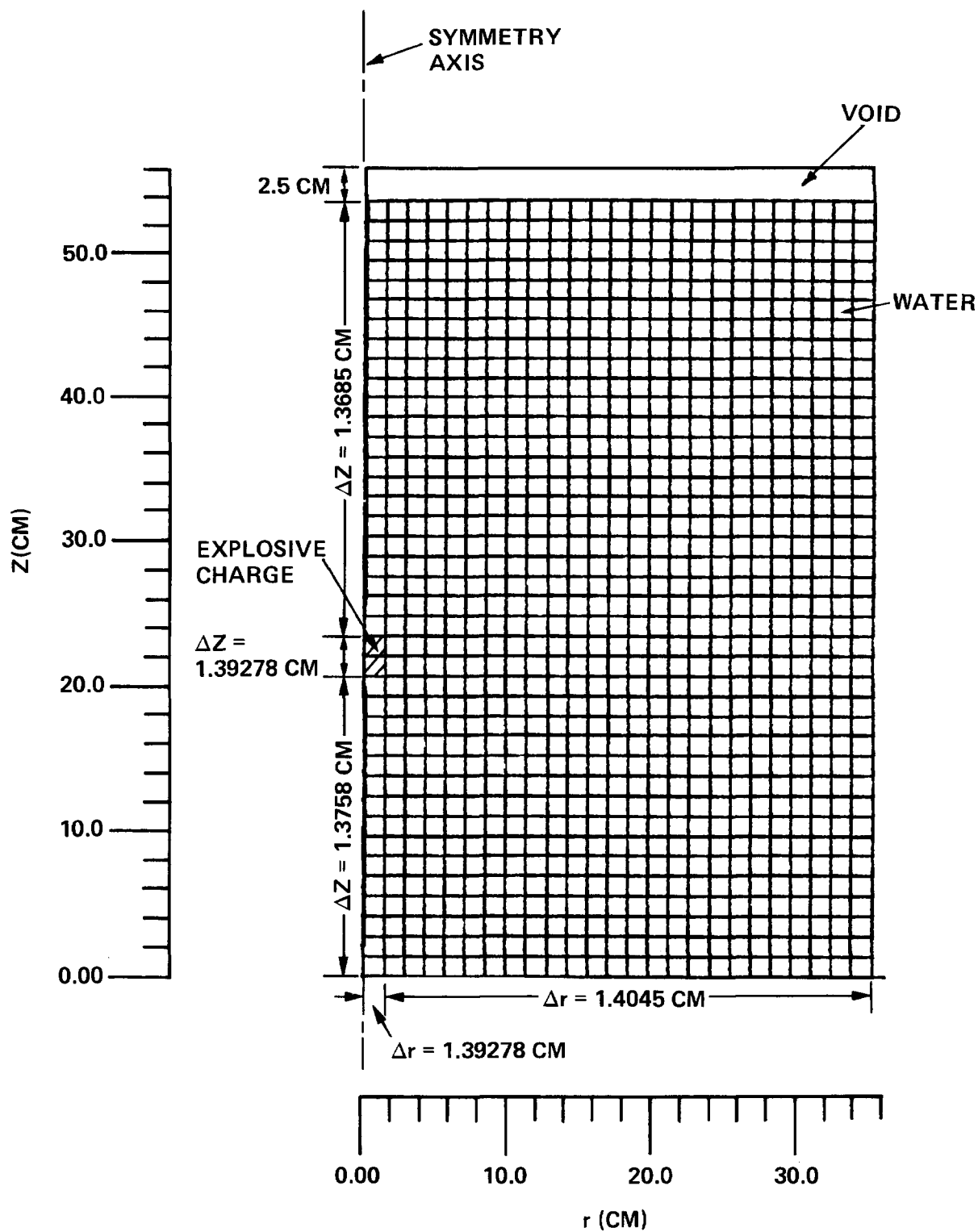


Figure 8.147. Initial mesh configuration used for the APRICOT 3 calculation.

The boundaries on all sides are frictionless, rigid walls. On the top boundary, the mesh is separated from the wall by 2.5 cm; that boundary is treated as a free surface until the fluid has moved up far enough to close the gap and interact with the wall.

Because of the large distortions produced by the expanding explosive detonation products, it was necessary to use the ALE rezoning feature. At the time this calculation was done, however, all of the presently available mesh rezoning options had not been developed. Therefore, a special mesh rezoner was programmed specifically for this problem. That special mesh rezoner will not be discussed here; however, if the calculation were to be repeated now, standard rezone options could be used.

This calculation involves two distinct materials: the gaseous products from the explosive detonation and the liquid water. Since separate equations of state were used to describe these materials, they had to be kept separated in the computational mesh. Therefore, the surface between the two materials was treated as a Lagrangian surface. This was part of the specially programmed mesh rezoner but now is a standard option. It should be noted that at very late times in this calculation, when the pressures in and around the explosive had dropped to very low levels, mixing was allowed between the two materials, i.e., the surfaces of the two cells originally containing the explosive were no longer treated as Lagrangian surfaces. This was done to eliminate some of the extreme distortions that were developing in the mesh immediately outside the explosive cells.

The material properties for the two materials are discussed in detail in Reference 21. Here we will briefly summarize the models and properties used for this calculation.

The explosive equation of state was

$$p = 0.92453 E/V + 0.054925 V^{-3.09303}$$

where

p = pressure in megabars,

E = internal energy density in Mbar-cm³/cm³,

V = relative volume = ρ/ρ_0

and

ρ = density in gm/cm³,

ρ_0 = reference density = 1.67 gm/cm³.

The water equation of state was derived from the Hugoniot equation of state for water

$$p = p_H(V) + 0.28[E - E_H(V)]/V$$

where p_H and E_H are the pressure and internal energy density, respectively, along the shock Hugoniot. The shock Hugoniot can be described by the following relationship between the shock velocity u_s and the particle velocity u_p :

$$u_s = 0.1483 + 2.086 u_p - 1.398 u_p^2.$$

(The velocity units are cm/ sec.) Using this equation along with the shock jump conditions (Rankine-Hugoniot equation), the water equation of state can be expressed in the following form:

$$p = p_H(V)[1 - 0.14(1 - V)/V] + 0.28 E/V$$

where

$$p_H(V) = u_p(0.1483 + 2.06 u_p - 1.398 u_p^2)$$

and

$$u_p = \frac{2.086(1 - V) - 1 + [2.086(1 - V) - 1]^2 + 0.8293(1 - V)^2}{2.796 (1 - V)}$$

when $V \neq 1$, and $u_p = 0$ when $V = 1$. The units and variable definitions here are the same as were used for the explosive equation of state. The reference density for water was $\rho_0 = 1.0 \text{ gm/cm}^3$.

Because of the form of the equation of state for the explosive products, they can never reach a tensile state; therefore it was not necessary to define tensile properties for that material. However, special tensile properties were prescribed for the water. The body of water as a whole was able to support a negative pressure of -25 bars for the first 500 sec of the calculation. After that time no tension was permitted. This is discussed more fully in Reference 21.

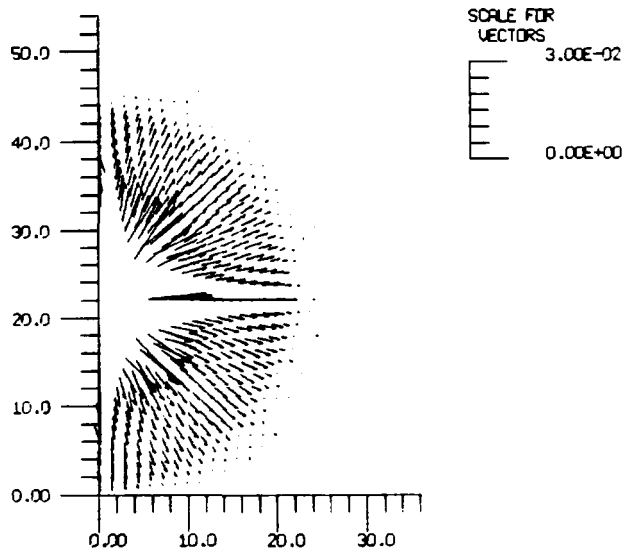
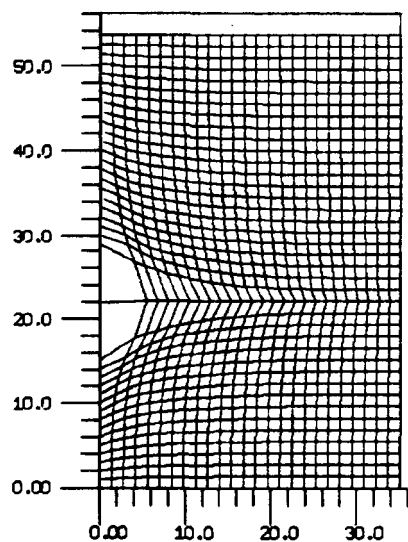
The initial conditions in the water were $E_1 = 0.0$ and $V_1 = 1.0$ (or $\rho_1 = \rho_0$), so that $p_1 = 0.0$. In the explosive $E_1 = 0.3958 \text{ Mbar-cm}^3/\text{gm}$ and $V_1 = 1.0$, which gives an initial pressure of $p_1 = 0.11604 \text{ Mbar}$.

It should be noted that these initial conditions do not accurately represent the conditions that are produced by the detonation of the explosive charge. In order to reproduce those conditions accurately, far better spatial resolution would be required in and around the explosive than was used for this calculation. However, at a large distance from the charge (greater than about ten charge radii), any errors introduced by the approximate initial conditions should be negligible. Since we are only interested in the pressures on the walls, which are more than ten charge radii from the charge, the approximate initial conditions should be adequate.

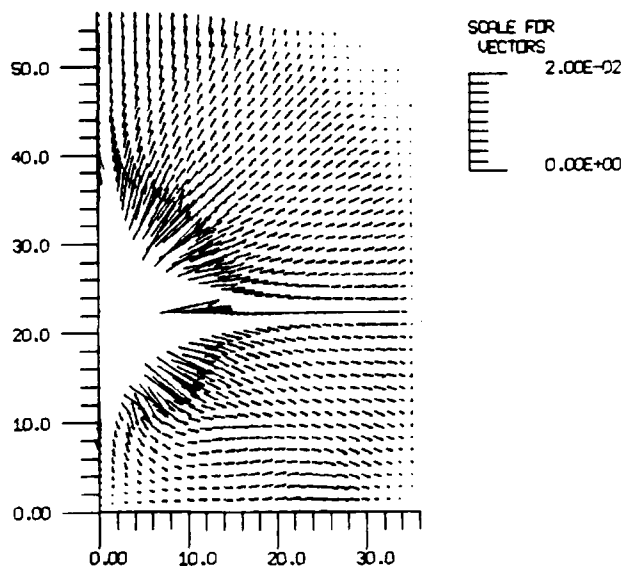
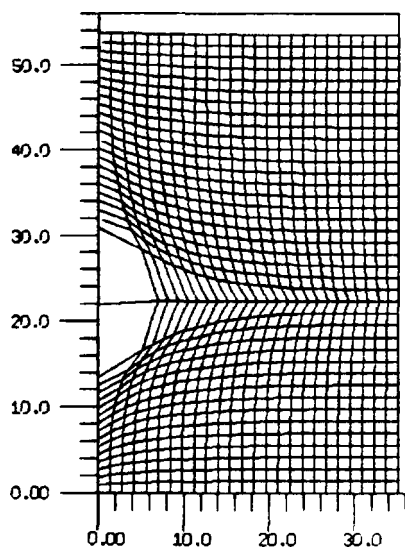
8.3.4.3 Results. The mesh configuration and velocity field are shown in Figure 8.148 for several times from 100 μ sec up to the final computed time of 1100 μ sec. These show that a spherical wave was generated initially which started to interact with the bottom of the container at about 100 μ sec. By a time of 200 μ sec the wave had interacted with the side of the container as well as with the free surface at the top. At 300 μ sec a fairly complicated flow pattern had been established reflecting the interaction of waves reflected from the boundaries. This complicated flow pattern continued up through 500 μ sec. After that time the pressure had been relieved throughout most of the fluid, and the flow coasted upward until it interacted with the top of the container. That interaction started at about 700 μ sec in a small region directly above the explosive charge. By 900 μ sec, the next time shown in Figure 8.148, a substantial part of the water surface had stagnated against the top of the container. The plots at 1000 μ sec show that the stagnation of the top surface had been nearly completed by that time. By the final computed time of 1100 μ sec, the stagnation of the flow extended a substantial distance down into the fluid.

The mesh and velocity vector plots provide only qualitative information about the calculation. A more quantitative evaluation can be accomplished by comparing the results of this calculation with data obtained from the COVA 1 experiments and with the results from the equivalent explicit STEALTH calculation.

In the COVA 1 experiments a number of pressure gauges were placed along the floor, wall, and ceiling of the pressure vessel to measure the reflected shock pressure, or, in the case of the ceiling gauges, the pressures resulting from the stagnation of the fluid against the top surface. The location of these gauges is provided in Table 8.24.

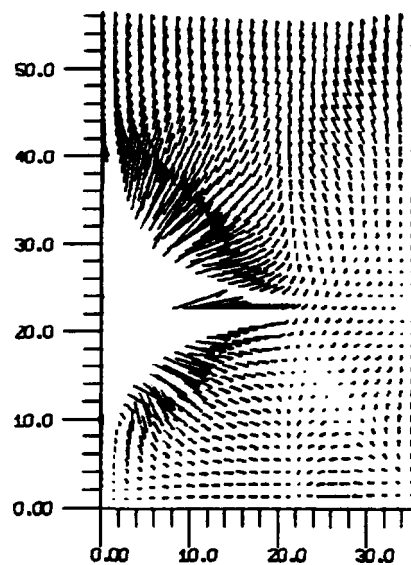
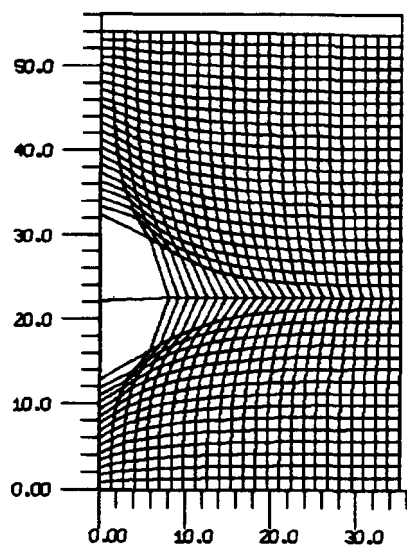


$t = 100 \mu\text{sec}$



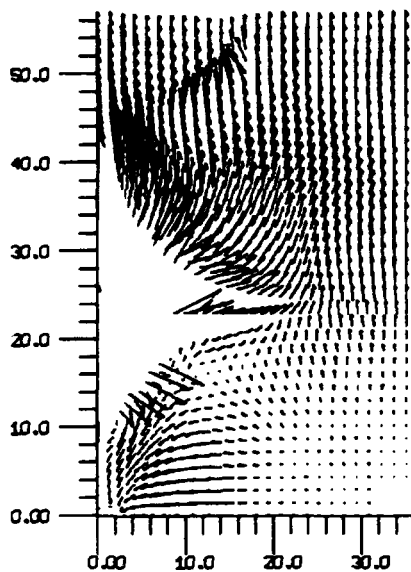
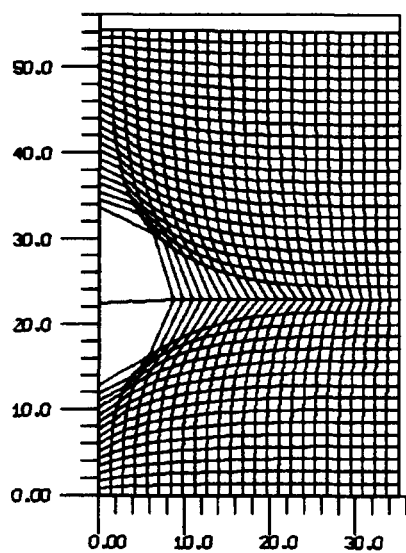
$t = 200 \mu\text{sec}$

Figure 8.148. Mesh configuration and velocity field at several times for the APRICOT 3 calculation.



SCALE FOR
VECTORS
1.60E-02
0.00E+00

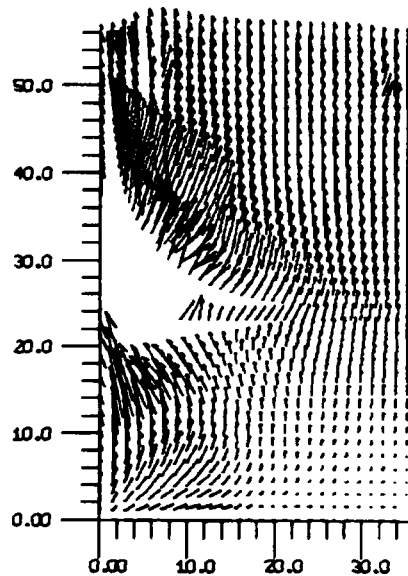
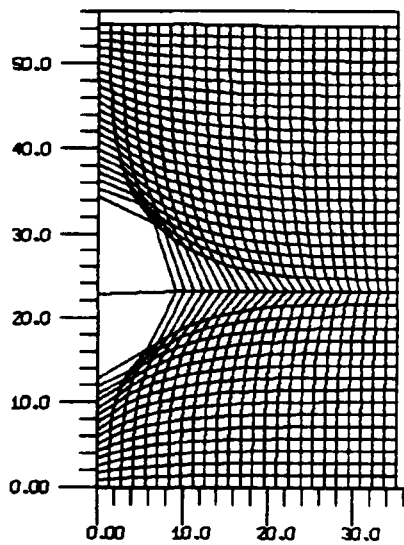
$t = 300 \mu\text{sec}$



SCALE FOR
VECTORS
1.20E-02
0.00E+00

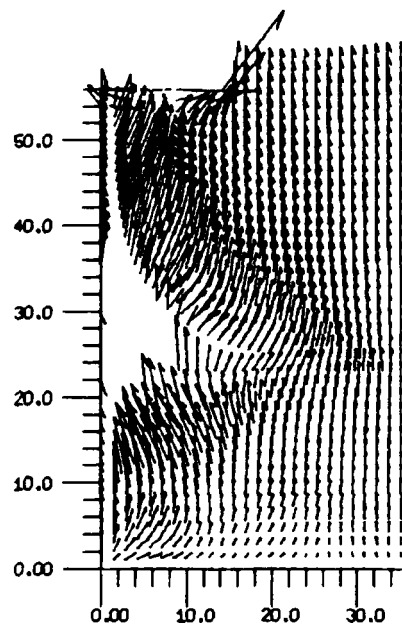
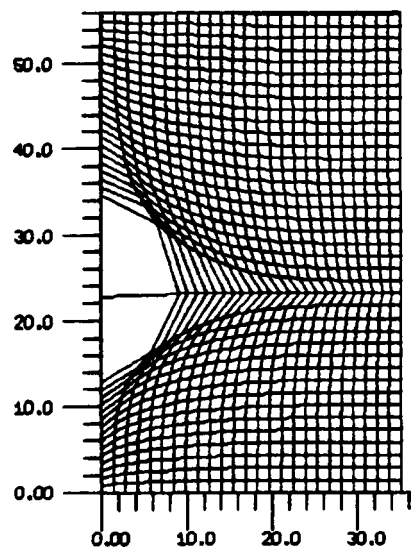
$t = 400 \mu\text{sec}$

Figure 8.148 (continued)



SCALE FOR
VECTORS
1.40E-02
0.00E+00

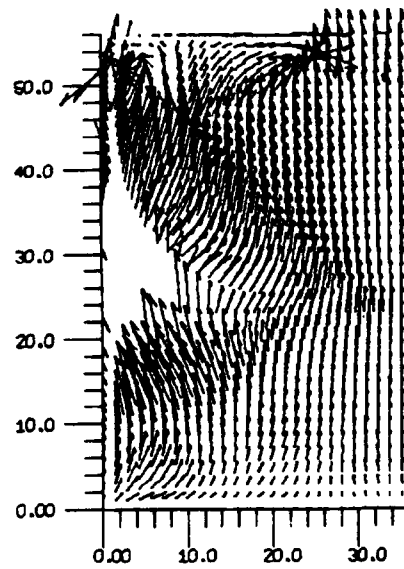
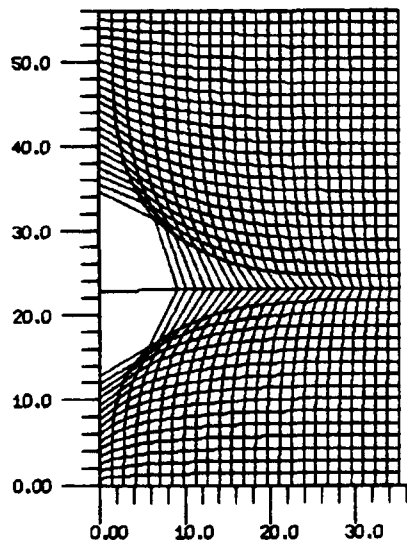
$t = 500 \mu\text{sec}$



SCALE FOR
VECTORS
9.00E-03
0.00E+00

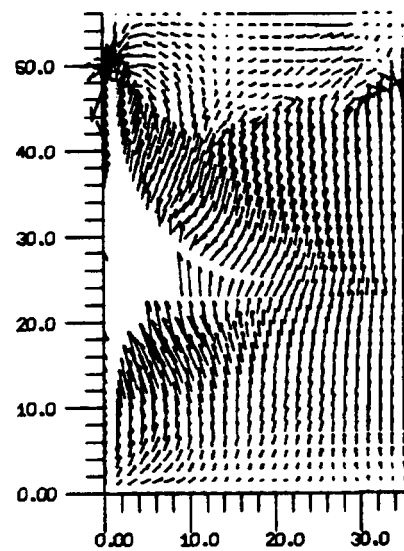
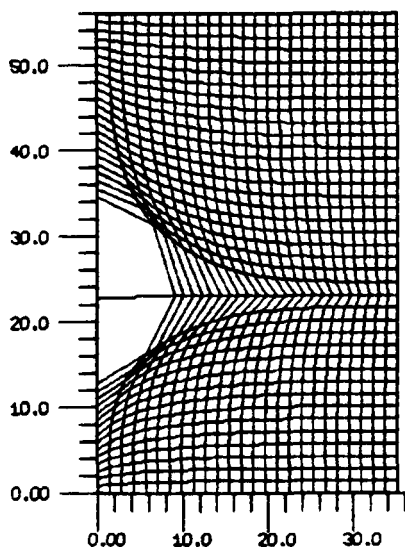
$t = 900 \mu\text{sec}$

Figure 8.148 (continued)



SCALE FOR
VECTORS
8.00E-03
0.00E+00

$t = 100 \mu\text{sec}$



SCALE FOR
VECTORS
1.20E-02
0.00E+00

$t = 1100 \mu\text{sec}$

Figure 8.148 (continued)

TABLE 8.24

GAGE LOCATIONS FOR COVA 1 EXPERIMENTS
AND APRICOT 3 CALCULATIONS

Vessel Floor Gages

<u>Gage Number</u>	<u>Radius (cm)</u>
1	2.4
2	4.2
3	8.0
4	10.5
5	16.0
6	24.0
7	32.0

Vessel Wall Gages

<u>Gage Number</u>	<u>Height (cm)</u>
8	1.6
9	5.6
10	14.0
11	18.2
12	28.0
13	46.0

Vessel Ceiling Gages

<u>Gage Number</u>	<u>Radius (cm)</u>
14	2.4
15	4.2
16	8.0
17	10.5
18	16.0
19	24.0
20	32.0

To provide a comparison with the measured pressures, the calculated pressures in the zones nearest most of the measurement stations were monitored continuously throughout the calculation. These are shown in Figure 8.149. Although these zones moved somewhat during the calculation, according to the ALE rezone prescription (which prescribed nearly Lagrangian motion in the regions adjacent to the vessel walls), the error introduced by that motion was small. The largest motion was experienced by the zone associated with gage 13 which ended up a little more than 2 cm from its initial position. However, the pressure wave reflections measured by the wall and floor gages were over by about 500 μ sec and the pressure in the fluid had dropped to zero. By that time the zone had moved only about 1 cm, or less than a zone width. The movement for all other monitored zones was considerably less.

The peak pressures at the gage locations along the floor and wall are provided in Figures 8.150 and 8.151, respectively. Similarly, wave arrival times are provided in Figures 8.152 and 8.153*. In both cases, the results from this calculation are compared with the experimental measurements as well as with the results from the explicit STEALTH calculation.

In general, the calculated pressures and arrival times were in reasonable agreement with both the data and the explicit STEALTH calculation, although some discrepancies were found. In general, the peak pressure predictions for the second wave (which results from the shock reflection from either the bottom or the side wall) were better than for the initial shock reflection. This was also true for the explicit STEALTH calculation. The biggest discrepancies were found for floor gages near the symmetry axis where the strongest shocks occurred. In this region (and to a lesser extent in the region on the wall immediately to the right of the

* The error bars plotted for the wave arrival times calculated by implicit STEALTH represent the time between the arrival of the wave front (at $1/2 p_{\max}$) and the peak.

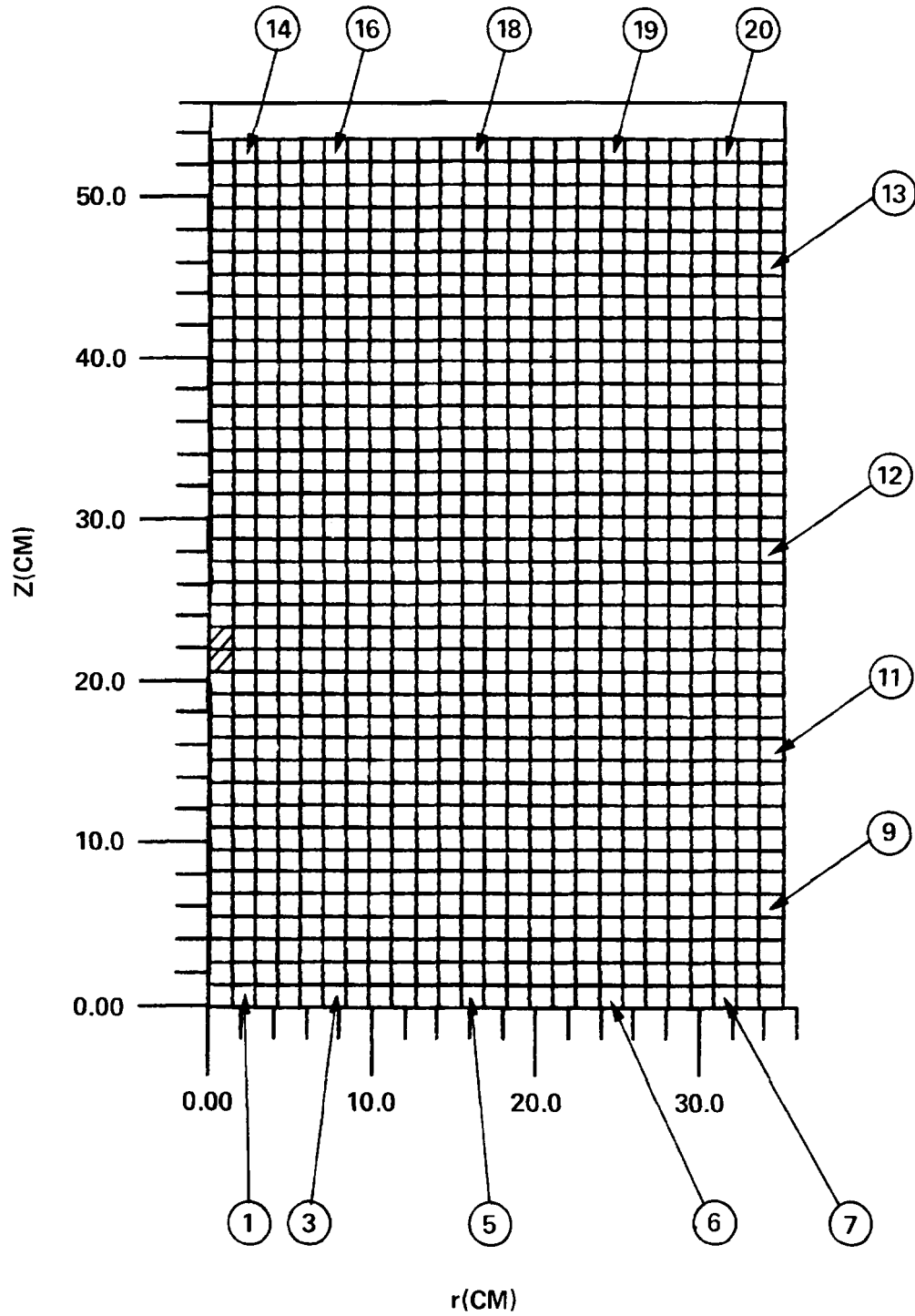


Figure 8.149. Location of the zones that were monitored in the APRICOT 3 calculation for comparison with the COVA 1 experimental results. The numbers in the circles indicate the number of the corresponding gage.

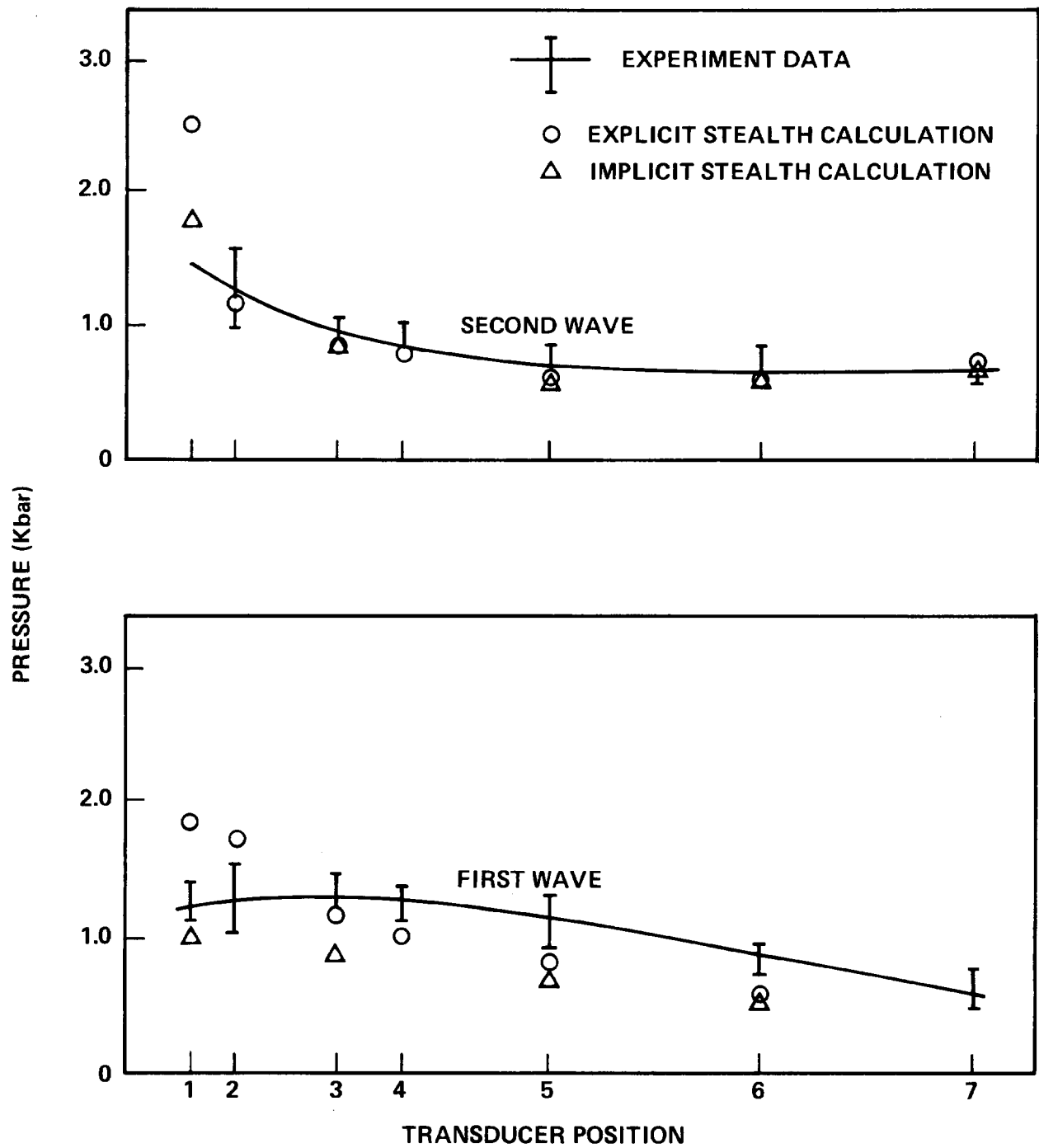


Figure 8.150. Comparison of peak pressures at gage locations on the vessel floor.

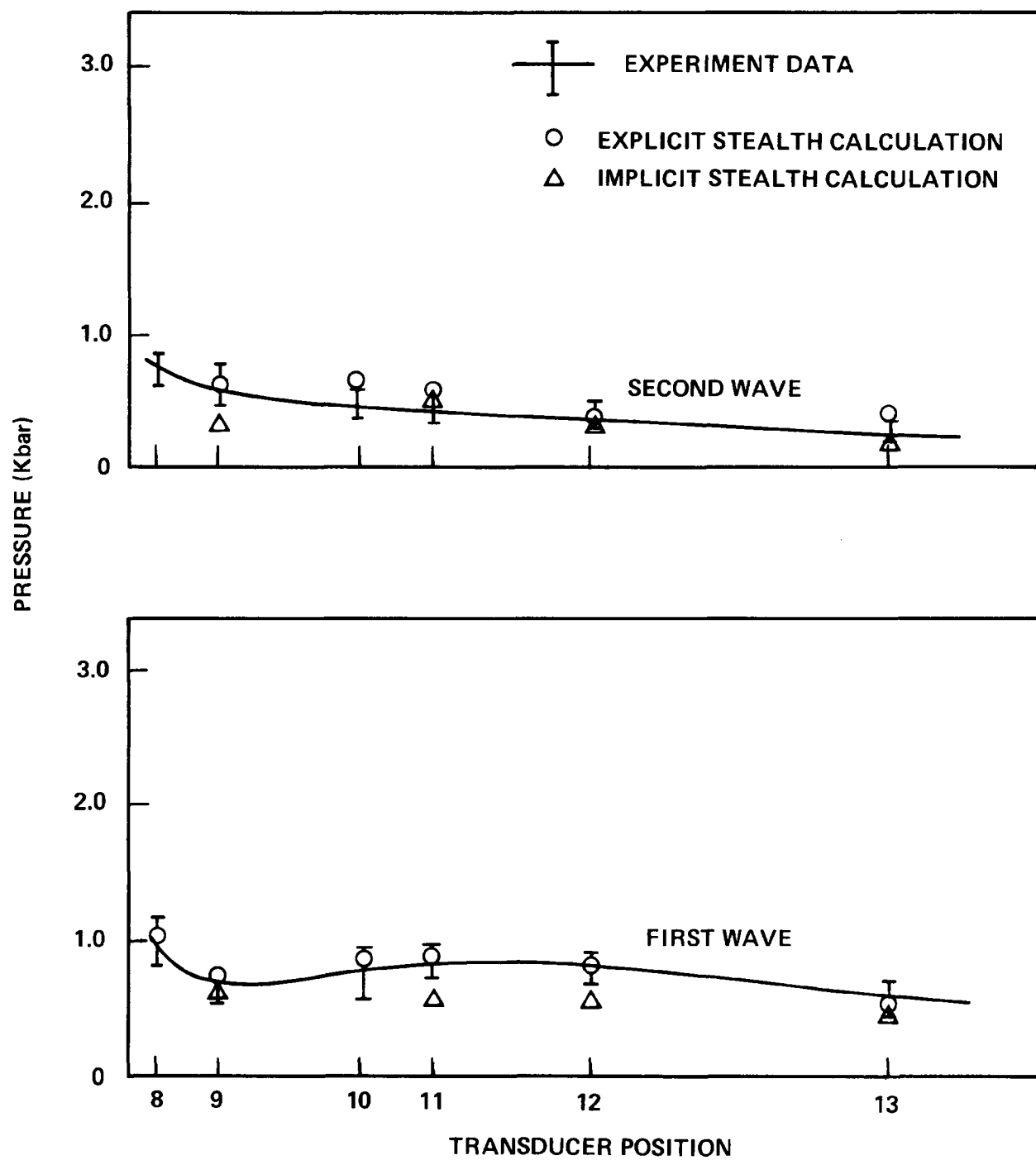


Figure 8.151. Comparison of peak pressures at gage locations on the vessel wall.

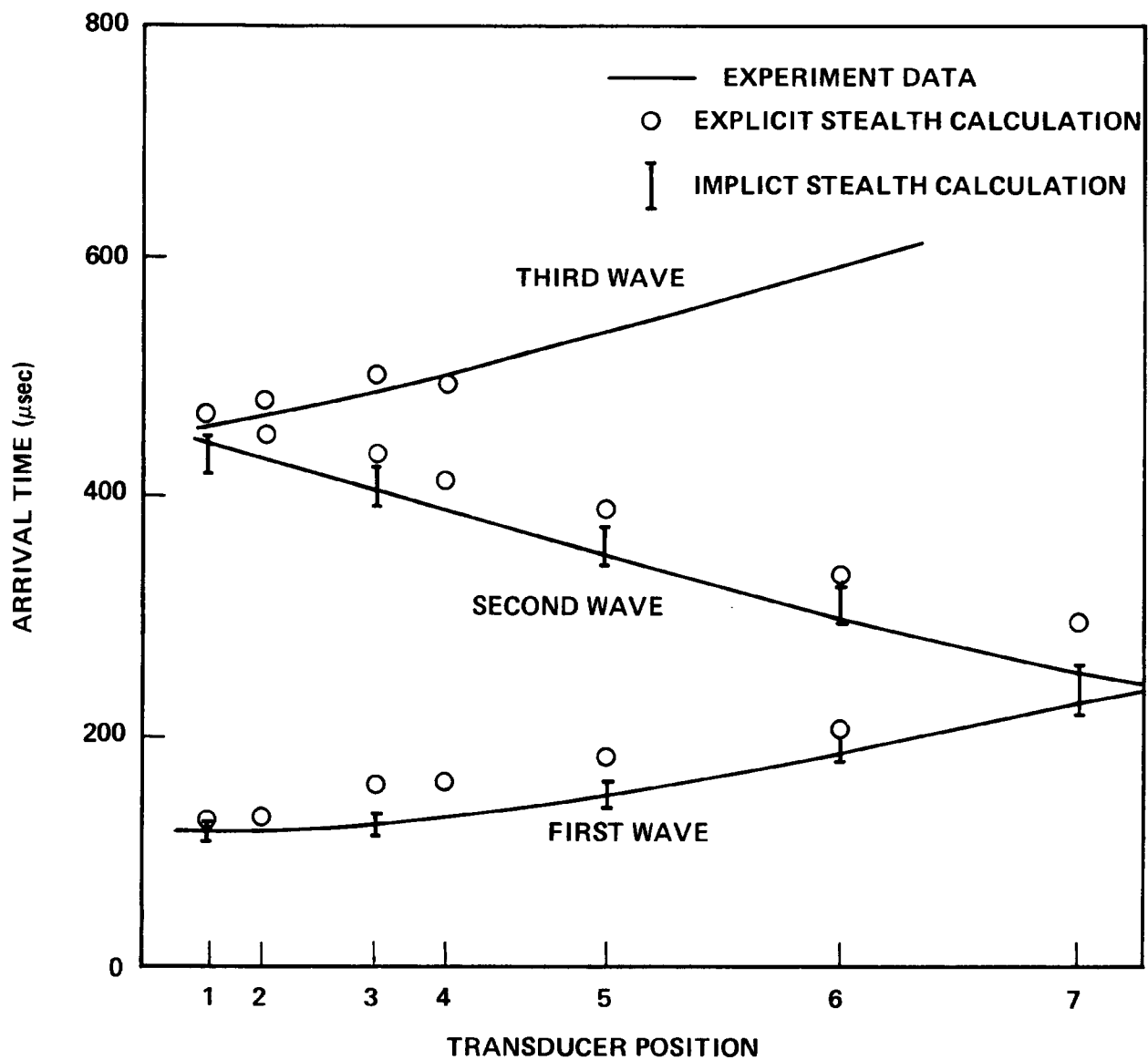


Figure 8.152. Comparison of wave arrival times at gage locations on the vessel floor.

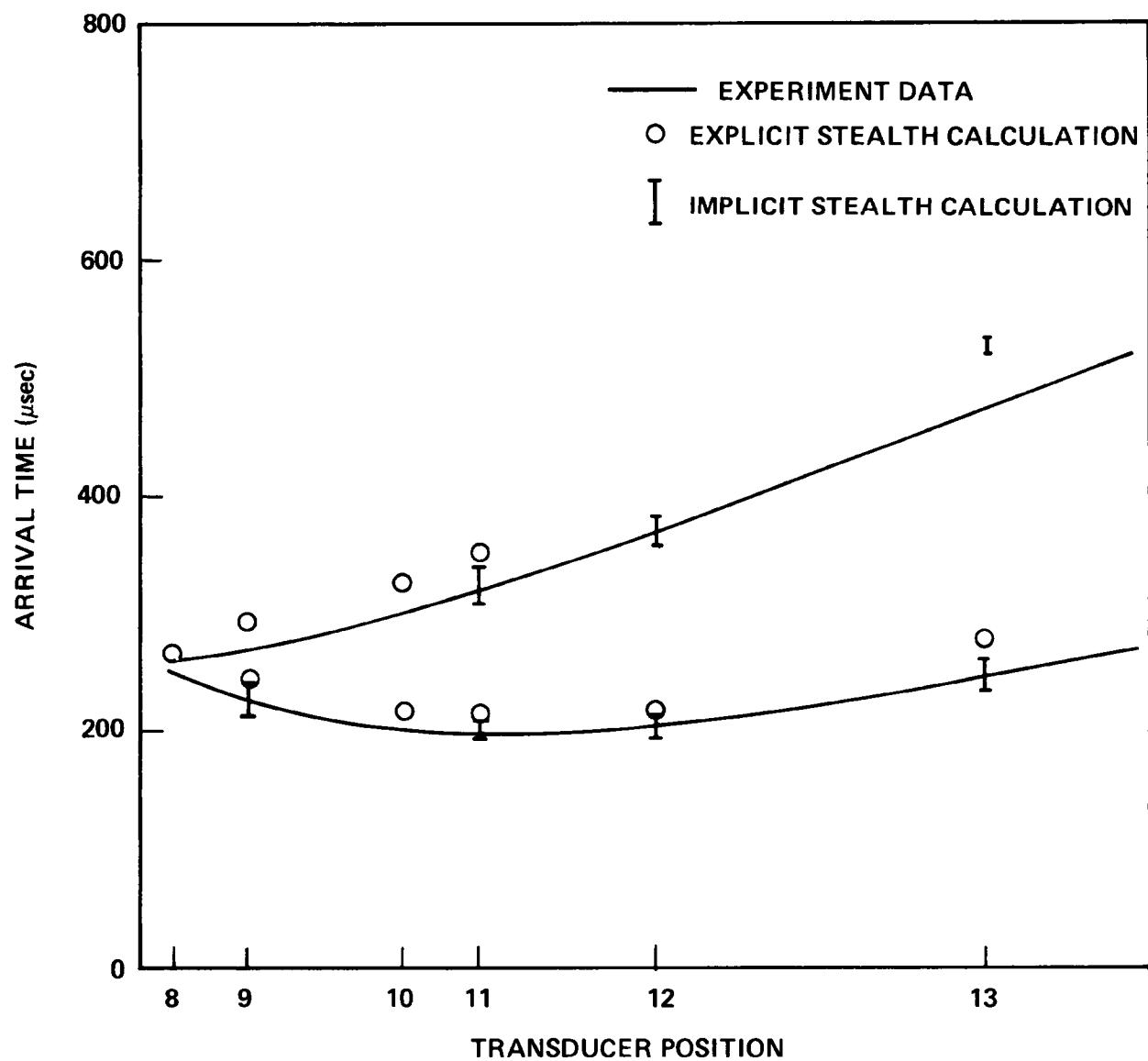


Figure 8.153. Comparison of wave arrival times at gage locations on the vessel wall.

charge) the peak pressures predicted by the implicit STEALTH calculations were substantially less than those predicted by explicit STEALTH. Examination of the waveforms shows that the higher frequencies calculated by explicit STEALTH were damped out in the implicit calculation. This apparently resulted in the attenuation of the peak pressures in the regions where the pressure waves were the sharpest.

Pressure waveforms for three floor gages (gages 3, 5, and 6) and one wall gage (gage 11) are provided in Figure 8.154 through 8.157. Those figures show a comparison of waveforms calculated by the implicit and explicit versions of STEALTH. The characteristics described above (i.e., the damping of the high frequencies and the attenuation of the peak pressures) are apparent. This feature is characteristic of the implicit method used for STEALTH (i.e., one based on the ICE methodology); it has been observed for other codes of this type (Reference 24). However, we do not consider this to be a serious shortcoming for these codes. The implicit versions of STEALTH were not developed for problems of this type which can usually be handled more economically by explicit methods. Given that fact, we consider the generally good agreement for the floor and wall gages to be encouraging.

The peak pressures and arrival times at the ceiling gages are provided in Figures 8.158 and 8.159, respectively. The agreement here (particularly for pressures) is not as good as was observed for the floor and wall gages. However, this is probably due to the spall model used in the calculations. The fluid that stagnated against the ceiling in the calculation was not a uniform slug of water but consisted of water zones that had spalled when the initial shock wave reflected from the free surface. In the finite difference representation this was like discrete "slabs" of water impacting the ceiling as successive rows of spalled zones compressed and stagnated. In reality, the spalling or cavitation is likely to occur on a smaller scale than could be modeled well by the approach used in this calculation (which was the same as that used in the explicit STEALTH calculation). Any

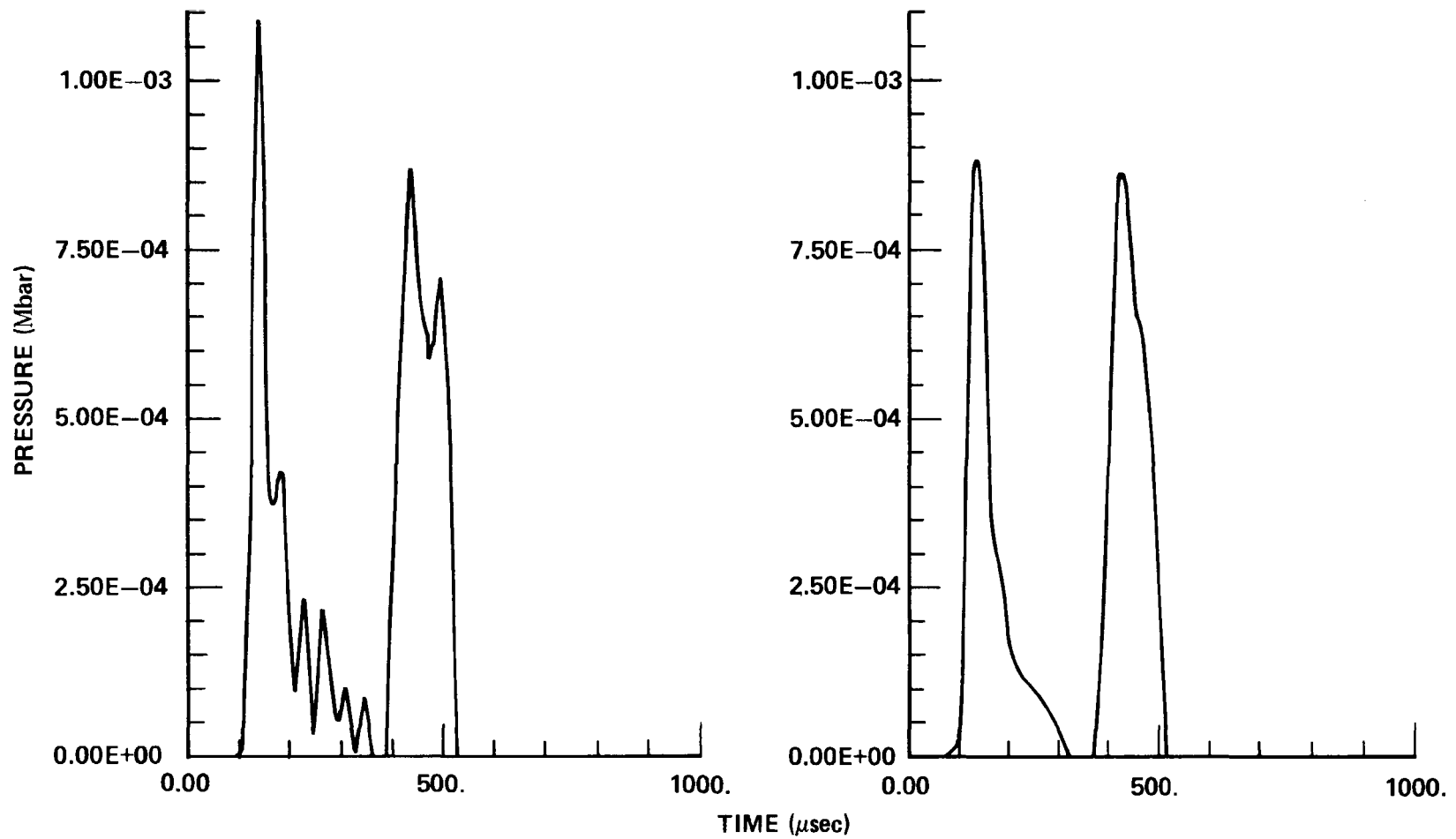


Figure 8.154. Comparison of pressure histories near the location of gage 3 for the explicit (left) and implicit (right) calculations of APRICOT 3.

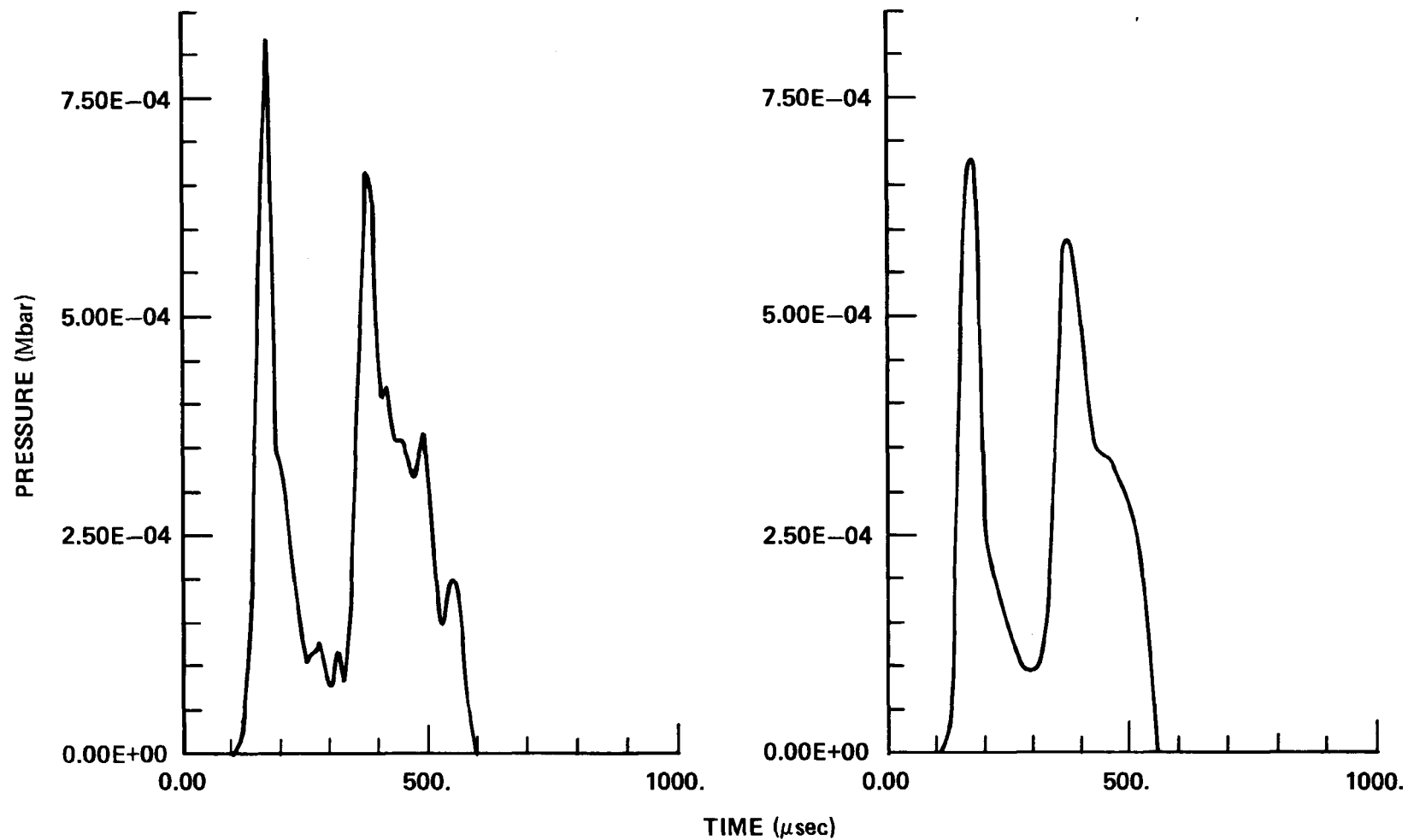


Figure 8.155. Comparison of pressure histories near the location of gage 5 for the explicit (left) and implicit (right) calculations of APRICOT 3.

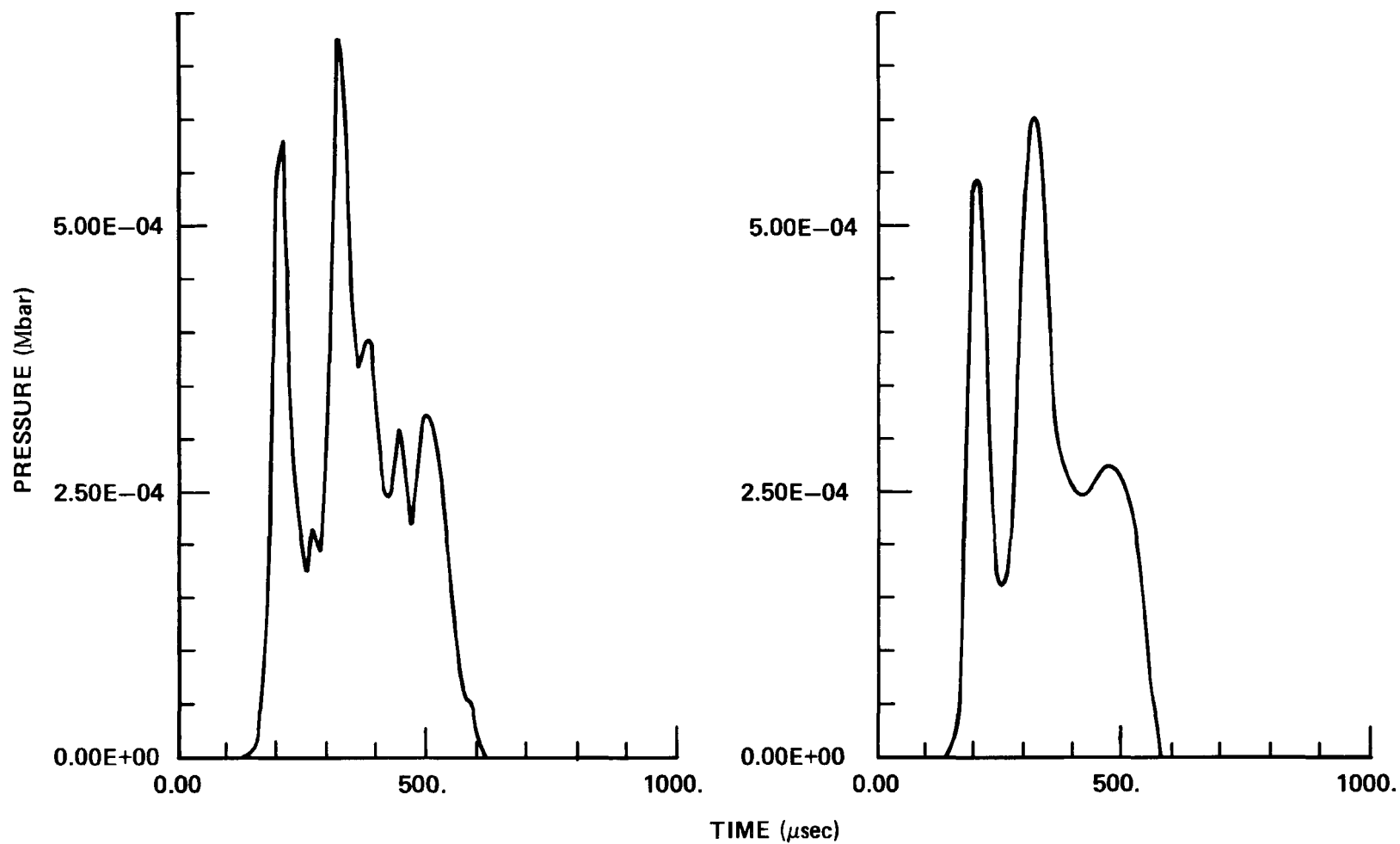


Figure 8.156. Comparison of pressure histories near the location of gage 6 for the explicit (left) and implicit (right) calculations of APRICOT 3.

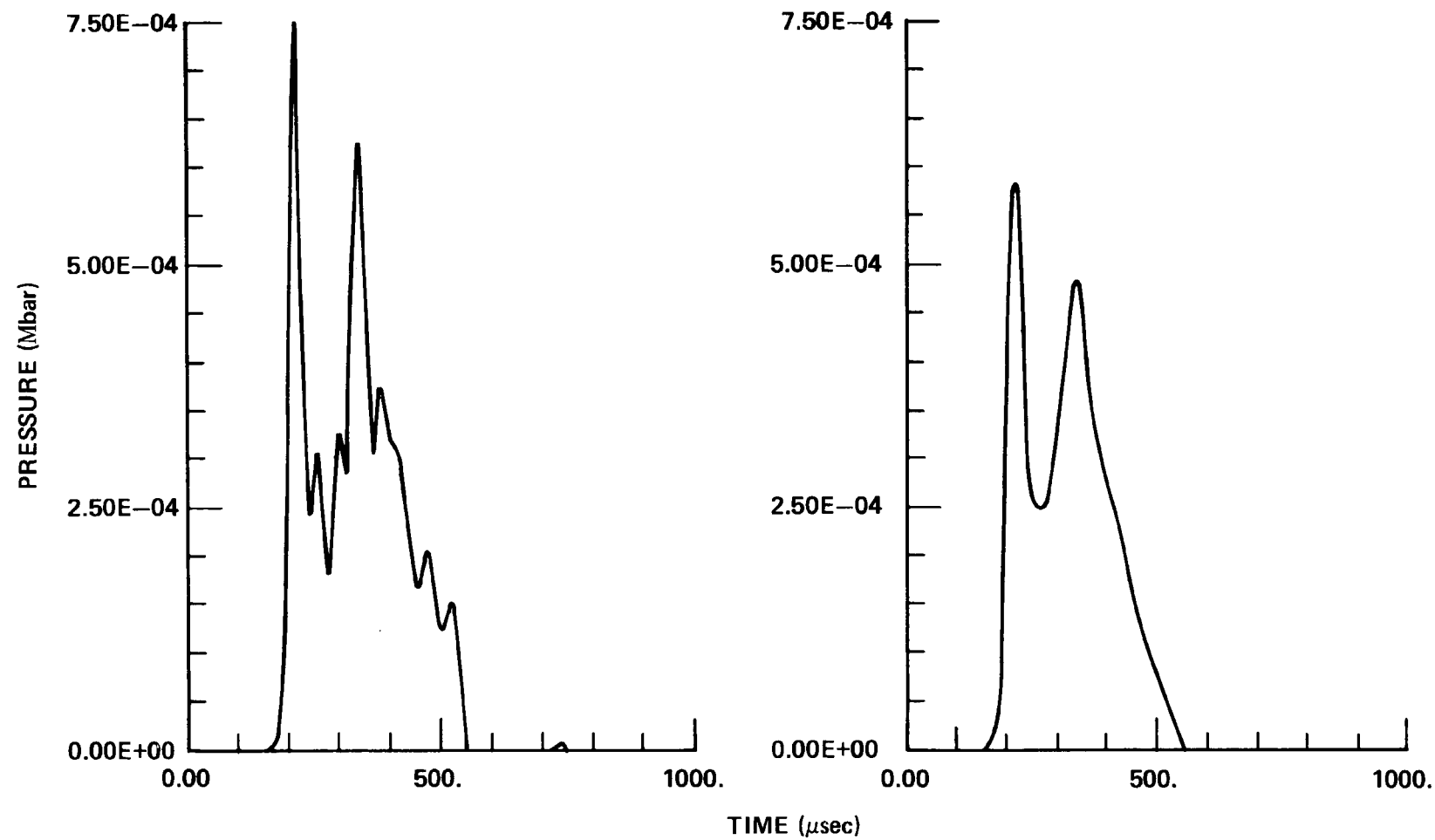


Figure 8.157. Comparison of pressure histories near the location of gage 11 for the explicit (left) and implicit (right) calculations of APRICOT 3.

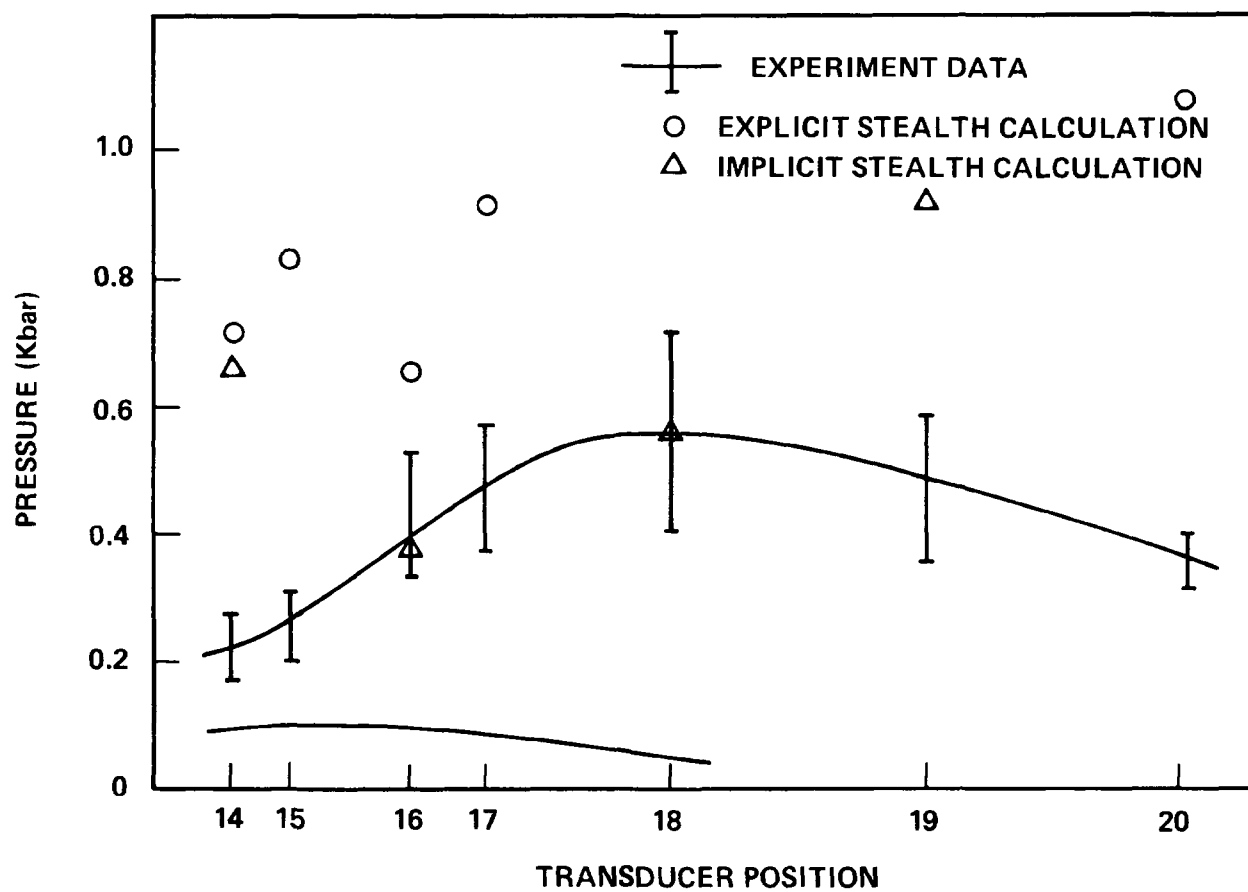


Figure 8.158. Comparison of peak pressures at gage locations on the vessel ceiling.

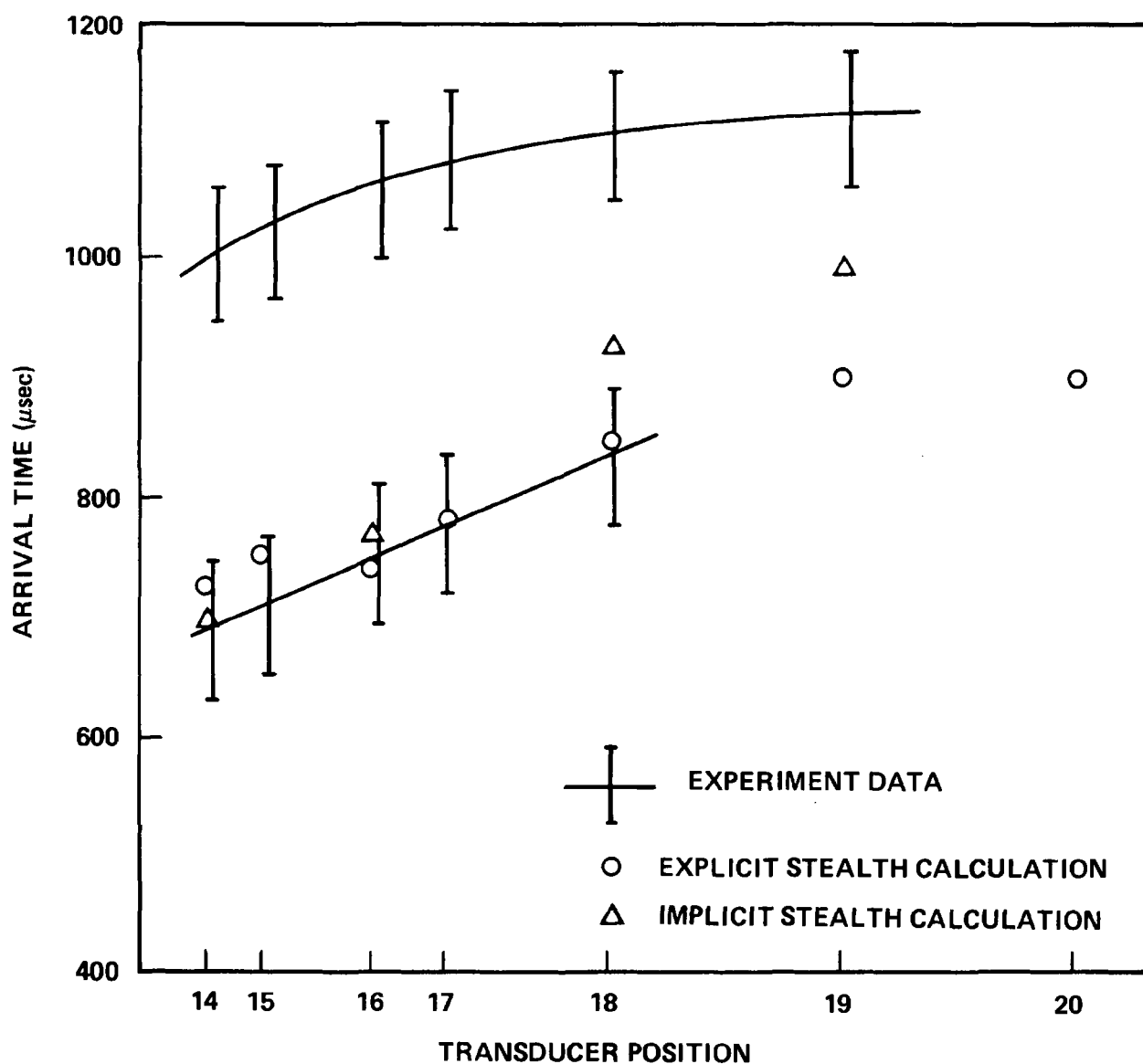


Figure 8.159. Comparison of wave arrival times at gage locations on the vessel ceiling.

attempt to provide a better model for this aspect of the problem was beyond the scope of this computational effort.

8.3.4.4 Input Deck. Because this calculation was not run using standard input alone, but required substantial internal modification to the code (e.g, special equation of state models, special mesh rezoner), and because we do not recommend it for use as a test calculation, the input deck has not been included.

APPENDIX
FILES (FLS)

NFCRD = card input file name = 5
NFLIB = library input file name = 3
NFKBD = on-line keyboard input file name = 4
NFPRT = print output file name = 6
NFSCP = scope output file name = 1
NFSTG = storage output file name = 7
NFMSG = message output file name = 2
NFPLT = plot output file name = 8
NFARO = archive output-records file name = 9
NFRSI = restart input-records file name = 10
NFRSO = restart output-records file name = 11
NFIO1 = scratch I/O number 1 file name = 12
NFIO2 = scratch I/O number 2 file name = 13
NFIO3 = scratch I/O number 3 file name = 14
NFIO4 = scratch I/O number 4 file name = 15
NFCMN = intermediate (binary) common block dump file name = 16
NFARI = archive input-records file name = 17

APPENDIX
FUNCTIONS (FNC)

PRIMARY FUNCTIONS

Polynomial (function type 1)

$$y = a_1 + a_2x + a_3x^2 + a_4x^3$$

Rational (function type 2)

$$y = \frac{a_1 + a_2x}{1 + a_3x + a_4x^2}$$

Exponential #1 (function type 3)

$$y = (a_1 + a_2x + a_3x^2)e^{-a_4x}$$

Exponential #2 (function type 4)

$$y = a_1 + a_2e^{(a_3x^2 + a_4x)}$$

Exponential #3 (function type 5)

$$y = a_1e^{(a_2e^{a_3x})} + a_4$$

Trigonometric #1 (function type 6)

$$y = a_1[1 - \cos(a_2\pi x)] + a_3[1 + \sin(a_4\pi x)]$$

Trigonometric #2 (function type 7)

$$y = a_1 \sin(a_2\pi x) + a_3 \cos(a_4\pi x)$$

DERIVATIVES OF FUNCTIONS

Polynomial (function type 1)

$$y' = a_2 + 2a_3x + 3a_4x^2$$

Rational (function type 2)

$$y' = \frac{(a_1 + a_2x)(a_3 + 2a_4x)}{1 + a_3x + a_4x^2} \left(\frac{a_2}{1 + a_3x + a_4x^2} \right)$$

Exponential #1 (function type 3)

$$y' = \left[(a_2 - a_1a_4) + (2a_3 - a_2a_4)x - a_3a_4x^2 \right] e^{-a_4x}$$

Exponential #2 (function type 4)

$$y' = a_2 e^{(a_3x^2 + a_4x)} (a_4 + 2a_3x)$$

Exponential #3 (function type 5)

$$y' = a_1 a_2 a_3 e^{a_3x} e^{(a_2 e^{a_3x})}$$

Trigonometric #1 (function type 6)

$$y' = a_1 a_2 \pi \sin(a_2 \pi x) + a_3 a_4 \pi \cos(a_4 \pi x)$$

Trigonometric #2 (function type 7)

$$y' = a_1 a_2 \pi \cos(a_2 \pi x) - a_3 a_4 \pi \sin(a_4 \pi x)$$

APPENDIX
IDENTIFIERS (IDS)

1 TIM	2 TIE	3 TDE	4 THE	5 TKE	6 TEG	7 TXM	8 TYM	9 TXK	10 TYK
11 XPN	12 XVL	13 XAC	14 YPN	15 YVL	16 YAC	17 ZPN	18 ZVL	19 ZAC	20
21 GXK	22 GYK	23 GZK	24 XHF	25 YHF	26 ZHF	27 XVX	28 YVX	29 ZVX	30 GMS
31 NOR	32 NBM	33 NBT	34 NBV	35 ACT	36 MPN	37 IND	38 NBR	39	40
41 DLL	42 RLV	43 COM	44 QDA	45 VSR	46 DNS	47 ZMS	48 TRV	49	50
51 ZIE	52 ZDE	53 ZHE	54 ZSE	55 ZKE	56 ZXM	57 ZYM	58 ZZM	59	60
61 TMP	62 CON	63 SHC	64 PRH	65 AVS	66 SSP	67 BFS	68 IGN	69	70
71 TXX	72 TYY	73 TZZ	74 TXY	75 TYZ	76 TXZ	77 EXX	78 EYY	79 EZZ	80 EXY
81 SXX	82 SYX	83 SZZ	84 SXY	85 SYZ	86 SZX	87 YLD	88 SHR	89	90
91 EX1	92 EX2	93 EX3	94 EX4	95 EX5	96 EX6	97	98	99	100

Variables 1 - 10 are global variables, while the rest are either grid-point or zone-related. Variable definitions may be found in Appendix CVN of Volume 3.

APPENDIX
MATERIAL MODELS (MAT)

There are several independent categories of information which must be specified to form the complete mechanical-thermal response model for a fluid. They are:

1. Thermodynamic model, $p = p(u, V)$
2. Viscosity model, $\underline{s} = s(u, \dot{\epsilon})$
3. Energy release model, $\dot{u} = \dot{u}(t)$
4. Heat flow model, $\dot{h} = \dot{h}(u, V)$
5. Artificial viscosity, $q = q(\frac{\dot{V}}{V})$

The minimum set of models must be chosen to satisfy boundary and initial conditions. The functions, p , s , $\dot{u}$, and $\dot{h}$ may take on any convenient form -- analytic or tabular.

On the following pages, standard (i.e., already programmed) models for each modeling category are described according to the model-type value specified. Standard models use the function capability wherever possible.

Special (i.e., user-supplied) models are programmed into subroutines specifically set aside for special programming. The names of these user-supplied subroutines are always five (5) characters as opposed to normal subroutine names which are composed of six (6) characters. The names of special subroutines are formed by joining the prefix MY to a root of an appropriate model identifier while the equivalent standard subroutine uses the root ZON as a prefix. The following user-supplied subroutines are available for material modeling:

<u>Standard Subroutine</u>	<u>User-supplied Subroutine</u>	<u>Description</u>
ZONSDV	MYSDV	stress deviators*
ZONYLD	MYYLD	yield stress**
ZONSHR	MYSHR	viscosity coefficients
ZONSPL	MYSPL	spall strength**
ZONTMP	MYTMP	temperature
ZONCON	MYCON	conductivity
ZONSHC	MYSHC	specific heat capacity
ZONPRH	MYPRH	pressure equation of state
ZONERL	MYERL	energy release
ZONSSS	MYSSS	sound speed squared

Any combination of standard and/or user-supplied subroutines may be used to achieve a particular set of material-response characteristics.

The calling sequence of the material modeling subroutines may be changed by re-programming subroutine ZONMDL (zone model).*** However, care must be taken that certain state variables in each zone be updated. These variables are summarized below.

*The stress deviators are used for the viscous stresses in the implicit fluid mechanics versions.

**Not used for the implicit fluid dynamics versions.

***ZONPRH is also called from subroutine ZONDRV in the implicit, compressible flow version as part of the implicit iteration. This call cannot be changed. The other material modeling subroutines are called from ZONMDL after the iteration has converged.

<u>Variable Description</u>	<u>Symbol</u>	<u>FORTTRAN Array Name</u>	<u>Standard Model Subroutine Name</u>	<u>User-supplied Model Subroutine Name</u>
Internal energy density	u	ZIE	ZONMDL	ZONMDL
Pressure	p	PRH	ZONPRH	MYPRH
Normal xx stress	σ_{xx}	TXX	ZONSTR	ZONSTR
Normal yy stress	σ_{yy}	TYY	ZONSTR	ZONSTR
Normal zz stress	σ_{zz}	TZZ	ZONSTR	ZONSTR
Shear xy stress	σ_{xy}	TXY	ZONSTR	ZONSTR
Specific heat capacity	C	SHC	ZONSHC	MYSHC
Temperature	T	TMP	ZONTMP	MYTMP
Conductivity	k	CON	ZONCON	MYCON
Sound speed squared	c ²	SSS	ZONSSS	MYSSS

In the explicit versions of STEALTH the user is allowed the flexibility of creating user supplied routines to replace a number of other subroutines (e.g., users supplied versions of ZONTRV and ZONSTN may be developed for special symmetries. However, in the implicit versions of the code this cannot be done easily since other parts of the code would have to be changed also. For these versions, the only subroutine other than the material modeling subroutines listed above for which a user supplied subroutine may be specified is subroutine ZONZSE which computes the energy source term in the internal energy equation.

THERMODYNAMIC MODEL

The thermodynamic model is a relationship between scalar properties of a material. Certain sets of properties (e.g., pressure (p), internal energy density (u), and relative volume (V)) form what is called a complete equation of state because mechanical, thermal, and caloric properties are included. The purpose of the pressure equation of state is to compute pressure from internal energy and relative volume. (Use of relative volume

requires that a reference density, ρ^0 , be defined; $V \equiv \rho^0/\rho$ where ρ is the density.)

Pressure Equation of State

Correspondence between FORTRAN input names and scientific notation is shown below.

MEOS = equation of state, model=type value
 EOS0 = equation-of-state parameter, b_0
 EOS1 = equation-of-state parameter, b_1
 EOS2 = equation-of-state parameter, b_2
 EOS3 = equation-of-state parameter, b_3
 EOS4 = equation-of-state parameter, b_4
 EOS5 = equation-of-state parameter, b_5
 EOS6 = equation-of-state parameter, b_6
 EOS7 = equation-of-state parameter, b_7
 EOS8 = equation-of-state parameter, b_8
 EOS9 = equation-of-state parameter, b_9

MEOS = 1.0

Pressure is a function of compression (μ) where $\mu \equiv \frac{1}{V} - 1$.

$$p = f(b_1, b_2, b_3, b_4, \mu) , \quad b_5 \leq \mu \leq b_6 .$$

The functional form f is the standard function type given by the value b_0 (see Appendix "Functions"). For example, if $b_0 = 1.0$, then the pressure equation of state is

$$P = b_1 + b_2\mu + b_3\mu^2 + b_4\mu^3 .$$

MEOS = 2.0

Pressure is a function of internal energy density (u) where
 $u = \hat{u}\rho^0$.

$$p = f(b_1, b_2, b_3, b_4, u) , \quad b_5 \leq u \leq b_6 .$$

The functional form f is the standard function type given by the value b_0 (see Appendix "Functions"). For example, if $b_0 = 3.0$, then the pressure equation of state is

$$p = b_1 + b_2 u + b_3 u^2 + b_4 e^{-b_4 u}$$

MEOS = 3.0

Pressure is a function of internal energy density and compression.

$$p = f_1(b_1, b_2, b_3, b_4, \mu) + u [f_2(b_8, b_9, \mu)] \quad b_5 \leq \mu \leq b_6$$

The functional forms f_1 and f_2 are the standard function types given by the values b_0 and b_7 , respectively (see Appendix "Functions"). For example, if $b_0 = 5.0$, and $b_7 = 2.0$, then the pressure equation of state is

$$p = b_1 e^{(b_2 e^{b_3 \mu})} + b_4 + u(b_8 + b_9 \mu)$$

For f_2 , the coefficients b_8 and b_9 correspond to the first two function coefficients, a_1 and a_2 . The other two coefficients, a_3 and a_4 , are assumed to be zero.

MEOS = 4.0*

p - α compaction model. For the theoretical background of this model, see the following reference:

W. Herrmann, J. Appl. Phys. 40 p.2490 (1969)

(not yet programmed)

MEOS = 5.0*

JWL chemical explosive model. For the theoretical background of this model, see the following reference:

E. L. Lee, H. C. Hornig and J. W. Kury, "Adiabatic Expansion of High Explosive Detonation Products," UCRL-50422, Lawrence Radiation Laboratory, Livermore, California, May 2, 1968.

(not yet programmed)

MEOS = 6.0, 7.9, 8.0, 9.0, 10.0

User-supplied, pressure equation-of-state models. Model logic is programmed into subroutine MYPRH. An example of MYPRH is presented at the end of this Appendix.

* Not used for the implicit, fluid dynamics versions.

STRENGTH/VISCOSITY MODEL

In the explicit versions of STEALTH the standard strength model is made up of a yield stress (Y) model, a shear modulus (G) model, and a spall strength (p_{min}) model. In the implicit, compressible flow versions this section of the code is used for the viscosity model. The yield stress and spall strength models are omitted and the shear modulus routines are used to calculate the shear and bulk viscosity coefficients.

Correspondence between FORTRAN input names and scientific notation is shown below.

MSHR = model type for viscosity coefficients
SHR0 = shear viscosity parameter, ζ_0
SHR1 = shear viscosity parameter, ζ_1
SHR2 = shear viscosity parameter, ζ_2
SHR3 = shear viscosity parameter, ζ_3
SHR4 = shear viscosity parameter, ζ_4
SHR5 = bulk viscosity parameter, κ_0
SHR6 = bulk viscosity parameter, κ_1
SHR7 = bulk viscosity parameter, κ_2
SHR8 = bulk viscosity parameter, κ_3
SHR9 = bulk viscosity parameter, κ_4

MSHR = 1.0

Shear and bulk viscosity coefficients are zero:

$\zeta = 0$, $\kappa = 0$.

MSHR = 2.0

Shear and bulk viscosity coefficients are constant:

$$\zeta = \zeta_0 \quad , \quad \kappa = \kappa_0 \quad .$$

MSHR = 3.0

Shear and bulk viscosity coefficients are functions of relative volume (V) only:

$$\begin{aligned}\zeta &= f(\zeta_1, \zeta_2, \zeta_3, \zeta_4, V) \quad , \\ \kappa &= f(\kappa_1, \kappa_2, \kappa_3, \kappa_4, V) \quad .\end{aligned}$$

The functional form f is the standard function type given by the values of ζ_0 and κ_0 (see Appendix "Functions"). For example, if $\zeta_0 = 2.0$ then the shear viscosity coefficient is

$$\zeta = \frac{\zeta_1 + \zeta_2 V}{1 + \zeta_3 V + \zeta_4 V^2}$$

MSHR = 4.0

Shear and bulk viscosity coefficients are functions of internal energy density (u) only:

$$\begin{aligned}\zeta &= f(\zeta_1, \zeta_2, \zeta_3, \zeta_4, u) \\ \kappa &= f(\kappa_1, \kappa_2, \kappa_3, \kappa_4, u) \quad .\end{aligned}$$

The functional form of f is the standard function type given by the value of ζ_0 or κ_0 (see Appendix "Functions"). For example, if $\zeta_0 = 1.0$, then the shear viscosity coefficient is

$$\zeta = \zeta_1 + \zeta_2 e^{(\zeta_3 u^2 + \zeta_4 u)}$$

MSHR = 5.0

Shear and bulk viscosity coefficients are functions of pressure (p) only:

$$\zeta = f(\zeta_1, \zeta_2, \zeta_3, \zeta_4, p) \quad ,$$

$$\kappa = f(\kappa_1, \kappa_2, \kappa_3, \kappa_4, p) \quad .$$

The functional form f is the standard function type given by the value κ_0 (see Appendix "Functions"). For example, if $\zeta_0 = 1.0$, then the shear viscosity coefficient is

$$\zeta_0 = 1 + \zeta_2 p + \zeta_3 p^2 + \zeta_4 p^3$$

MSHR = 6.0, 7.0, 8.0, 9.0, 10.0

User-supplied shear and bulk viscosity models. Model logic is programmed into subroutine MYSHR.

ENERGY RELEASE MODEL

The energy release model is a relationship between the chemically evolved energy density (E) of a material and the chemical components of the material.

Correspondence between FORTRAN input names and scientific notation is shown below.

MERL = energy release model-type value

ERL0 = energy release parameter, r_0

ERL1 = energy release parameter, r_1

ERL2 = energy release parameter, r_3

ERL4 = energy release parameter, r_4

MERL = 1.0

Energy release is zero.

E = 0.0

MERL = 2.0

Energy release is a Chapman-Jouguet explosive
(logic to be added)

MERL = 3.0, 4.0, 5.0

No models presently defined.

MERL = 6.0, 7.0, 8.0, 9.0, 10.0

User-supplied energy release models. Model logic is
programmed into subroutine MYERL.

HEAT FLOW MODEL

The heat flow model is made up of a conductivity (k) model and a specific heat capacity (C_v) model. Each model contributes to the heat flow calculation in a different way.

Conductivity Model

Correspondence between FORTRAN input names and scientific notation is shown below. ($k \geq 0$.)

MCON = conductivity model-type value
CON0 = conductivity parameter, k_0
CON1 = conductivity parameter, k_1
CON2 = conductivity parameter, k_2
CON3 = conductivity parameter, k_3
CON4 = conductivity parameter, k_4

MCON = 1.0

Conductivity is zero (no heat conduction model).

$k = 0.0$

MCON = 2.0

Conductivity is a constant.

$k = k_0$

MCON = 3.0

Conductivity is a function of temperature (T) only.

$$k = f(k_1, k_2, k_3, k_4, T)$$

The functional form f is the standard function given by the value k_0 (see Appendix "Functions"). For example, if $k_0 = 2.0$, then the conductivity model is

$$k = \frac{k_1 + k_2 T}{1 + k_3 T + k_4 T^2}$$

MCON = 4.0, 5.0

No models presently defined.

MCON = 6.0, 7.0, 8.0, 9.0, 10.0

User-supplied, conductivity models. Model logic is programmed into MYCON.

Specific Heat Capacity Model

Correspondence between FORTRAN input names and scientific notation is shown below. ($C_v \geq 0$.)

MSHC = specific heat capacity model-type value

SHC0 = specific heat capacity parameter, c_0

SHC1 = specific heat capacity parameter, c_1

SHC2 = specific heat capacity parameter, c_2

SHC3 = specific heat capacity parameter, c_3

SHC4 = specific heat capacity parameter, c_4

MSHC = 1.0

Specific heat capacity is zero.

$$C_V = 0.0$$

MSHC = 2.0

Specific heat capacity is a constant.

$$C_V = c_0$$

MSHC = 3.0

Specific heat capacity is a function of temperature (T) only.

$$T = f(c_1, c_2, c_3, c_4, T)$$

The functional form f is the standard function given by the value c_0 (see Appendix "Functions"). For example, if $c_0 = 2.0$, then the specific heat capacity model is

$$C_V = \frac{c_1 + c_2 T}{1 + c_3 T + c_4 T^2}$$

MSHC = 4.0, 5.0

No models presently defined.

MSHC = 6.0, 7.0, 8.0, 9.0, 10.0

User-supplied, specific heat capacity models. Model logic is programmed into MYSHC.

EXAMPLE OF USER-SUPPLIED MODEL

USER SUPPLIED MODEL FOR APPENDIX MAT

```

SUBROUTINE MYPRH
C
C      PURPOSE -
C      (*) CALCULATE THE PRESSURE
C      FROM A USER SPECIFIED MODEL
C
C      DATA IN -
C      (*) CMN VAR RLVN, /ZONVAR/
C      (*) CMN VAR DNSN, /ZONVAR/
C      (*) CMN VAR ZIEN, /ZONVAR/
C      (*) CMN VAR MCCYC, /PRBVAR/
C      (*) CMN VAR NFMSG, /PRBVAR/
C      (*) CMN VAR SSMIN, /PRBVAR/
C      (*) CMN VAR EOS2, /MATVAR/
C      (*) CMN VAR RDN, /MATVAR/
C
C      DATA OUT -
C      (*) CMN VAR PRHN, /ZONVAR/
C      (*) CMN VAR SSSN, /ZONVAR/
C      (*) CMN VAR NPHAN, /TWOPHA/
C
C      THIS IS A MIXED, TWO-PHASE EQUATION OF STATE FOR WATER.
C      49 POINTS DEFINE THE SATURATION LINE FOR WATER AND STEAM.
C      THE ROUTINE HAS A TABLE SEARCH THROUGH LINES OF CONSTANT
C      PRESSURE AND CONSTANT TEMPERATURE, FOLLOWED BY A LINEAR
C      INTERPOLATION BETWEEN LINES.
C      NPHAN IS THE NUMBER OF PHASES (1 OR 2)
C
C      ** *** THIS ROUTINE ASSUMES A REFERENCE DENSITY OF 1.0 **
C
C      *CALL ZONVAR
C
C      *CALL PRBVAR
C
C      *CALL TIMVAR
C
C      *CALL MATVAR
C
C      PHASE INDICATOR SWITCH
C      COMMON /TWOPHA/ NPHAN
C
C      TABLE VARIABLES
C      DIMENSION TSAT(49),PSAT(49),VSATF(49),VSATG(49),
1      ESATF(49),ESATG(49)
C
C      FIRST CALL SWITCH
C      DATA NSW /2/
C
C      START SEARCH SWITCH
C      DATA KSTART /2/
C
C      TSAT IS THE SATURATION TEMPERATURE (CELCIUS)
C      PSAT IS THE SATURATION PRESSURE (BARS)
C      VSATF IS THE SPECIFIC VOLUME OF SATURATED LIQUID (M**3/KG)
C      VSATG IS THE SPECIFIC VOLUME OF SATURATE VAPOR (M**3/KG)
C      ESATF IS THE ENERGY OF SATURATED LIQUID (J/KG)

```


C
C

ESATG IS THE ENERGY OF SATURATED VAPOR (J/KG)

DATA TSAT /

* 0.	1.000000E-02,	1.000000E+01,	2.000000E+01,
* 3.000000E+01,	4.000000E+01,	5.000000E+01,	6.000000E+01,
* 7.000000E+01,	8.000000E+01,	9.000000E+01,	1.000000E+02,
* 1.100000E+02,	1.200000E+02,	1.300000E+02,	1.400000E+02,
* 1.500000E+02,	1.600000E+02,	1.700000E+02,	1.800000E+02,
* 1.900000E+02,	2.000000E+02,	2.100000E+02,	2.200000E+02,
* 2.300000E+02,	2.400000E+02,	2.500000E+02,	2.577777E+02,
* 2.600000E+02,	2.622222E+02,	2.644444E+02,	2.666666E+02,
* 2.688888E+02,	2.700000E+02,	2.800000E+02,	2.900000E+02,
* 3.000000E+02,	3.100000E+02,	3.200000E+02,	3.300000E+02,
* 3.400000E+02,	3.500000E+02,	3.600000E+02,	3.700000E+02,
* 3.710000E+02,	3.720000E+02,	3.730000E+02,	3.740000E+02,
* 3.741500E+02			

*/

DATA PSAT /

* 6.108000E+02,	6.112000E+02,	1.227100E+03,	2.336800E+03,
* 4.241800E+03,	7.375000E+03,	1.233500E+04,	1.991900E+04,
* 3.116100E+04,	4.735800E+04,	7.010900E+04,	1.013250E+05,
* 1.432700E+05,	1.985400E+05,	2.701100E+05,	3.613600E+05,
* 4.759700E+05,	6.180400E+05,	7.920200E+05,	1.002700E+06,
* 1.255300E+06,	1.555000E+06,	1.908000E+06,	2.320200E+06,
* 2.797900E+06,	3.348000E+06,	3.977600E+06,	4.527170E+06,
* 4.694360E+06,	4.866180E+06,	5.042830E+06,	5.224300E+06,
* 5.410730E+06,	5.505810E+06,	6.419100E+06,	7.444900E+06,
* 8.591700E+06,	9.869400E+06,	1.128900E+07,	1.286400E+07,
* 1.460800E+07,	1.653700E+07,	1.867400E+07,	2.105300E+07,
* 2.130600E+07,	2.156300E+07,	2.182000E+07,	2.209000E+07,
* 2.210000E+07			

*/

DATA VSATF /

* 1.000210E-03,	1.000210E-03,	1.000400E-03,	1.001800E-03,
* 1.004400E-03,	1.007900E-03,	1.012100E-03,	1.017100E-03,
* 1.022800E-03,	1.029000E-03,	1.035900E-03,	1.043500E-03,
* 1.051500E-03,	1.060300E-03,	1.069700E-03,	1.079800E-03,
* 1.090600E-03,	1.102100E-03,	1.114400E-03,	1.127500E-03,
* 1.141500E-03,	1.156500E-03,	1.172600E-03,	1.190000E-03,
* 1.208700E-03,	1.229100E-03,	1.251200E-03,	1.269800E-03,
* 1.275400E-03,	1.281600E-03,	1.287300E-03,	1.293500E-03,
* 1.299100E-03,	1.302200E-03,	1.332100E-03,	1.365500E-03,
* 1.403600E-03,	1.447500E-03,	1.499200E-03,	1.562000E-03,
* 1.639000E-03,	1.741000E-03,	1.894000E-03,	2.220000E-03,
* 2.290000E-03,	2.380000E-03,	2.510000E-03,	2.800000E-03,
* 3.170000E-03			

*/

DATA VSATG /

* 2.062880E+02,	2.061460E+02,	1.064220E+02,	5.783600E+01,
* 3.292900E+01,	1.954600E+01,	1.204500E+01,	7.677600E+00,
* 5.045300E+00,	3.408300E+00,	2.360900E+00,	1.673000E+00,
* 1.210100E+00,	8.917100E-01,	6.683200E-01,	5.086600E-01,
* 3.925700E-01,	3.068500E-01,	2.426200E-01,	1.938500E-01,
* 1.563500E-01,	1.271900E-01,	1.042650E-01,	8.606200E-02,
* 7.147200E-02,	5.967400E-02,	5.005600E-02,	4.376200E-02,
* 4.213400E-02,	4.057300E-02,	3.907500E-02,	3.763700E-02,
* 3.625800E-02,	3.558800E-02,	3.013300E-02,	2.553700E-02,
* 2.164300E-02,	1.831600E-02,	1.545100E-02,	1.296700E-02,
* 1.077900E-02,	8.805000E-03,	6.943000E-03,	4.930000E-03,
* 4.680000E-03,	4.400000E-03,	4.050000E-03,	3.470000E-03,

```

* 3.170000E-03
* /
DATA ESATF /
* -4.221093E+01, -3.284131E-04, 4.198877E+04, 8.385766E+04,
* 1.256557E+05, 1.674626E+05, 2.092875E+05, 2.510797E+05,
* 2.929681E+05, 3.348513E+05, 3.768274E+05, 4.189943E+05,
* 4.611494E+05, 5.034895E+05, 5.460111E+05, 5.887098E+05,
* 6.316809E+05, 6.748189E+05, 7.182174E+05, 7.619695E+05,
* 8.060671E+05, 8.506016E+05, 8.954627E+05, 9.409390E+05,
* 9.869182E+05, 1.033485E+06, 1.080823E+06, 1.118171E+06,
* 1.128873E+06, 1.139784E+06, 1.150698E+06, 1.161592E+06,
* 1.172481E+06, 1.178160E+06, 1.228249E+06, 1.279834E+06,
* 1.332941E+06, 1.387714E+06, 1.445076E+06, 1.505906E+06,
* 1.572057E+06, 1.643209E+06, 1.726631E+06, 1.845262E+06,
* 1.864209E+06, 1.885680E+06, 1.914232E+06, 1.970148E+06,
* 2.024880E+06
* /
DATA ESATG /
* 2.374999E+06, 2.375004E+06, 2.388410E+06, 2.402849E+06,
* 2.416322E+06, 2.429848E+06, 2.443425E+06, 2.456070E+06,
* 2.468783E+06, 2.481590E+06, 2.494480E+06, 2.506483E+06,
* 2.517629E+06, 2.528960E+06, 2.539480E+06, 2.550191E+06,
* 2.560148E+06, 2.568354E+06, 2.576840E+06, 2.583627E+06,
* 2.589734E+06, 2.595220E+06, 2.599062E+06, 2.602319E+06,
* 2.603028E+06, 2.603211E+06, 2.601897E+06, 2.599362E+06,
* 2.598528E+06, 2.597714E+06, 2.596711E+06, 2.595733E+06,
* 2.594548E+06, 2.593859E+06, 2.586573E+06, 2.575880E+06,
* 2.563050E+06, 2.546232E+06, 2.525574E+06, 2.499193E+06,
* 2.465540E+06, 2.419392E+06, 2.351346E+06, 2.227209E+06,
* 2.205288E+06, 2.178123E+06, 2.141629E+06, 2.069348E+06,
* 2.024880E+06
* /

```

```

C
NAMELIST /EOSDUMP/ RLVN, ZIEN, PRHN, KK, LL, K, L, VF1, VF2,
* VG1, VG2, EF1, EF2, EG1, EG2, VFG1, VFG2, VF12, VG12, VFG12,
* EFG1, EFG2, EF12, EG12, EFG12, A, B, C, DIS, SOL1, SOL2,
* NSLIM1, NSLIM2, VF, VG, EF, EG, QTY, PRAT, DBDV, DCDV, SSSN,
* NPHAN

```

```

C
C LOCAL STORAGE FOR SUBROUTINE NAME

```

```

DATA NSBLFT, NSBRHT/3H MY,3HPRH/

```

```

*CALL ENTSBR

```

```

C
C CONVERT TABLE VALUES TO CORRECT PROBLEM
C UNITS ON FIRST CALL ONLY

```

```

IF(NSW.NE.2) GO TO 100

```

```

NSW = 1

```

```

DO 20 L=1,49

```

```

PSAT(L) = 1.0E-05 * PSAT(L)

```

```

VSATF(L) = 1.0E+03 * VSATF(L)

```

```

VSATG(L) = 1.0E+03 * VSATG(L)

```

```

ESATF(L) = 1.0E-02 * ESATF(L)

```

```

ESATG(L) = 1.0E-02 * ESATG(L)

```

```

20 CONTINUE

```

```

WRITE(NFMSG,25)(TSAT(L),PSAT(L),VSATF(L),VSATG(L),

```

```

1 ESATF(L),ESATG(L),L=1,49)

```

```

25 FORMAT(1H1,33X,24HSATURATION LINE (METRIC),///4X,11HTEMPERATURE,
15X,8HPRESSURE,14X,16HVOLUME (M**3/KG),7X,

```

```

* 22HINTERNAL ENERGY (J/KG),

```

```

2 /4X,11H (DEG C) ,5X,8H (PA) ,9X,5HWATER,10X,5HSTEAM,10X,

```

```

35HWATER,10X,5HSTEAM/(1P6E15.5))
C
C      ZIEN IS THE ZONE INTERNAL ENERGY
C      RLVN IS THE ZONE RELATIVE VOLUME
C      QTY IS THE QUALITY
100 CONTINUE
C
C      CHECK REFERENCE DENSITY
IF(ABS(RDN - 1.0).LE.1.E-6) GO TO 105
WRITE(NFMSG,1005)
*      RDN
*      WRITE(NFPRT,1005)
*      RDN
1005 FORMAT
*      (/
*      /10X,10H E R R O R
*      /10X,29HREFERENCE DENSITY MUST BE 1.0
*      /10X, 8HVALUE IS, 1PE15.8
*      )
NSERR = 4
NSEXT = 4
GO TO 990
105 ESATVOL= .0
PSATVOL= .0
VSATZIE= .0
PSATZIE= .0
NSWRAP = 1
C
C      SEARCH THROUGH TABLE FOR A PAIR OF ADJACENT ENTRIES
C      WHOSE PRESSURES BRACKET AN INTERPOLATED PRESSURE BASED
C      ON QUALITY
C      SEARCH FOR PAIR OF ADJACENT TABLE ENTRIES SUCH THAT 0<PRAT<1
106 DO 110 KK=KSTART,48
LL = KK - 1
VF1 = VSATF(LL)
VG1 = VSATG(LL)
VF2 = VSATF(KK)
VG2 = VSATG(KK)
VFG1 = VG1 - VF1
VFG2 = VG2 - VF2
VF12 = VF2 - VF1
VG12 = VG2 - VG1
VFG12 = VG12 - VF12
EF1 = ESATF(LL)
EG1 = ESATG(LL)
EF2 = ESATF(KK)
EG2 = ESATG(KK)
EFG1 = EG1 - EF1
EFG2 = EG2 - EF2
EF12 = EF2 - EF1
EG12 = EG2 - EG1
EFG12 = EG12 - EF12
A = - VF12 * EFG12 + VFG12 * EF12
B = - VF12 * EFG1 + (RLVN - VF1) * EFG12 -
*      VFG12 * (ZIEN - EF1) + VFG1 * EF12
C = (RLVN - VF1) * EFG1 - VFG1 * (ZIEN - EF1)
DIS = B ** 2 - 4.0 * A * C
IF(DIS.LT.0.0) GO TO 110
SQDIS = SQRT(DIS)
SOL1 = (- B + SQDIS) / (2.0 * A)

```

```

      SOL2 = (- B - SQDIS) / (2.0 * A)
      NSLIM1 = 0
      NSLIM2 = 0
      IF(SOL1.GE.0..AND.SOL1.LE.1.) NSLIM1 = 1
      IF(SOL2.GE.0..AND.SOL2.LE.1.) NSLIM2 = 1
      IF(NSLIM1.EQ.0.AND.NSLIM2.EQ.0) GO TO 110
      IF(NSLIM1.EQ.1.AND.NSLIM2.EQ.1) GO TO 500
      PRAT = SOL1
      IF(NSLIM2.EQ.1) PRAT = SOL2
      GO TO 120
110 CONTINUE
C
C      TABLE ENTRY NOT FOUND -- TRY WRAPAROUND FROM BOTTOM
      IF(NSWRAP.EQ.2) GO TO 1000
      NSWRAP = 2
      KSTART = 2
      GO TO 106
120 VF = VF1 + PRAT * VF12
      VG = VG1 + PRAT * VG12
      EF = EF1 + PRAT * EF12
      EG = EG1 + PRAT * EG12
      QTY = (RLVN - VF) / (VG - VF)
      KSTART = KK - 2
      IF(QTY.LT.0.) GO TO 250
      IF(QTY.GT.1.) GO TO 1000
C
C      2-PHASE
      PRHN = PSAT(LL) + PRAT * (PSAT(KK) - PSAT(LL))
C
C      FIND 2-PHASE SOUND SPEED
      DBDV = EFG12 + PRHN * VFG12
      DCDV = EFG1 + PRHN * VFG1
      SSSN = RLVN ** 2 * (PSAT(KK) - PSAT(LL)) *
      * (PRAT * DBDV + DCDV) / (2.0 * A * PRAT + B)
      NPHAN = 2
      GO TO 300
C
C      1-PHASE
C      FIND SATURATED STATE WITH THIS ENERGY
250 DO 260 K=KK,49
      IF(ZIEN.LE.ESATF(K)) GO TO 270
260 CONTINUE
      GO TO 1000
270 L = K - 1
      VSATZIE = VSATF(L) + (VSATF(K) - VSATF(L)) *
      * (ZIEN - ESATF(L)) / (ESATF(K) - ESATF(L))
      PSATZIE = PSAT(L) + (PSAT(K) - PSAT(L)) *
      * (ZIEN - ESATF(L)) / (ESATF(K) - ESATF(L))
C
C      COMPRESS ALONG LINE OF CONSTANT ENERGY
      PRHN = PSATZIE + EOS2 * (1.0 / RLVN - 1.0 / VSATZIE)
      SSSN = EOS2
      NPHAN = 1
C
C      CHECK FOR MINIMUM SOUND SPEED
300 IF(SSSN.LT.SSSMIN) SSSN = SSSMIN
      DPDV = -SSSN * DNSN * DNSN
      GO TO 990
C
C      TWO ROOTS FOUND

```

```

500 PRINT *, 13H2 ROOTS FOUND, SOL1, SOL2
    WRITE(NFMSG,EOSDUMP)
    NSERR = 2
    NSEXT = 2
    GO TO 990

C
C      INTERNAL ENERGY IS ABOVE THE SATURATION LINE
C      AND QUALITY IS ALWAYS BETWEEN ZERO AND ONE
1000 CONTINUE
    WRITE(NFMSG,1010)
1010 FORMAT(33H ZONE STATE OUT OF RANGE OF TABLE    )
    WRITE(NFMSG,EOSDUMP)
    NSERR = 2
    NSEXT = 2

C
*CALL EXTSBR
C
C      END OF SUBROUTINE MYPRH
C      RETURN
C      END

```

APPENDIX
MAXIMUMS (MAX)

Variable	Maximum		Description
	1D	2D	
MAXGRD	25	25	Maximum grids allowed
MAXBLK	75	75	Maximum blocks allowed
MAXMAT	10	10	Maximum materials allowed
MAXGPT	200	51	Maximum grid points allowed (I-lines)
MAXZON	199	51	Maximum zones allowed
MAXRZN	100	100	Maximum rezoned zones allowed
MAXBDY	50	50	Maximum boundary value locations allowed
MAXMBD	10	10	Maximum momentum boundary data allowed
MAXTBD	10	10	Maximum thermal boundary data allowed
MAXWPT	100	100	Maximum wall points allowed
MAXREG	20	20	Maximum regions allowed
MAXPRT	100	100	Maximum print edits allowed
MAXRSY	100	100	Maximum regional summary edits allowed
MAXRST	100	100	Maximum restart edits allowed
MAXARV	200	200	Maximum archive edits allowed
MAXDBG	100	100	Maximum debug edits allowed
MAXPLT	100	100	Maximum plots allowed
MAXEDT	40	40	Maximum edit specifications allowed
MAXSEG	25	25	Maximum segments allowed
MAXVAR	100	100	Maximum variables allowed
MAXBUF	1000	1000	Maximum buffers allowed (J-lines)
MAXTTL	70	70	Maximum title characters allowed
MAXCDN	24	24	Maximum code name characters allowed
MAXDAT	6	6	Maximum date characters allowed
MAXTIM	6	6	Maximum time characters allowed
MAXEOS	10	10	Maximum equation-of-state models allowed
MAXYLD	10	10	Maximum yield models allowed
MAXSHR	10	10	Maximum shear modulus models allowed
MAXSPL	10	10	Maximum spall models allowed
MAXERL	10	10	Maximum energy release models allowed
MAXCON	10	10	Maximum conductivity models allowed
MAXSHC	10	10	Maximum specific heat capacity models allowed
MAXPBP	100	100	Maximum point-by-point initializations allowed

APPENDIX
MESSAGES (MSG)

CHRRERR message

```
*****  
E R R O R  
INPUT TYPE  
CHARACTER NAME aaa  
IS INCORRECT.  
ERROR OCCURRED IN SUBROUTINE *aaaaaa*  
*****
```

FLDERR message

```
*****  
E R R O R  
FIELD i  
ON INPUT RECORD TYPE iii  
HAS A VALUE eeeeeeeeeeee  
WHEN IT SHOULD BE ZERO OR BLANK.  
ERROR OCCURRED IN SUBROUTINE *aaaaaa*  
*****
```

LIMERR message

```
*****  
E R R O R  
INPUT RECORD TYPE iii  
HAS INCORRECT LIMITS.  
FIELD i CONTAINS MINIMUM VALUE iiiiii  
FIELD i CONTAINS MAXIMUM VALUE iiiiii  
ERROR OCCURRED IN SUBROUTINE *aaaaaa*  
*****
```

MDLERR message

```
*****  
E R R O R  
MODEL NUMBER ii  
IS NOT ALLOWED.  
ERROR OCCURRED IN SUBROUTINE *aaaaaa*  
*****
```


RGEERR message

```
*****  
E R R O R  
FIELD NUMBER i  
ON INPUT RECORD TYPE iii  
HAS A VALUE OUT OF PERMISSIBLE RANGE.  
THE VALUE = iiiiii  
MIN VALUE = iiiiii  
MAX VALUE = iiiiii  
ERROR OCCURRED IN SUBROUTINE *aaaaaaa*  
*****
```

SBRERR message

```
*****  
E R R O R  
NO LOGIC IN SUBROUTINE *aaaaaaa*  
*****
```

TYPERR message

```
*****  
E R R O R  
INPUT TYPE iii  
IS INCORRECT.  
FIRST  
DIGIT OF INPUT TYPE  
IS OUT OF PERMISSIBLE RANGE  
VALUE IS i  
RANGE IS 1 TO 6  
SECOND  
DIGIT OF INPUT TYPE  
IS OUT OF PERMISSIBLE RANGE  
VALUE IS i  
RANGE IS 1 TO 8  
THIRD  
DIGIT OF INPUT TYPE  
IS OUT OF PERMISSIBLE RANGE  
VALUE IS i  
RANGE IS 1 TO 9  
ERROR OCCURRED IN SUBROUTINE *aaaaaaa*  
*****
```

FLDCHK message

FIELD i ON INPUT RECORD aaa
CONTAINS A NON-ZERO VALUE eeeeeeeeeeeeee
ITS VALUE SHOULD HAVE BEEN ZERO OR
THE FIELD SHOULD HAVE BEEN LEFT BLANK.

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