

## **US-APWR**

# **Evaluation on Jet Impingement Issues Associated with Postulated Pipe Rupture**

**Non-Proprietary Version**

**May 2012**

**©2012 Mitsubishi Heavy Industries, Ltd.**

**All Rights Reserved**

**REVISION HISTORY**

Revision	Page	Description
0	All	Original Issue
1	Abstract 1 33 to 35 36 to 42 A3-1 to A3-21 A4-1 to A4-9 A5-1 to A5-12 A6-1 to A6-23	Changed the contents Changed the section 1 Changed all contents of section 3.3 Added Section 3.4 Added Appendix 3 Added Appendix 4 Added Appendix 5 Added Appendix 6
2	Abstract 24 to 26  40 46 47 52 53 57  54, 57 57, 57	Change the contents Added Section 2.4 , 2.4.1 and 2.4.2 and Figure 2-24 about blast wave evaluation Revised Figure 3-10 Revised the contents of section 3.4.4 Added Table 3-3 Revised the contents of section 4.1 Revised Figure 4-8 Deleted Equation 4-1 in Page 50 of previous revision due to typo Changed the title of section 4.1.1 and 4.1.2 Added Section 4.1.1 i) and 4.1.2 i)

**© 2012**

**MITSUBISHI HEAVY INDUSTRIES, LTD.**

All Rights Reserved

This document has been prepared by Mitsubishi Heavy Industries, Ltd. ("MHI") in connection with the U.S. Nuclear Regulatory Commission's ("NRC") licensing review of MHI's US-APWR nuclear power plant design. No right to disclose, use or copy any of the information in this document, other than that by the NRC and its contractors in support of the licensing review of the US-APWR, is authorized without the express written permission of MHI.

This document contains technology information and intellectual property relating to the US-APWR and it is delivered to the NRC on the express condition that it not be disclosed, copied or reproduced in whole or in part, or used for the benefit of anyone other than MHI without the express written permission of MHI, except as set forth in the previous paragraph.

This document is protected by the laws of Japan, U.S. copyright law, international treaties and conventions, and the applicable laws of any country where it is being used.

MITSUBISHI HEAVY INDUSTRIES, LTD.  
16-5, Konan 2-chome, Minato-ku  
Tokyo 108-8215 Japan

## **ABSTRACT**

Pipe rupture protection design is implemented to conform to Title 10 Code of Federal Regulations Part50, Appendix-A, General Design Criteria 4. The evaluation requirements and design policy described in this report are based on a defense-in-depth approach. The calculation method for the thrust force and jet impingement force are described in a Technical Report "MUAP-10017".

This report describes blast wave, jet pressure oscillation, and jet reflection calculation methodology.

The steam break blast wave is evaluated using CFD analysis with an instantaneous pipe break assumption. In the US-APWR, the term "steam piping" refers to the piping connected to the pressurizer upper head. Analysis, including consideration of plant layout, indicates that the blast wave does not impact the stress intensity of the SSCs and has no impact on the protection design. The change of layout in the future is considered, the evaluation methodology for blast wave is also provided.

Jet pressure oscillation is unlikely at the US-APWR operating pressures because the large jet flow expansion and large Mach Disk produce a stable downstream condition. Under such conditions, feedback from a disturbance at an impingement wall is unlikely. However, It is conservatively assumed that a jet pressure oscillation occurs through full blowdown process. The evaluation for jet pressure oscillation is provided.

When jet flow impinges on a wall, the impinging jet flow is redirected along the surface of the wall forming what is called the zone of influence (ZOI). Inside the ZOI, the impingement pressure includes effect of pressure due to flow parallel to the wall. Loads due to jet impingement reflection inside the ZOI are negligible. This report considers jet impingement on a parallel wall and the more likely case of an oblique.

---

## TABLE OF CONTENTS

LIST OF TABLES .....	iii
LIST OF FIGURES .....	iv
LIST OF ACRONYMS .....	vi
1.0 OVERVIEW .....	1
2.0 BLAST WAVE .....	2
2.1 BLAST WAVE OF STEAM PIPING .....	2
2.1.1 Free Blast Wave .....	2
2.1.2 Reflection of Blast Wave .....	7
2.2 BLAST WAVE OF SUB-COOLED WATER PIPING .....	14
2.3 BLAST WAVE ASSESSMENT IN US-APWR .....	16
2.3.1 Pressureizer Upper Piping Structure Integrity .....	16
2.3.2 Instrument Piping Structure Integrity .....	17
2.3.3 Reflection Amplification .....	17
2.3.4 Reflection Repititation .....	17
2.4 BLAST WAVE EVALUATION .....	24
2.4.1 Scope of Evaluation .....	26
2.4.2 Load of Blast Wave .....	26
3.0 JET PRESSURE OSCILLATION .....	27
3.1 STEAM PIPING .....	27
3.2 SUB-COOLED WATER PIPING .....	34
3.3 EFFECT OF SOURCE CONDITION CHANGE .....	36
3.4 EVALUATION OF JET PRESSURE OSCILLATION .....	39

---

3.4.1	Scope of Evaluation .....	41
3.4.2	Jet Load of Jet Pressure Oscillation Evaluation .....	42
3.4.3	Modeling.....	46
3.4.4	Acceptance Criteria .....	46
4.0	JET REFLECTION .....	48
4.1	JET REFLECTION EVALUATION.....	52
4.1.1	Scope of Evaluation .....	54
4.1.2	Load of Reflection Jet.....	57
5.0	REFERENCES.....	59

**APPENDIX**

Appendix1	Simplified Blast Wave Model .....	A1-1
Appendix2	Convergence Condition .....	A2-1
Appendix3	Outline of Blowdown Analysis .....	A3-1
Appendix4	Simple Beam Methodology in Consideration of Resonating High Frequency Mode .....	A4-1
Appendix5	Frequency of Jet Pressure Oscillation .....	A5-1
Appendix6	Example of Structural Analysis for Jet Pressure Oscillation .....	A6-1

**LIST OF TABLES**

Table 2-1	Comparison between Simplified Model and CFD	7
Table 2-2	Piping Specification	19
Table 3-1	Maximum Pressure of Single Phase Steam at Interval Stage	38
Table 3-2 (1/4)	Magnification Factor of Natural Frequency 5 Hz of Piping	39
Table 3-2 (2/4)	Magnification Factor of Natural Frequency 10 Hz of Piping	39
Table 3-2 (3/4)	Magnification Factor of Natural Frequency 15 Hz of Piping	40
Table 3-2 (4/4)	Magnification Factor of Natural Frequency 20 Hz of Piping	40
Table 3-3	Design Criteria and Load Combination	53

## LIST OF FIGURES

Figure 2-1	Blast Wave Simplified Model	3
Figure 2-2	Analysis Model	4
Figure 2-3	Blast Wave Pressure Contour	5
Figure 2-4	Blast Wave Static Pressure Distribution along Jet Axis	5
Figure 2-5	Blast Wave Pressure Attenuation by Distance	6
Figure 2-6	Relation between Incident Pressure Ratio and Reflection Amplification Factor	9
Figure 2-7	Front Reflection Analysis Model Outline	9
Figure 2-8	Distribution of Incident Pressure $p_s$ and Reflection Pressure $p_r$ for Front Reflection	10
Figure 2-9	Distribution of Reflection Amplification Factor for Front Reflection	10
Figure 2-10	Corner Reflection Analysis Model	11
Figure 2-11	Blast Wave Contour for Case of Reflection at Corner in Static Pressure	12
Figure 2-12	Relation between $r/d$ and Peak Pressure	13
Figure 2-13	Relation between $r/d$ and Reflection Amplification Factor	13
Figure 2-14	Sound Speed of Liquid-Gas Two Phase Flow	15
Figure 2-15	Piping Layouts at Upper Portion of Pressurizer	18
Figure 2-16	Case of Closest Distance between Break & Target Points	19
Figure 2-17	Piping Analysis Stress Model	20
Figure 2-18	Load Application Image	20
Figure 2-19	Example of Time History of Pressure Load(Piping Center Part)	21
Figure 2-20	Time History of Piping Stress (Piping Center)	21
Figure 2-21	Instrument Piping in Pressurizer Compartment	22
Figure 2-22	Closest Location from Break Point to Wall	23
Figure 2-23	Internal Size of Pressurizer Compartment	23
Figure 2-24	Evaluation Process of Blast Wave	25
Figure 2-25	Load image of Blast Wave	26
Figure 3-1	Relationship between Distance from Nozzle to Impingement Wall and Pressure Distribution at Impingement Wall	29
Figure 3-2	Pressure Distribution of Flat-Plate Impingement (D = nozzle diameter d)	30
Figure 3-3	Mechanizum of Generating Re-Circulation Flow	31
Figure 3-4	Relationship between Concave-Type Pressure Distribution Range and Pressure Oscillation Range(Reference 6-10)	32
Figure 3-5	Time-Freeze Planar Laser-induced Fluorescence(PLIF) Images of Jet	33
Figure 3-6	Flow Velocity Contour under PWR Condition with Sub-Cooling: 20°C	35



---

Figure 3-7	Steam Piping (Single Phase Flow)	35
Figure 3-8	Impingement Jet and Wall Pressure Distribution of Pressurized Hot Water (D = nozzle diameter d)	36
Figure 3-9	Jet Pressure after Blowdown in 8-inch Break Blowdown	37
Figure 3-10	Evaluation Process of Jet Pressure Oscillation	40
Figure 3-11	Load Time Histories of Jet Pressure Oscillation	45
Figure 4-1	Behavior of Jet Flow Impinging on a Perpendicular Surface	49
Figure 4-2	Front Reflection Analysis Model Outline	49
Figure 4-3	Expansion of Steam Jet	50
Figure 4-4	Speed Distribution of Flow Jet	50
Figure 4-5	Density of Flow Jet	50
Figure 4-6	Speed Distribution in Jet Flow Radiating along Wall at a Cross Section Parallel to Wall	51
Figure 4-7	Radial Force in Jet Flow Radiating along Wall	51
Figure 4-8	Evaluation Process of Jet reflection	53
Figure 4-9	Reflection Jet Expansion Model	55
Figure 4-10	Evaluation Range (Bird-Eye View)	56
Figure 4-11	Reflection Jet Model	58
Figure 4-12	Reflection Jet Model (Bird-Eye View)	58

## **LIST OF ACRONYMS**

The following list defines the acronyms used in this document.

MHI	Mitsubishi Heavy Industries, Ltd.
NRC	U.S. Nuclear Regulatory Commission
CFR	Code of Federal Regulations
GDC	General Design Criteria
CFD	Computer Fluid Dynamic
RCL	Reactor Coolant Loop
PLIF	Planar Laser-induced Fluorescence
ZOI	Zone of Influence
RCL	Reactor Coolant Loop
RCPB	Reactor Coolant Pressure Boundary

**1.0 OVERVIEW**



**2.0 BLAST WAVE**

**2.1 Blast Wave of Steam Piping**

**2.1.1 Free Blast Wave**

**2.1.1.1 Blast Wave Simplified Model**



**Figure 2-1 Blast Wave Simplified Model**

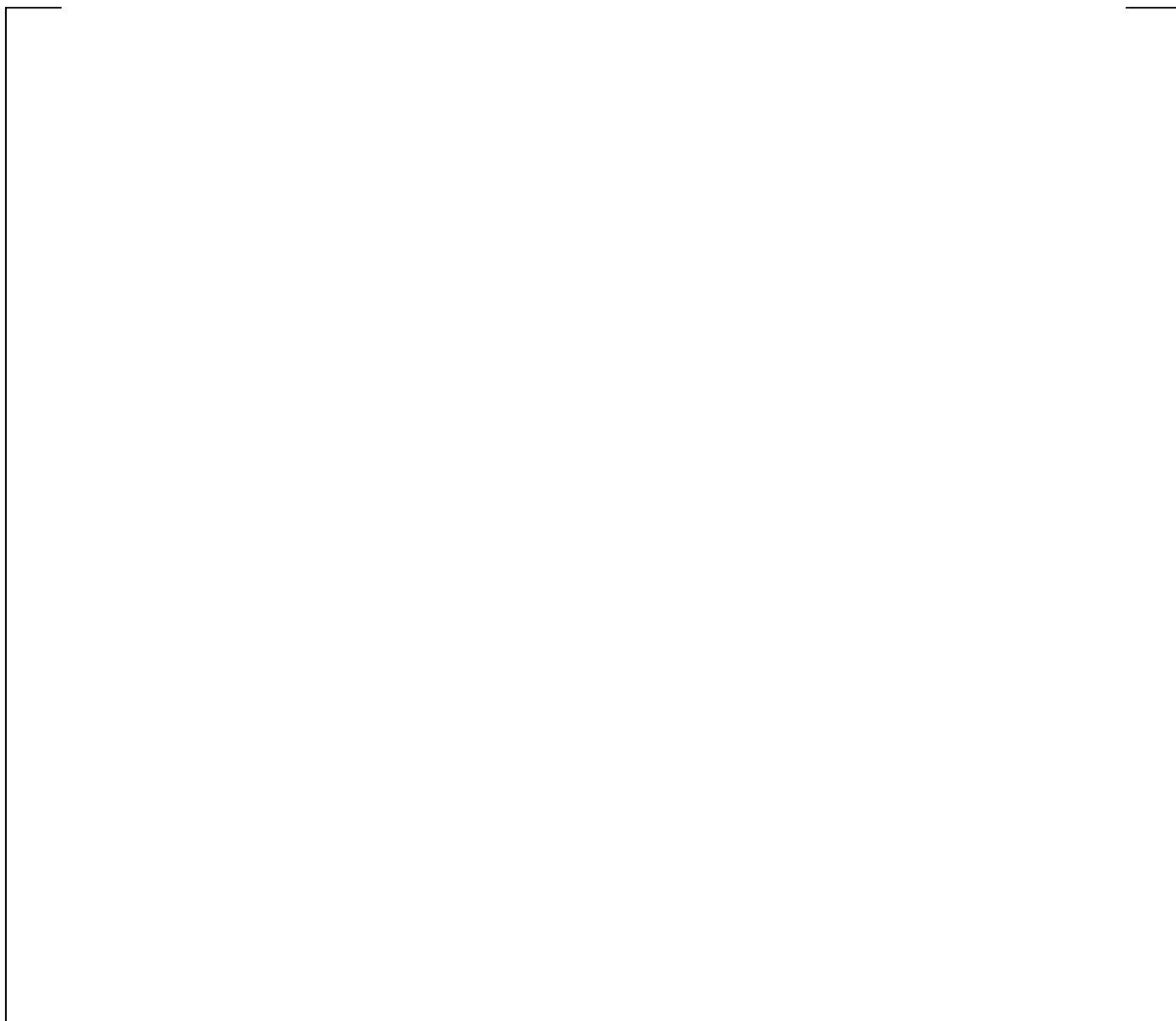
**2.1.1.2 CFD Analysis**

**a. Model Outline**



**b. Result**

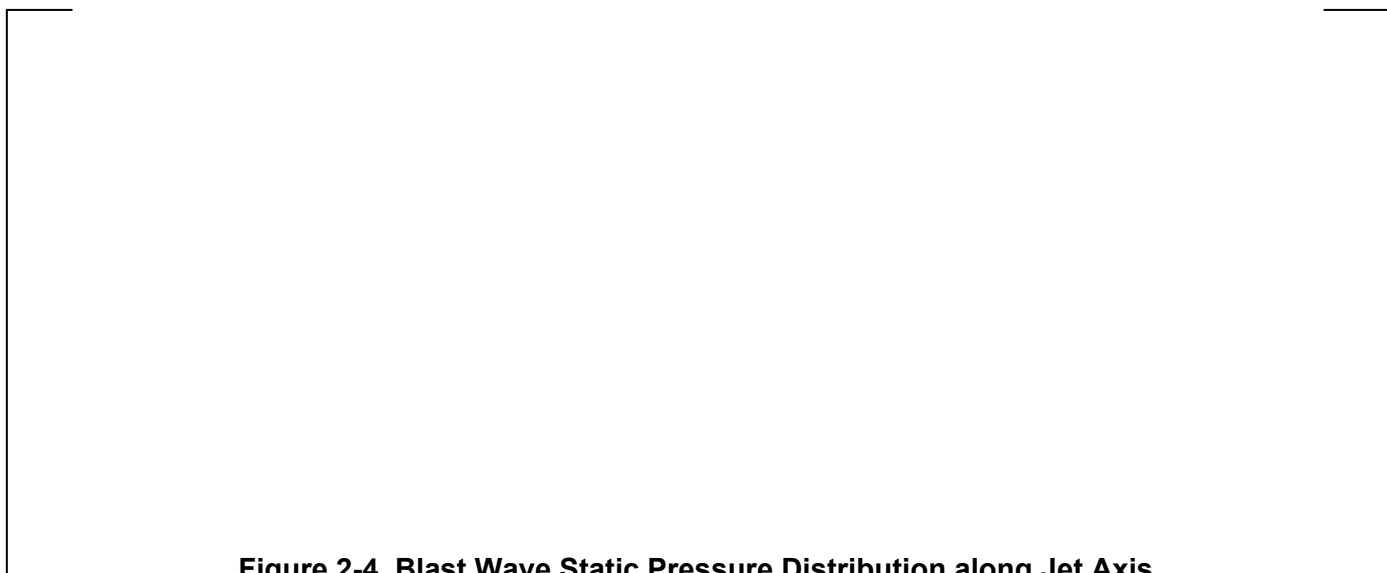




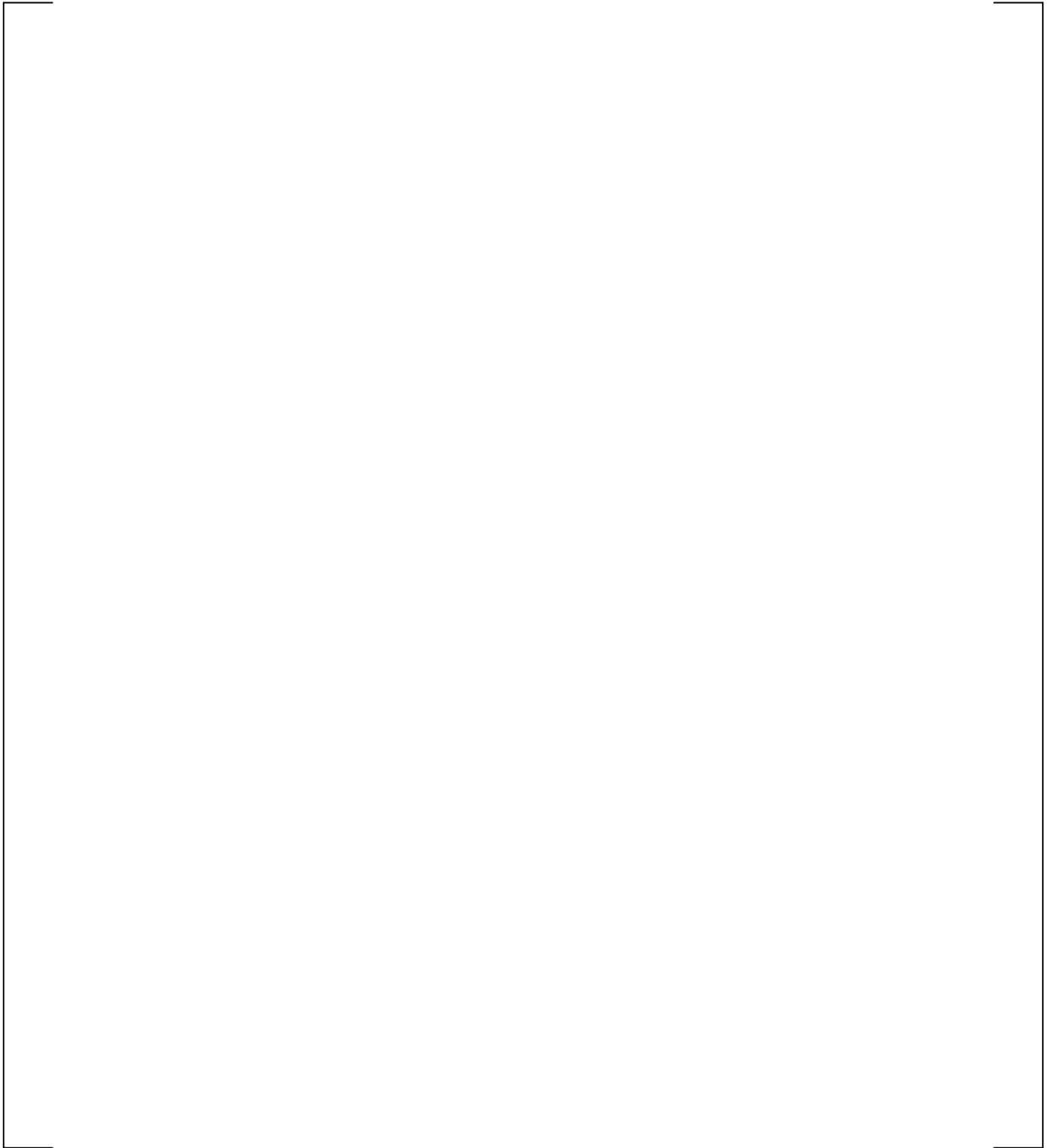
**Figure 2-2 Analysis Model**



**Figure 2-3 Blast Wave Pressure Contour**



**Figure 2-4 Blast Wave Static Pressure Distribution along Jet Axis**



**Figure 2-5 Blast Wave Pressure Attenuation by Distance**



**Table 2-1 Comparison between Simplified Model and CFD**

--	--

**2.1.2 Reflection of Blast Wave**

**2.1.2.1 Front Wall Reflection**

--	--

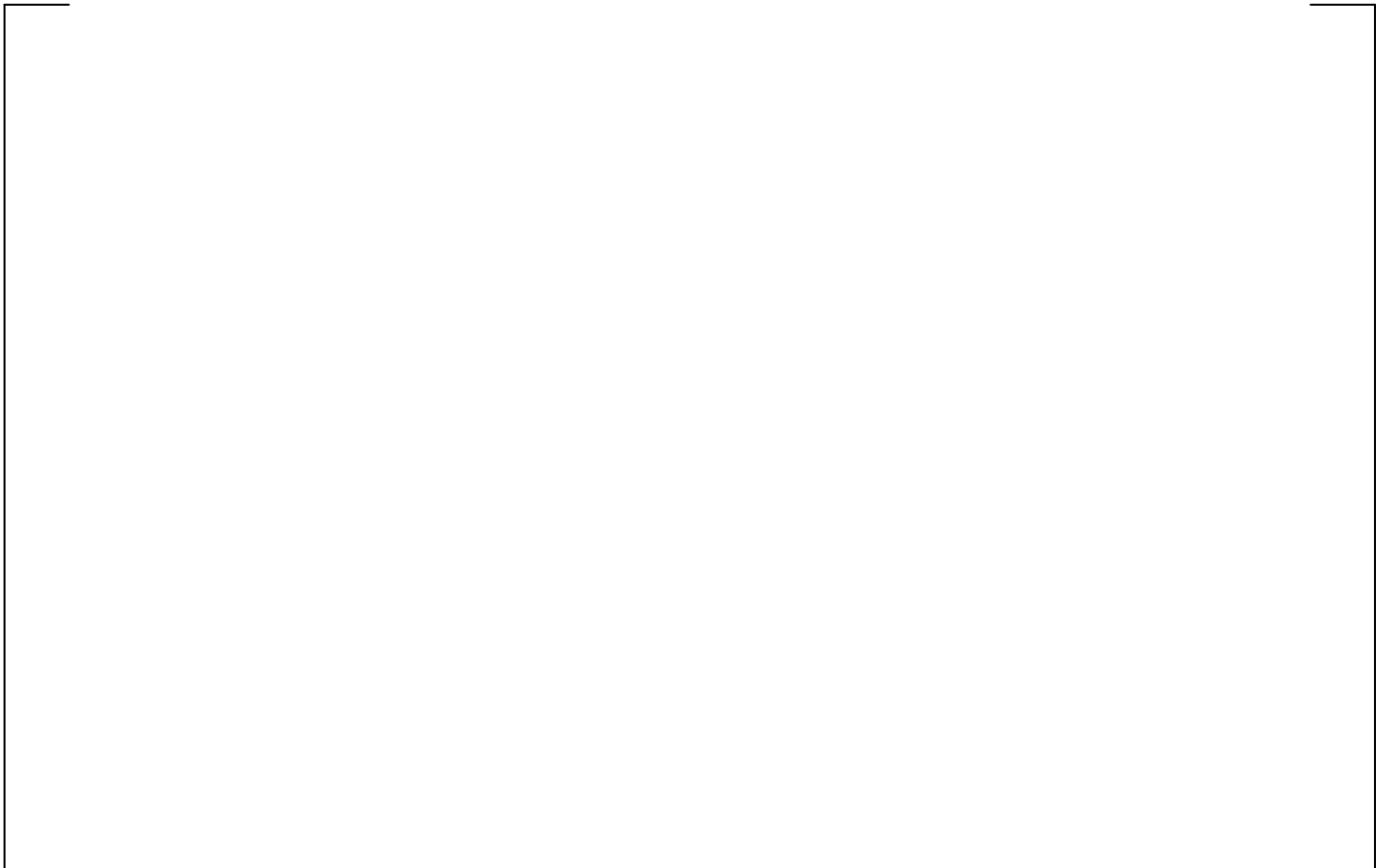


**2.1.2.2 Front and Side Wall Reflection**

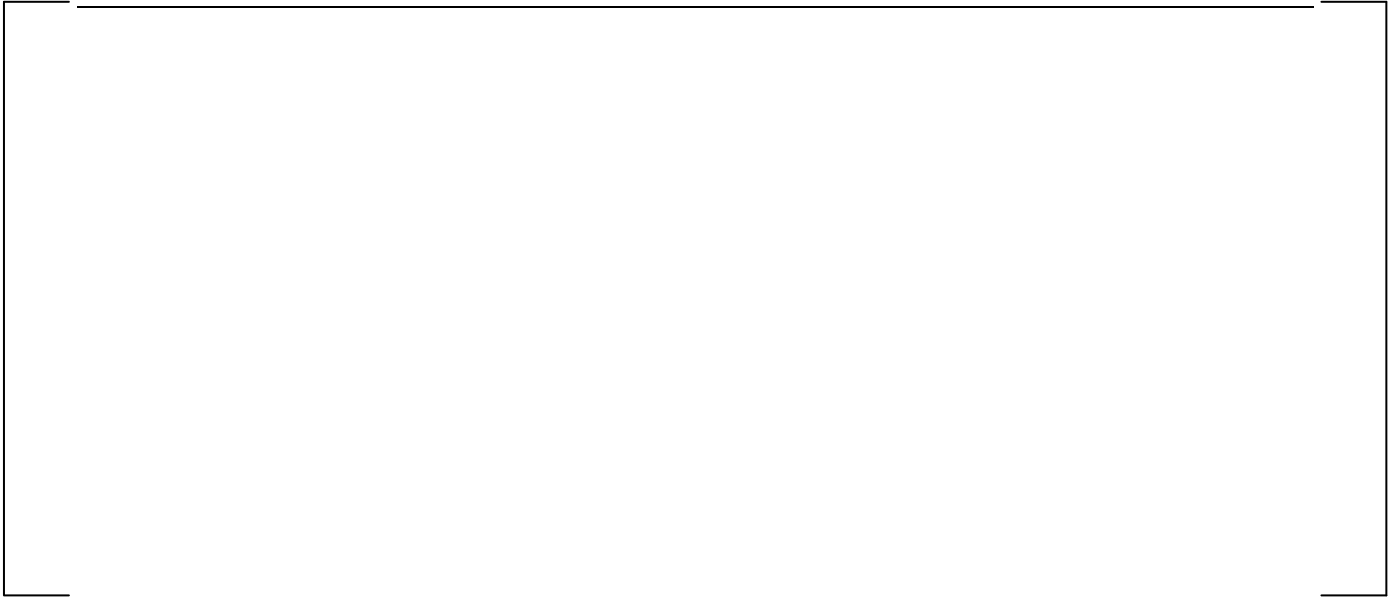




**Figure 2-6 Relation between Incident Pressure Ratio and Reflection Amplification Factor**



**Figure 2-7 Front Reflection Analysis Model Outline**



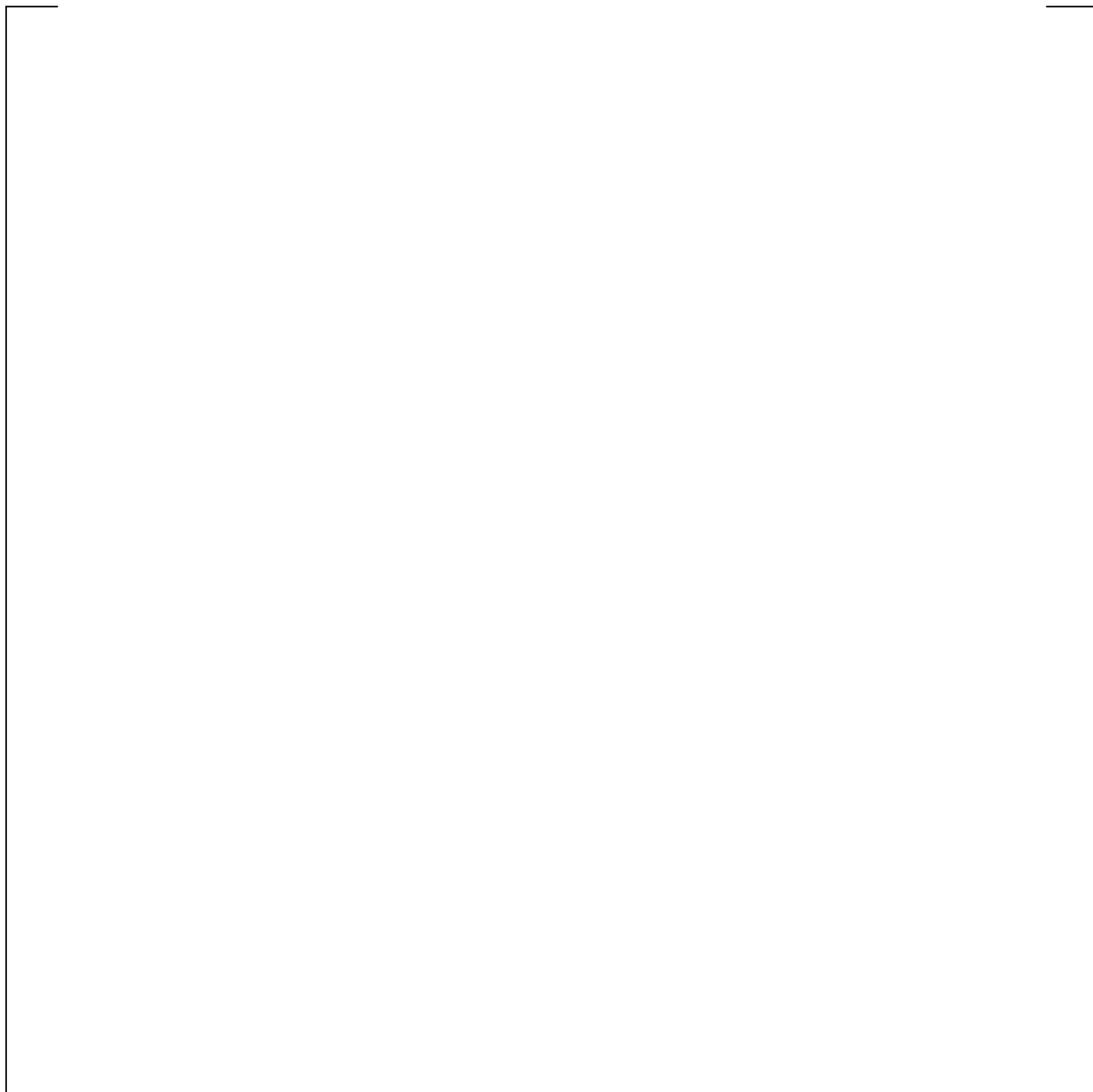
**Figure 2-8 Distribution of Incident Pressure  $p_s$  and Reflection Pressure  $p_r$   
for Front Reflection**



**Figure 2-9 Distribution of Reflection Amplification Factor for Front Reflection**



**Figure 2-10 Corner Reflection Analysis Model**



**Figure 2-11 Blast Wave Contour for Case of Reflection at Corner in Static Pressure**

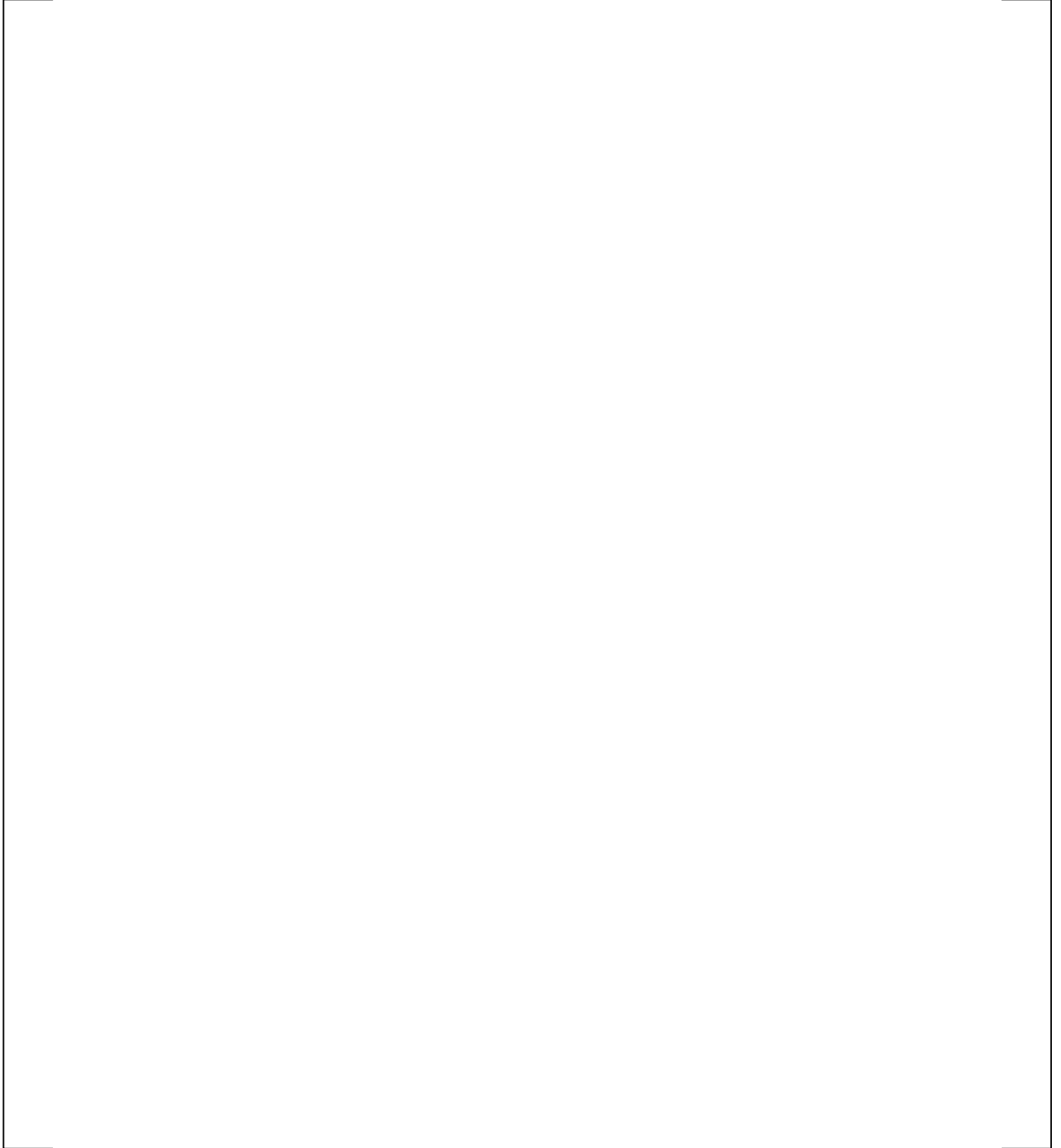


Figure 2-12 Relation between  $r/d$  and Peak Pressure



Figure 2-13 Relation between  $r/d$  and Reflection Amplification Factor

## **2.2 Blast Wave of Sub-cooled Water Piping**







**Figure 2-14 Sound Speed of Liquid-Gas Two Phase Flow**

**2.3 Blast Wave Assessment in US-APWR**



**2.3.1 Pressureizer Upper Piping Structure Integrity**



**2.3.1.1 Structural Analysis**



**2.3.2 Instrument Piping Structure Integrity**

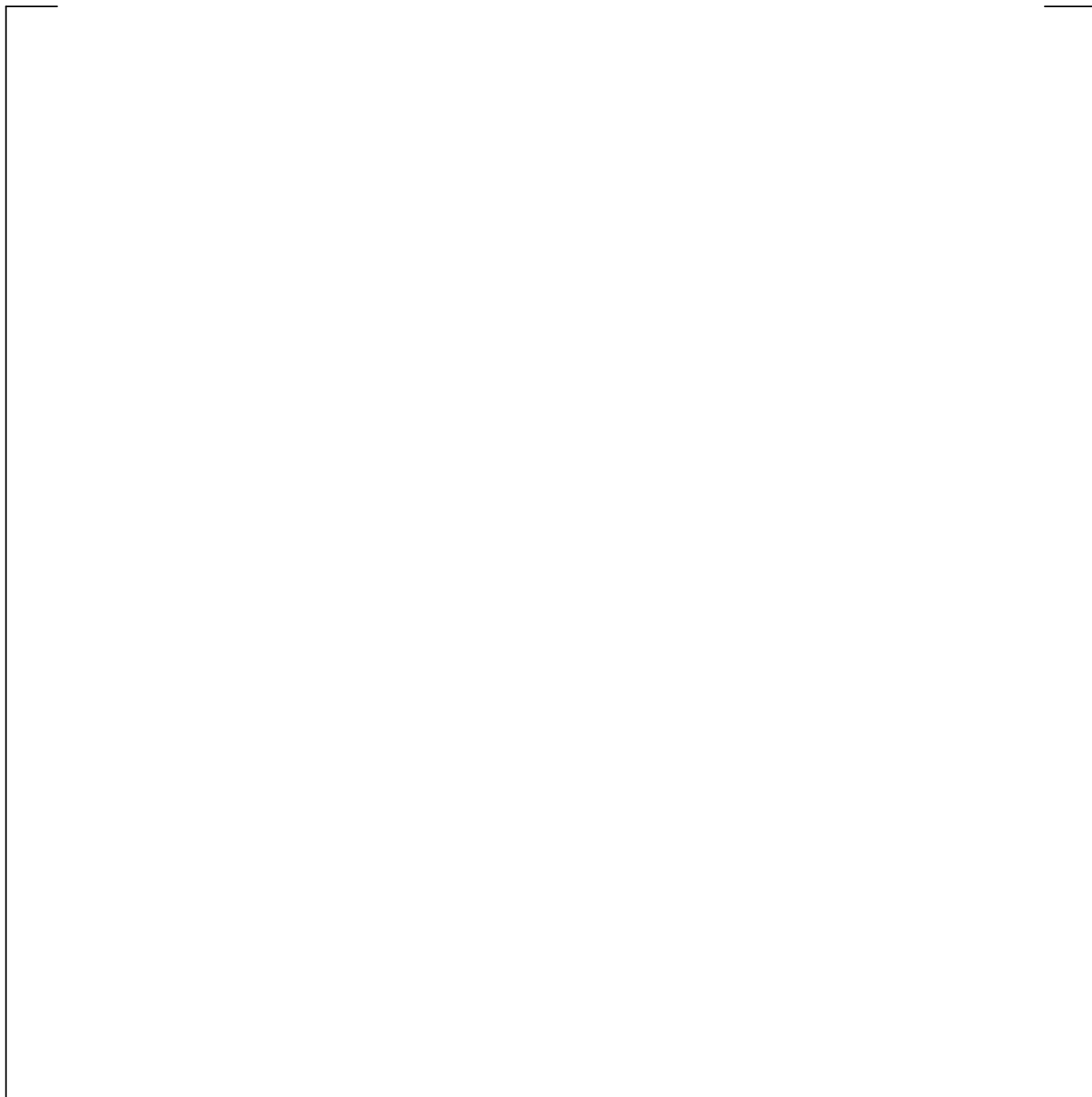
--	--

**2.3.3 Reflection Amplification**

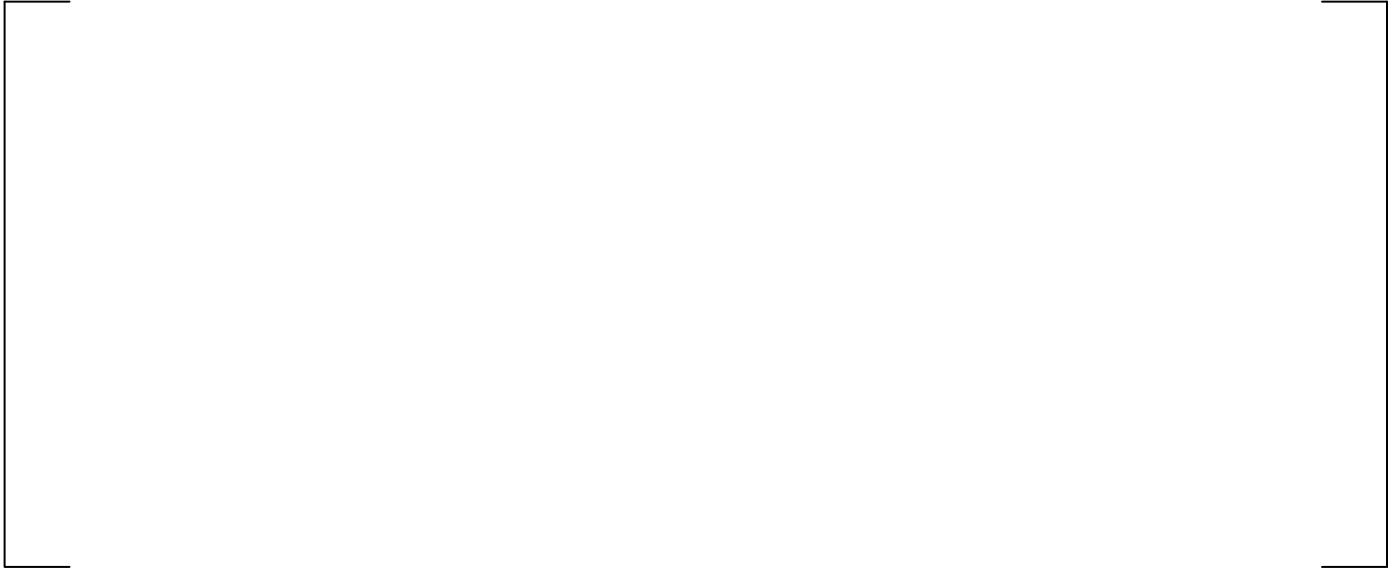
--	--

**2.3.4 Reflection Repitition**

--	--



**Figure 2-15 Piping Layouts at Upper Portion of Pressurizer**



**Figure 2-16 Case of Closest Distance between Break & Target Points**

**Table 2-2 Piping Specification**



**Figure 2-17 Piping Analysis Stress Model**



**Figure 2-18 Load Application Image**



**Figure 2-19 Example of Time History of Pressure Load (Piping Center Part)**



**Figure 2-20 Time History of Piping Stress (Piping Center)**



**Figure 2-21 Instrument Piping in Pressurizer Compartment**



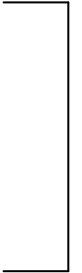
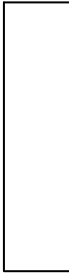


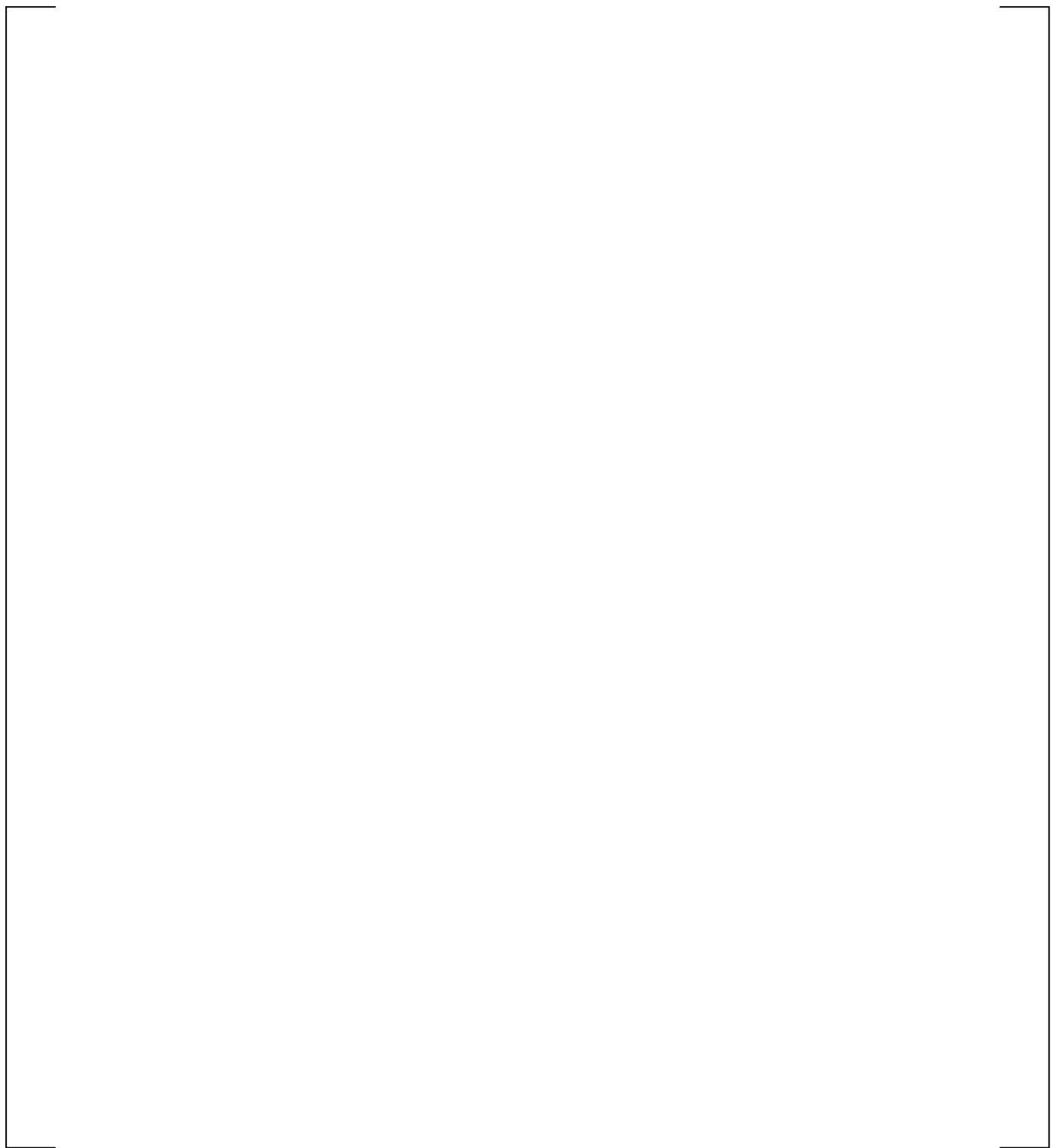
**Figure 2-22 Closest Location from Break Point to Wall**



**Figure 2-23 Internal Size of Pressurizer Compartment**

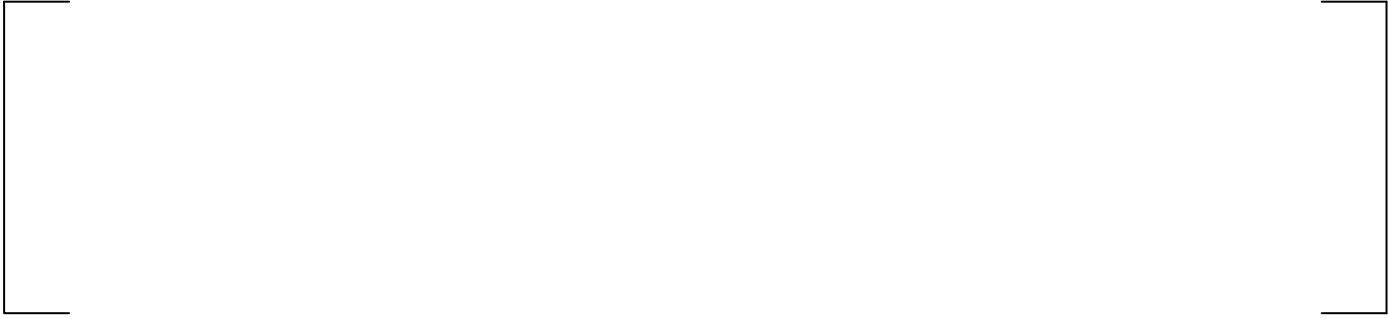
**2.4 Blast Wave Evaluation**





**Figure 2-24 Evaluation Process of Blast Wave**

**2.4.1 Scope of Evaluation**



**2.4.2 Load of Blast Wave**

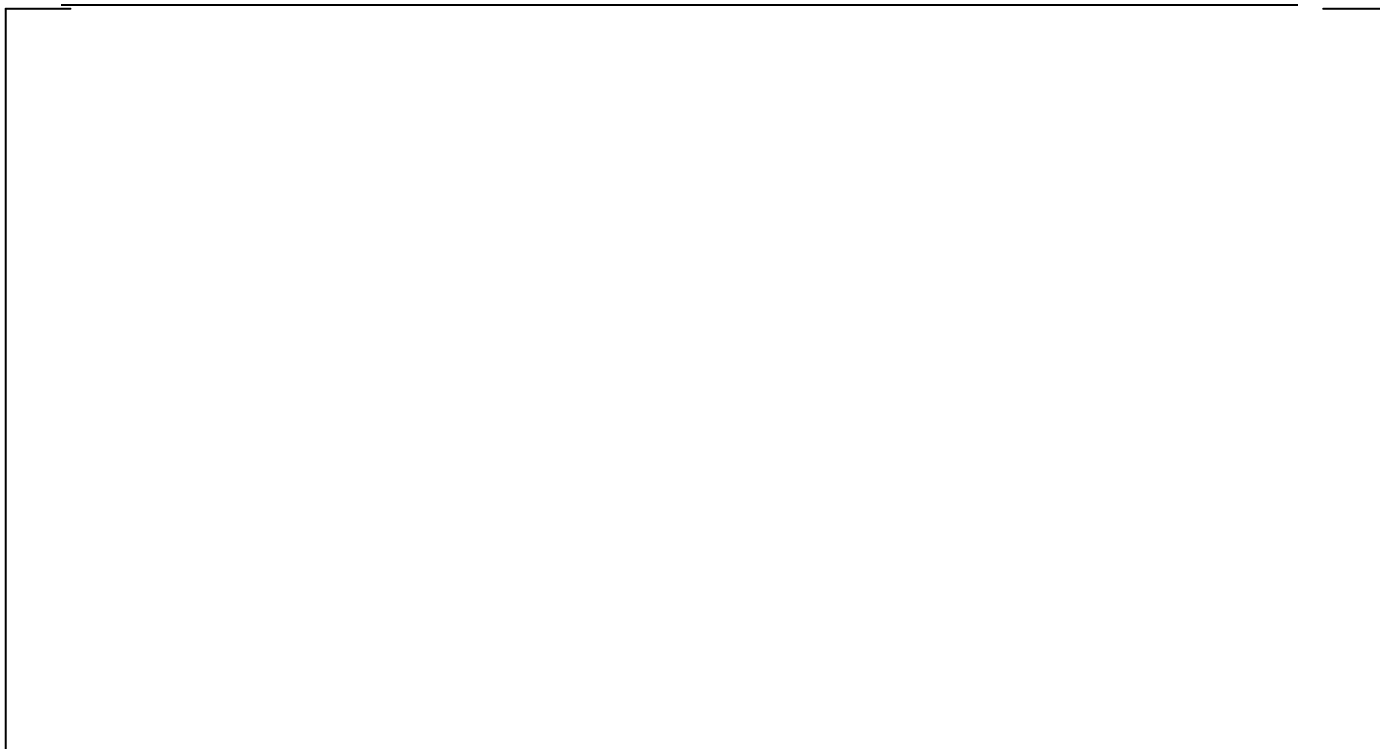


**Figure 2-25 Load Image of Blast Wave**

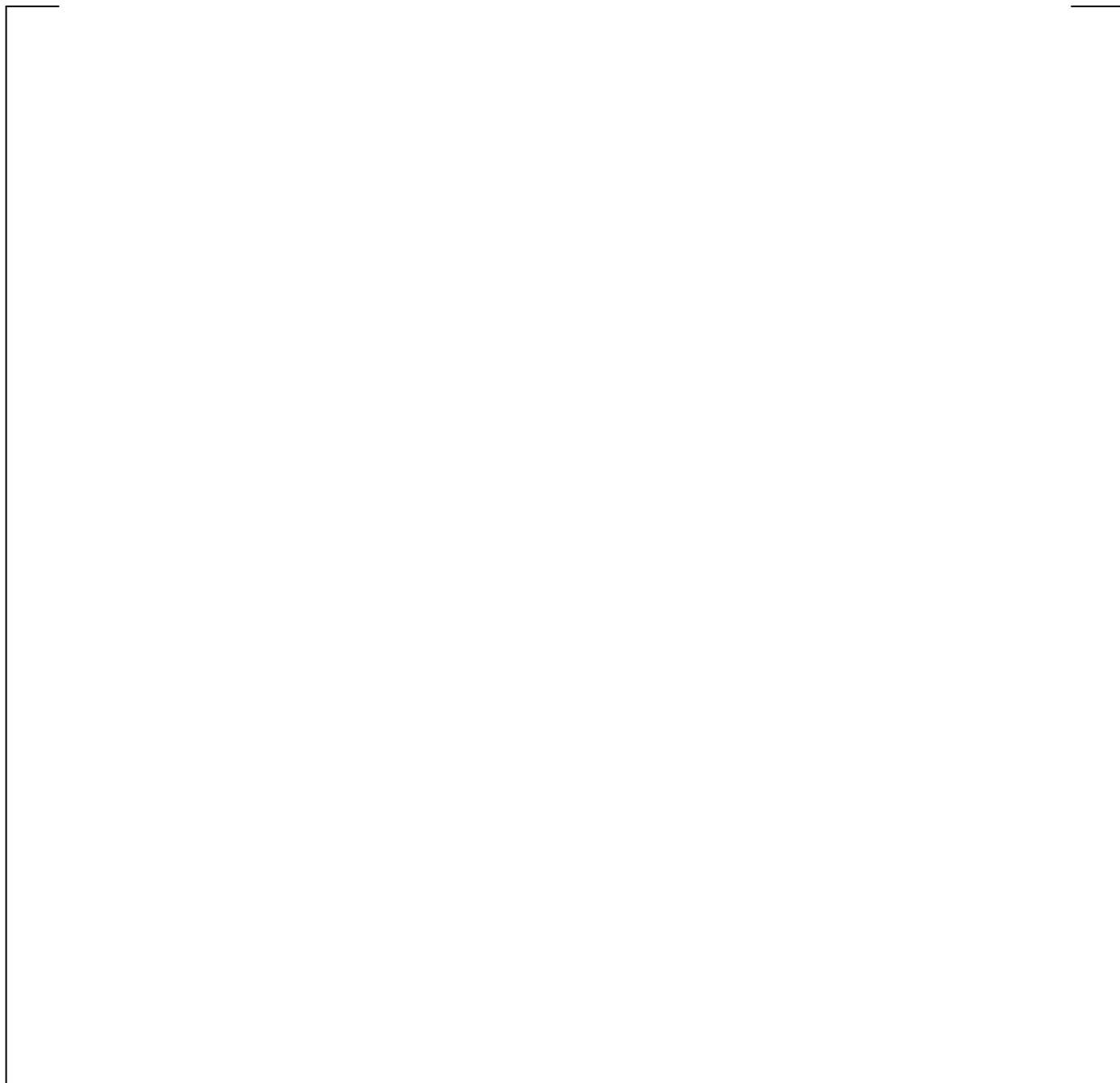
**3.0 JET PRESSURE OSCILLATION**

**3.1 Steam Piping**



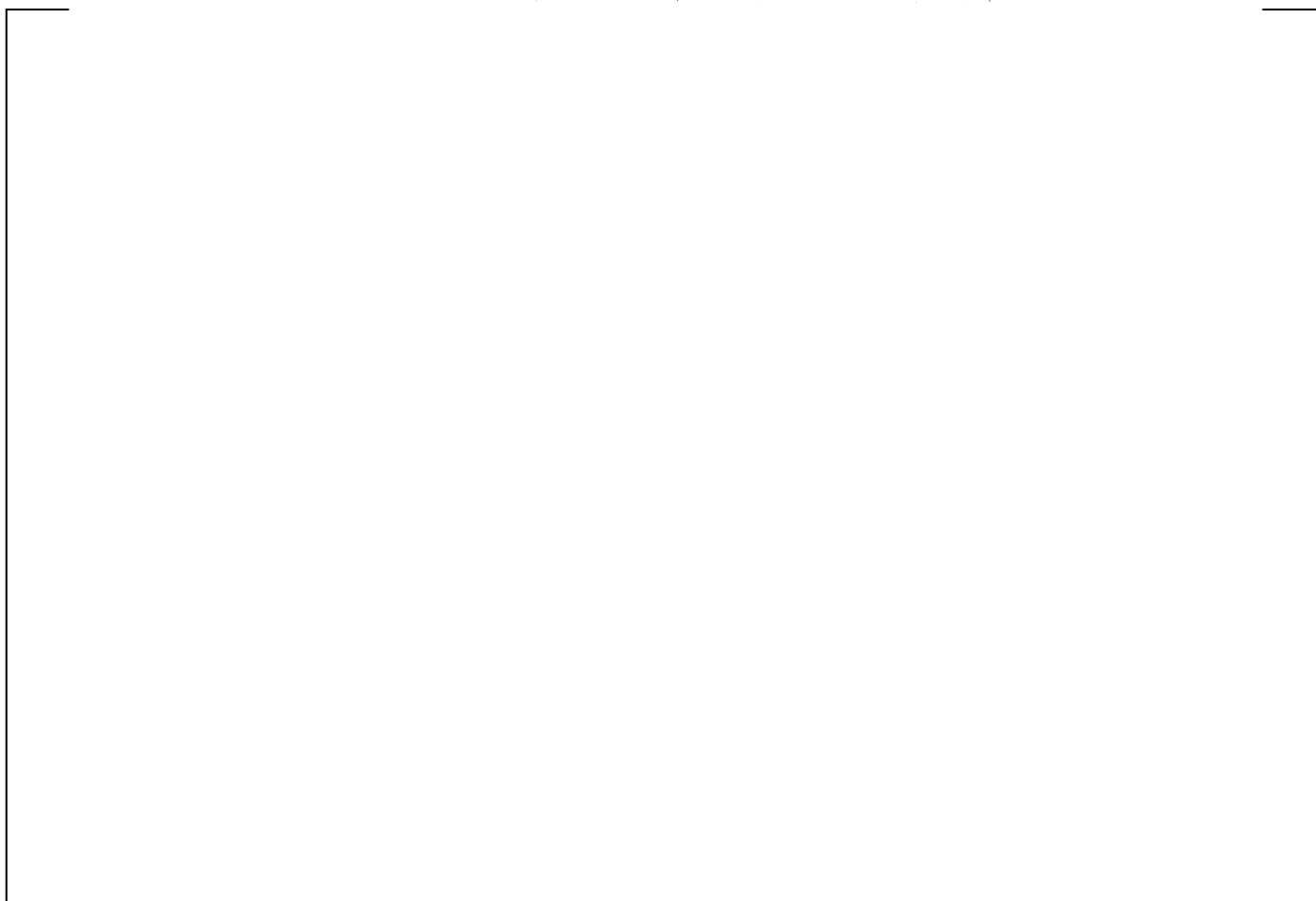


**Figure 3-1 Relationship between Distance from Nozzle to Impingement Wall and  
Pressure Distribution at Impingement Wall**



**Figure 3-2 Pressure Distribution of Flat-Plate Impingement ( $D = \text{nozzle diameter } d$ )**





**Figure 3-3 Mechanism of Generating Re-Circulation Flow**



**Figure 3-4 Relationship between Concave-Type Pressure Distribution Range  
and Pressure Oscillation Range(Reference 6-10)**



**Figure 3-5 Time-Freeze Planar Laser-Induced Fluorescence (PLIF) Images of Jet**

### **3.2 Sub-Cooled Water Piping**





**Figure 3-6 Flow Velocity Contour under PWR Condition with Sub-Cooling: 20° C**



**Figure 3-7 Steam Piping (Single Phase Flow)**



**Figure 3-8 Impingement Jet and Wall Pressure Distribution of Pressurized Hot Water**

(D = nozzle diameter d)

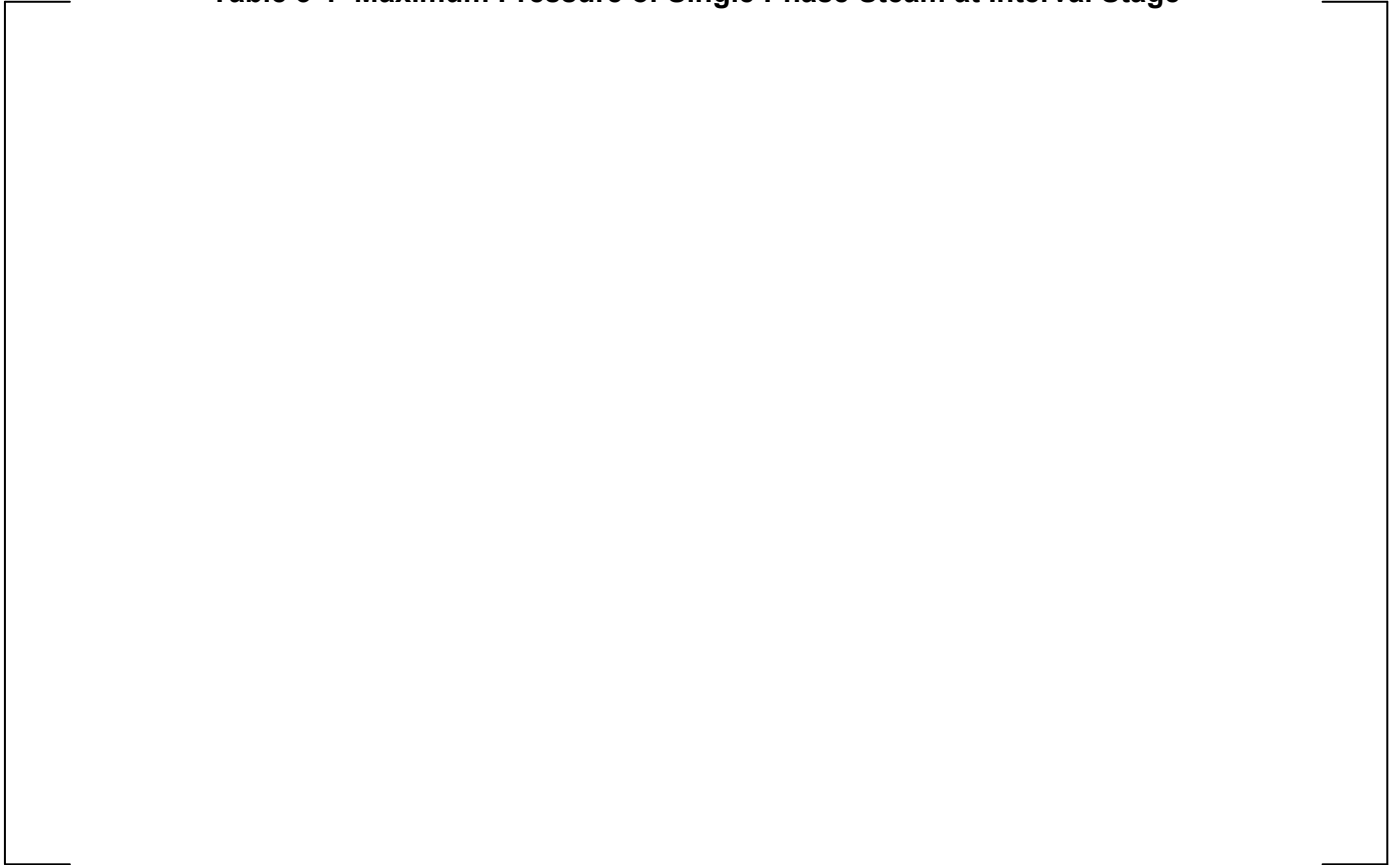
### 3.3 Effect of Source Condition Change





**Figure 3-9 Jet Pressure after Blowdown in 8-inch Break Blowdown**

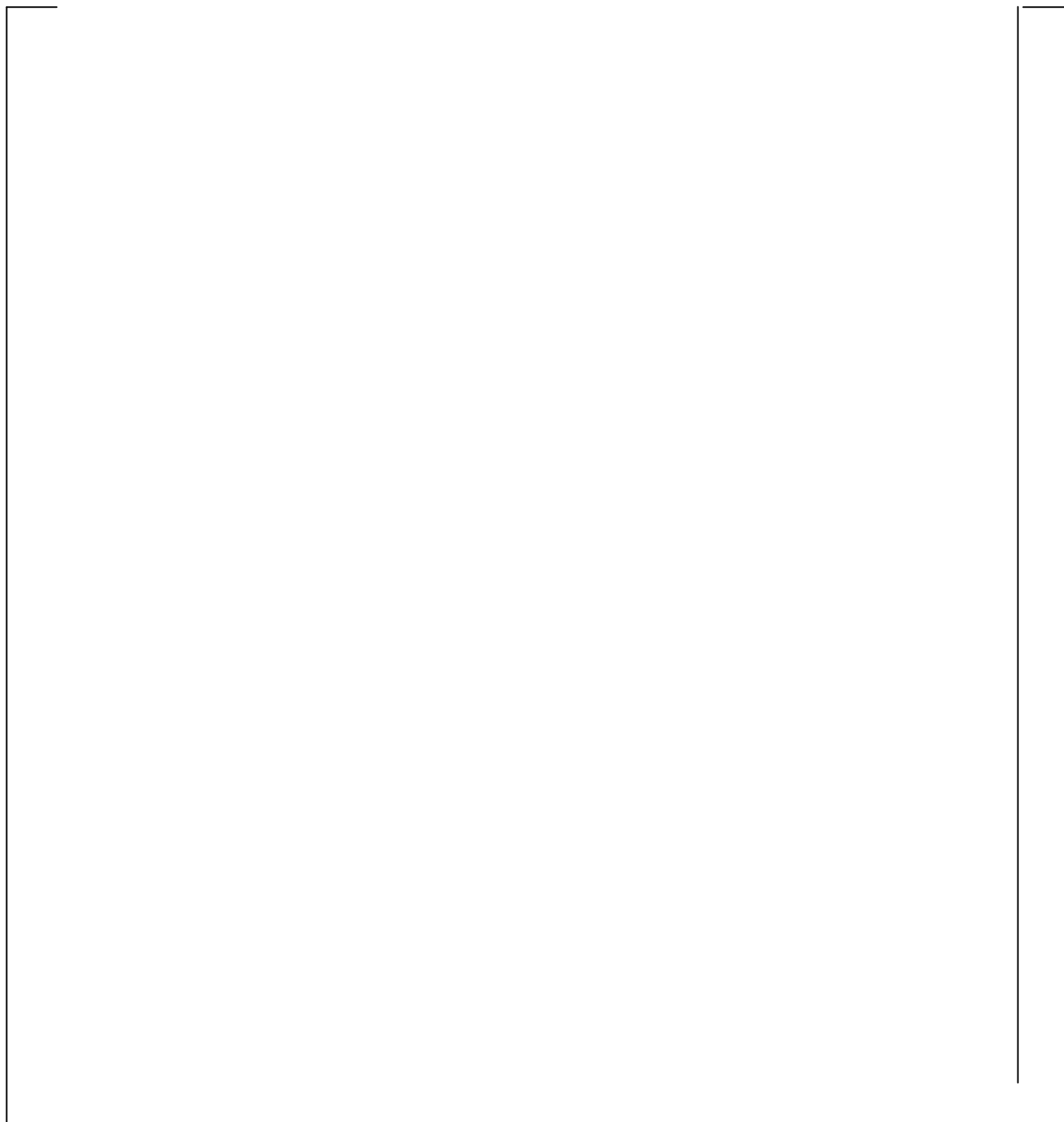
**Table 3-1 Maximum Pressure of Single Phase Steam at Interval Stage**





**3.4 Evaluation of Jet Pressure Oscillation**





**Figure 3-10 Evaluation Process of Jet Pressure Oscillation**

**3.4.1 Scope of Evaluation**



**3.4.2 Jet Load of Jet Pressure Oscillation Evaluation**

**Table 3-2 (1/4) Magnification Factor of Natural Frequency 5Hz of Piping**

An empty rectangular frame with a thin black border, intended for the content of Table 3-2 (1/4).

**Table 3-2 (2/4) Magnification Factor of Natural Frequency 10 Hz of Piping**

An empty rectangular frame with a thin black border, intended for the content of Table 3-2 (2/4).

**Table 3-2 (3/4) Magnification Factor of Natural Frequency 15 Hz of Piping**

An empty rectangular frame with a thin black border, intended for the content of Table 3-2 (3/4). The frame is currently blank.

**Table 3-2 (4/4) Magnification Factor of Natural Frequency 20 Hz of Piping**

An empty rectangular frame with a thin black border, intended for the content of Table 3-2 (4/4). The frame is currently blank.

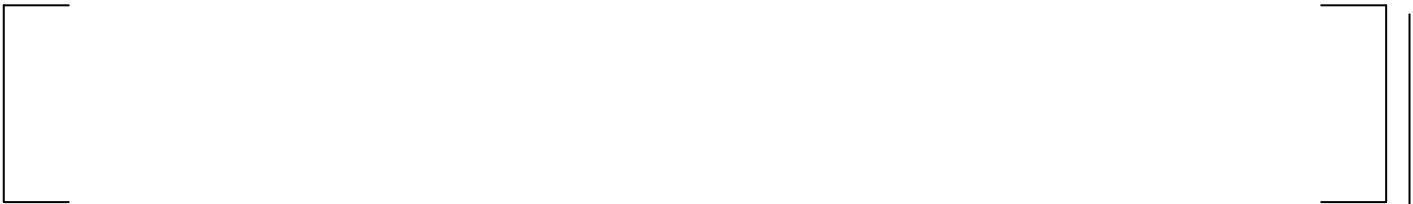


**Figure 3-11 Load Time Histories of Jet Pressure Oscillation**

**3.4.3 Modeling**



**3.4.4 Acceptance Criteria**

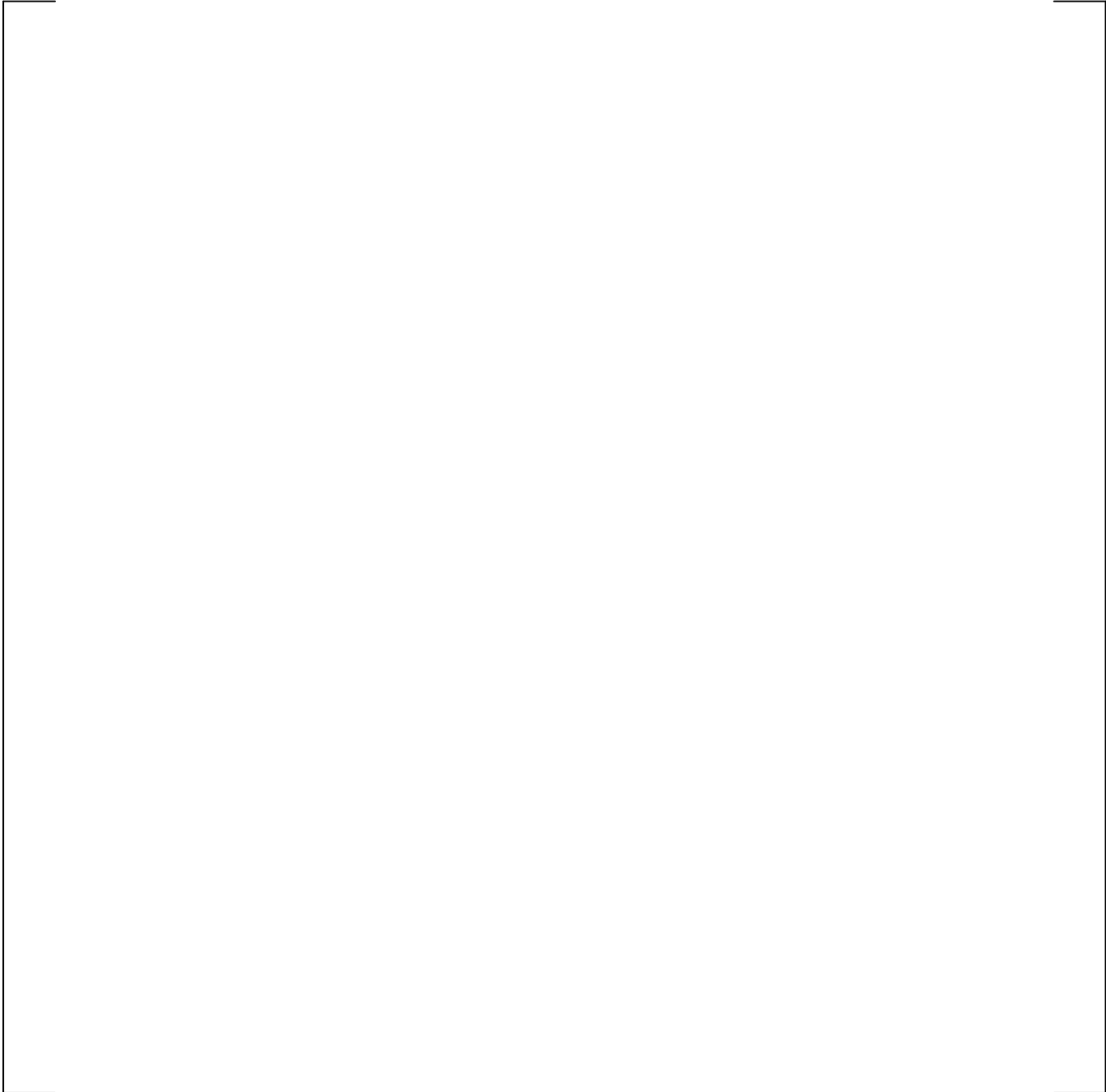




**Table 3-3 Design Criteria and Load Combination**

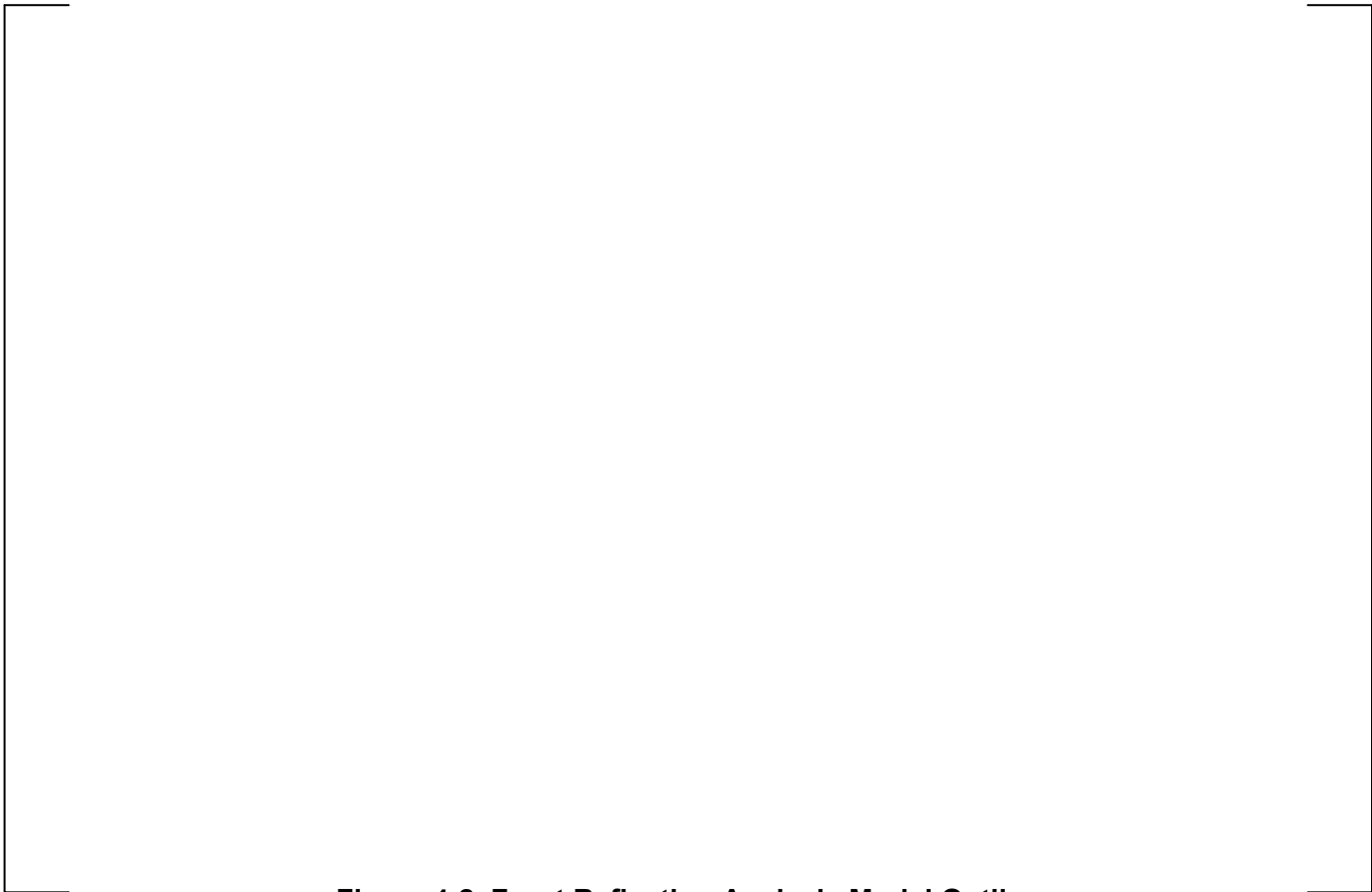
A large, empty rectangular frame with a thin black border, intended for the content of Table 3-3. The frame is currently blank.

#### **4.0 JET REFLECTION**





**Figure 4-1 Behavior of Jet Flow Impinging on a Perpendicular Surface**



**Figure 4-2 Front Reflection Analysis Model Outline**



**Figure 4-3 Expansion of Steam Jet**



**Figure 4-4 Speed Distribution of Flow Jet**

**Figure 4-5 Density of Flow Jet**



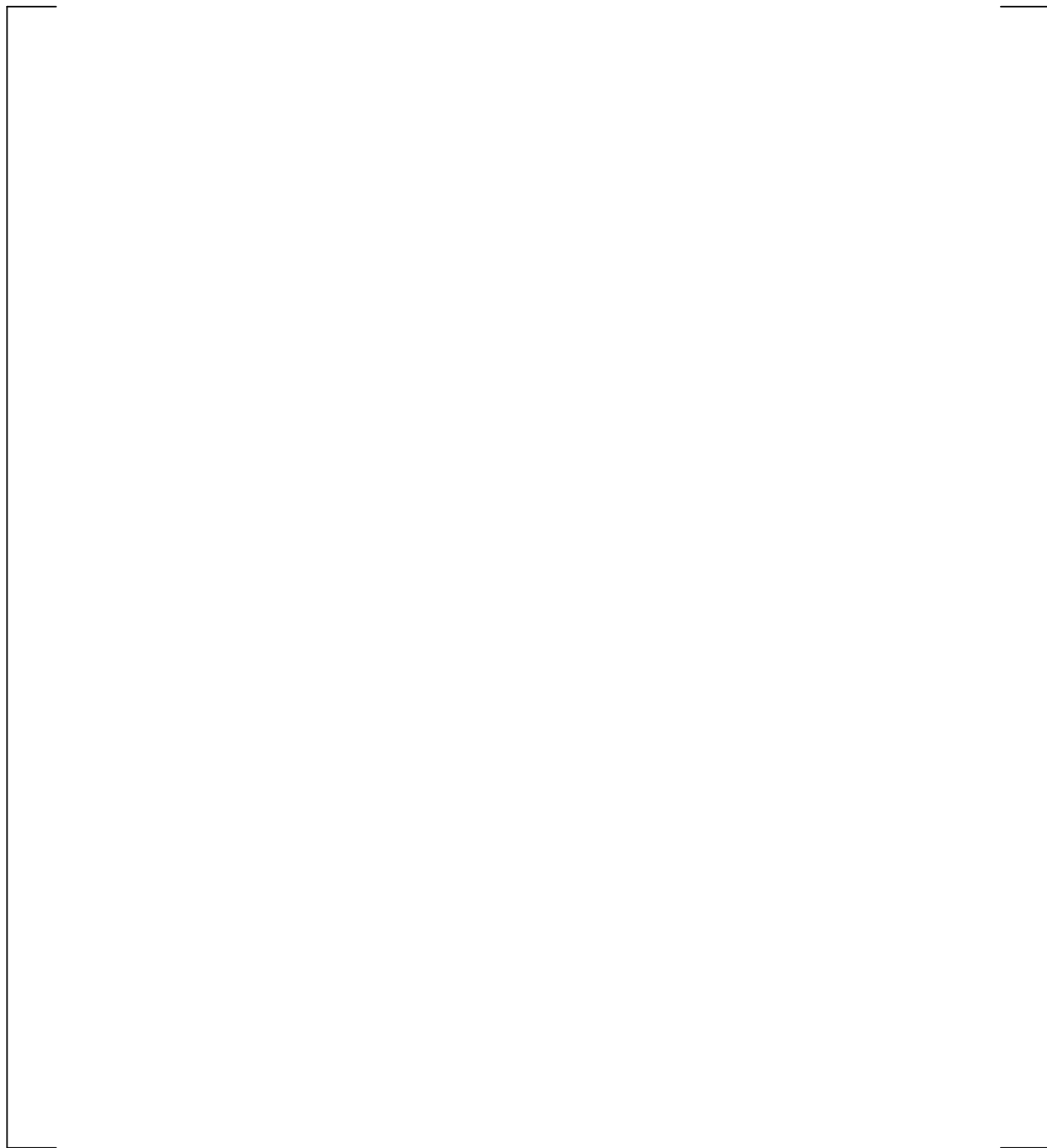
**Figure 4-6 Speed Distribution in Jet Flow Radiating along Wall  
at a Cross Section Parallel to Wall**



**Figure 4-7 Radial Force in Jet Flow Radiating along Wall**

**4.1 Jet Reflection Evaluation**





**Figure 4-8 Evaluation Process of Jet Reflection**

**4.1.1 Scope of Evaluation**







**Figure 4-9 Reflection Jet Expansion Model**

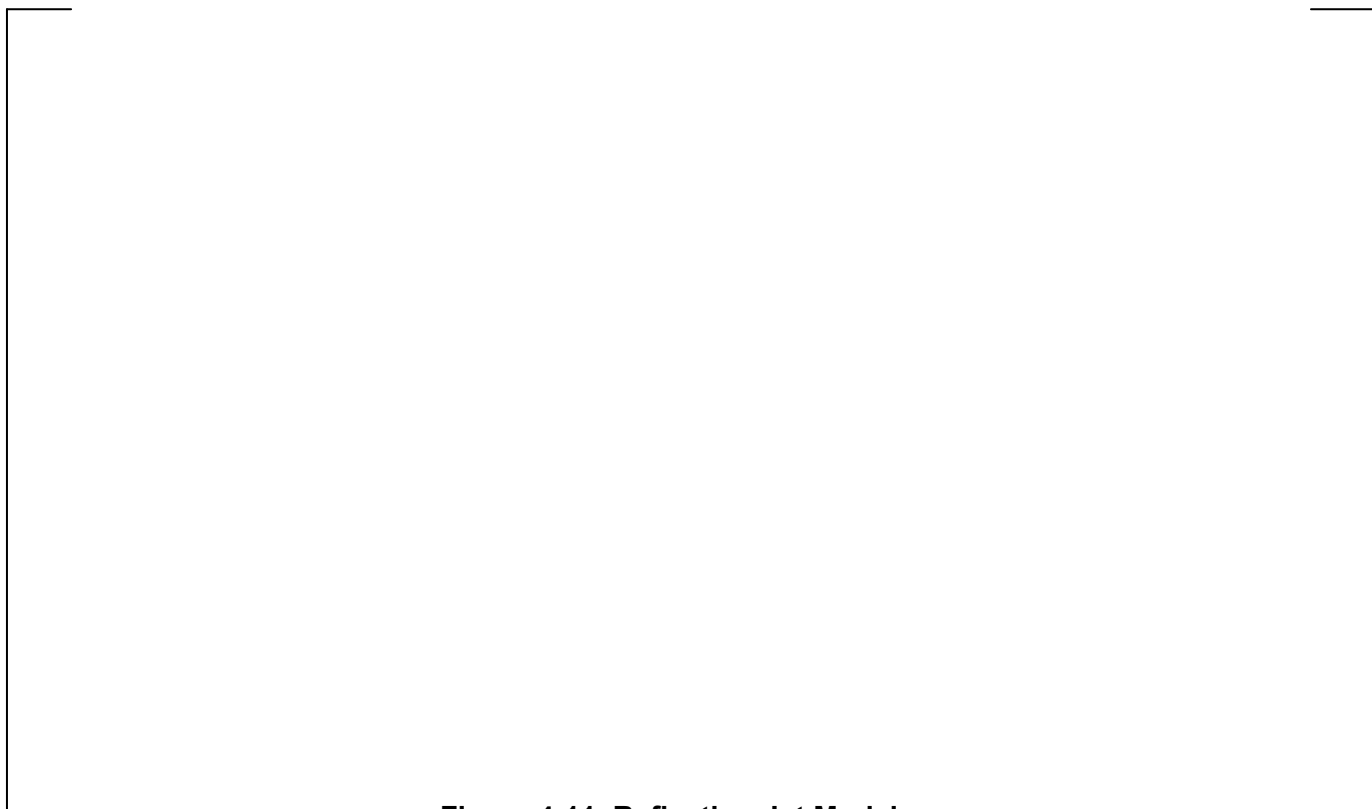
iii) ZOI of Jet Reflection



Figure 4-10 Evaluation Range (Bird-Eye View)

**4.1.2 Load of Reflection Jet**





**Figure 4-11 Reflection Jet Model**



**Figure 4-12 Reflection Jet Model (Bird-Eye View)**

**5.0 REFERENCES**

- 1-1 P.D.Smith, J.G.Hetherington, "Blast and Ballistic Loading of Structures", Butterworth Heinemann, pp.44-47, 1994.
- 1-2 T. Ito, "Acoustic Engineering", CORONA PUBLISHING CO.,LTD, 1976, (Revision 11)
- 1-3 Japanese Ministry of Technology and Industries, "Technology and Law to Prevent Pollution", 2000, (Revision5)
- 1-4 Japan Society of Mechanical Engineers, "Revised Handbook for Liquid-Gas Two Phase Flow", Page 378, 2006.
- 1-5 NRC Letter (ADAMS Accession No.NRR-106) dated March 31,2010 related to Generic Safety Issue-191.
- 1-6 H. Utsuno, M. Akamatsu, and T. Morii, H. Okada, and A. Minato, "Application of Compressible Two-Fluid Mode Code to Supersonic Two-Phase Jet Flow Analysis", The 13th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-13), September,2009.
- 2-1 Masuda, F., Nakatogawa, T., Kawanishi, K. and Isono, M., Experimental Study on an Impingement High-Pressure Steam Jet, Nuclear Engineering and Design 67-2, pgs 273-285, 1982.
- 2-2 F. S. Alvi, J. A. Ladd, W. W. Bower, "Experimental and Computational Investigation of Supersonic Impinging Jets", AIAA JOURNAL, Vol. 40, No. 4, April 2002
- 2-3 K. Kitade, T. Nakatogawa, H. Nishikawa, K. Kawanishi, T.Tsuruto, "Free Jet and Jet Impingement of High Pressure Steam" , Journal of Atomic Energy Society of Japan, Vol. 22, No.9, pp634-640. (In Japanese)
- 2-4 H.Ashkenas and F.S. Sherman, "Rarefied Gas Dynamics, Vol II" , Academic press, New York, pp 84-105, 1966.
- 2-5 S. I. Kim, S. O. Park, "Oscillatory Behavior of Super Sonic Impinging Jet Flows Shock Waves", 14(4), pp. 259-272, 2005
- 2-6 C. Y. Loh, "Computation of Tone Noise From Supersonic Jet Impinging on Flat Plates", NASA CR—2005-213426, AIAA—2005—0418 .March,2005

- 2-7 A. Krothapalli, E. Rajkuperan, F. Alvi, L.Lourenco, "Flow field and noise characteristics of a supersonic impinging jet", J.Fluid Mech.(1999), vol.392, pp.155-181, 1999
- 2-8 B. Henderson, "An Experimental Investigation into the Sound Producing Characteristics of Supersonic Impinging Jets", AIAA Paper 2001-2145, 2001
- 2-9 T. Yasunobu, T. Matsuoka, M. Tagami, "Pressure Fluctuation on Self Induce Flow Oscillation Caused by Under-Expanded Super Sonic Impinging Jet", The japan Society of Mechanical Enjineers,No.028-1,pp.141-142, 2002
- 2-10 A. (Wilkes) Inman, P M. Danehy, R J. Nowak, and D W. Alderfer, "Fluorescence Imaging Study of Impinging Underexpanded Jets", Extended abstract to be submitted to:46<sup>th</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 7-10 January 2008
- 2-11 kada, H. and Minato, A., the Japan Nuclear Energy Safety (JNES) paper titled "Application of Compressible Two-Fluid Mode Code to Supersonic Two-Phase Jet Flow Analysis", The 13th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-13) N13P1368 Kanazawa City, Ishikawa Prefecture, Japan, September 27-October 2, 2009.
- 2-12 Kitade, K., Nakatogawa, T., Nishikawa, H., Kawanishi, K., and Tsuruto, C., Experimental Study of Pipe Reaction Force and Jet Impingement Load at the Pipe Break, Trans. 5th Int. Conf. on SMiRT, F6/2, 1979.
- 3-1 N. Rajaratonam, TUBULENT JETS, Elsevier Scientific Publishing Company, Amsterdam,1976

## Appendix 1

### Simplified Blast Wave Model

**TABLE OF CONTENTS**

**LIST OF FIGURES** ..... A1-3

1.0 SYMLIFIED BLAST WAVE MODEL..... A1-4

    1.1 THE STEAM BALL ..... A1-5

    1.2 THE SHOCKED GAS REGION..... A1-6

    1.3 BLAST CONFINED TO UNIFORM AREA PROGRESSION..... A1-7



**LIST OF FIGURES**

FigureA1-1-1	SIMPLIFIED BLAST WAVE MODEL	A1-4
FigureA1-1-2	SHOCK CONFINED TO UNIFORM AREA	A1-7

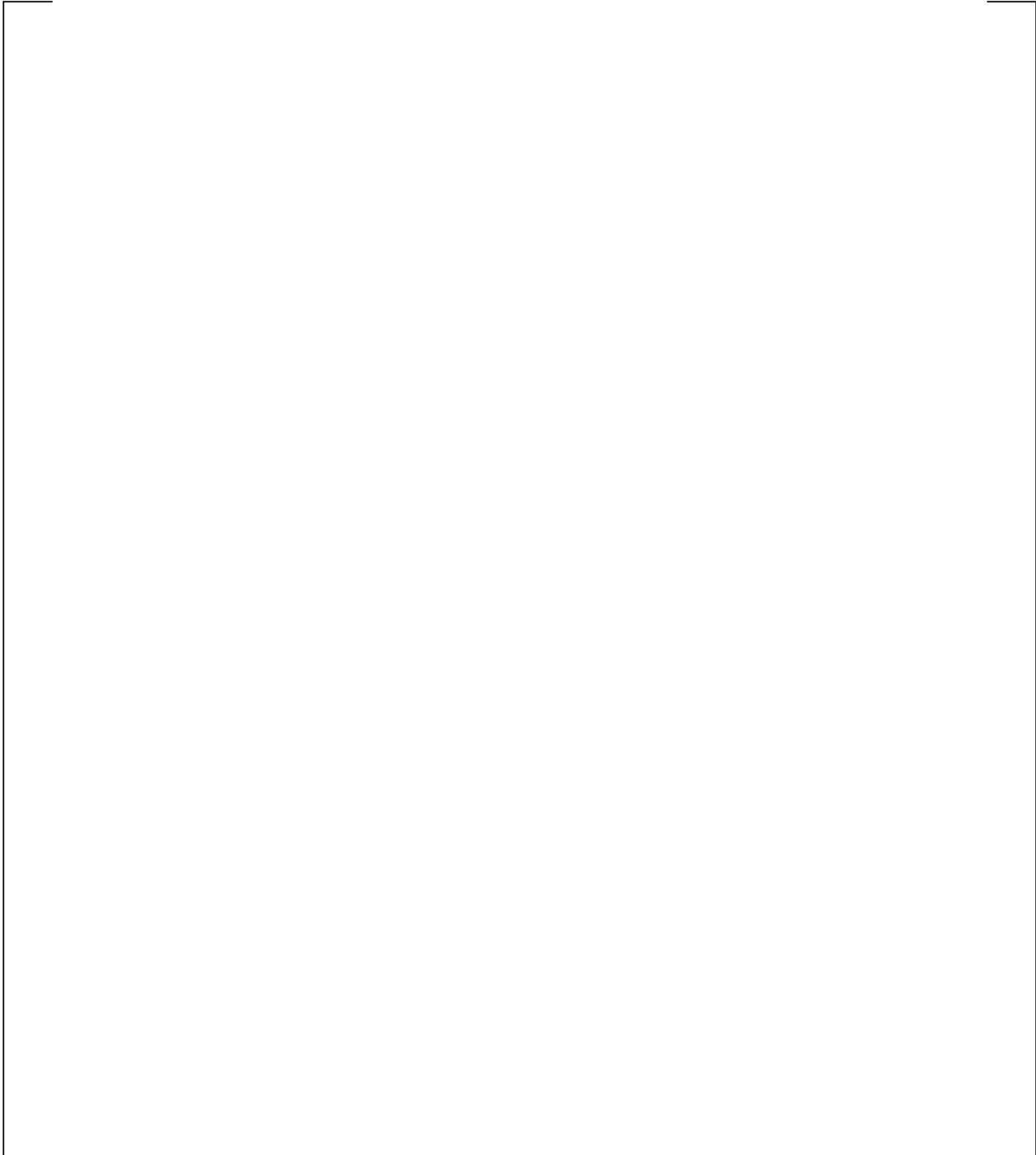
**1.0 SYMLIFIED BLAST WAVE MODEL**



**FigureA1-1-1 Simplified Blast Wave Model**



**1.1 The Steam Ball**



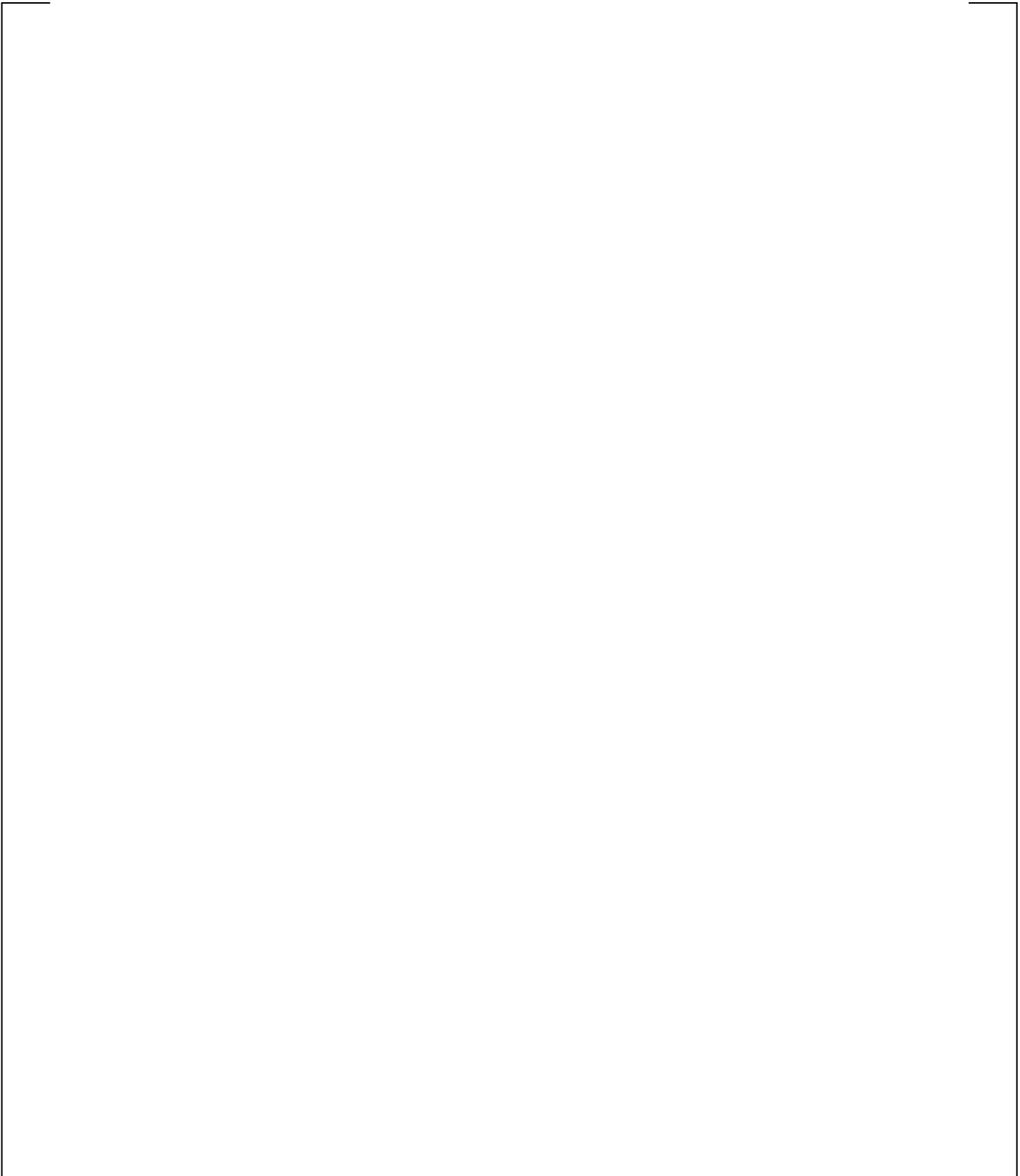
**1.2 The Shocked Gas Region**

**1.3 Blast Confined to Uniform Area Progression**



**Figure A1-1-2 Shock Confined to Uniform Area**











## Appendix 2

### Convergence Condition

---

**TABLE OF CONTENTS**

<b>LIST OF TABLES</b> .....	A2-3
<b>LIST OF FIGURES</b> .....	A2-4
1.0 ANSYS FLUENT.....	A2-5
1.1 CONVERGENCE CONDITION .....	A2-5
1.1.1 Implicit Time Integration.....	A2-5
1.1.2 Max Iterations/Time Step.....	A2-5
1.1.3 Judging Convergence.....	A2-5
1.2 ALGORITHM.....	A2-6
1.2.1 The Pressure-Based Coupled Algorithm .....	A2-7
1.2.2 QUICK Schem .....	A2-8
1.2.3 PRESTO! Schem.....	A2-9
2.0 ANSYS AUTODYN .....	A2-10
2.1 INTRODUCTION.....	A2-10
2.2 MULTI-MATERIAL EULER SOLVER USED IN BLAST WAVE CALUCULATION.....	A2-10
2.3 CALUCULATION ALGORITHMS .....	A2-10
2.3.1. Convergence Calculation.....	A2-10
2.3.2. Basic Physical Equations of the Euler Code.....	A2-10
2.3.3. Multi-Material Interface Tracking .....	A2-13
2.3.4. Pressure Calculation.....	A2-13
2.3.5. Computation Cycle of Multi-Material Euler .....	A2-14
2.4 TIME STEP .....	A2-14
3.0 REFERENCES .....	A2-16

**LIST OF TABLES**

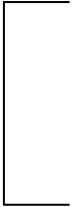
Table A2-2-1	Multi-Material Euler Solver Used in ANSYS AUTODYN	A2-10
--------------	---	-------

**LIST OF FIGURES**

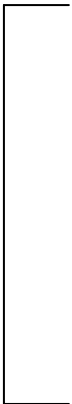
FigureA2-1-1	Example of Convergence Residual Calculation Results	A2-6
FigureA2-1-2	Overview of the Pressure-Based Solution Methods	A2-7
FigureA2-1-3	One-Dimensional Control Volume	A2-8
FigureA2-2-1	Computation Cycle of Multi-Material Euler	A2-14

**1.0 ANSYS FLUENT**

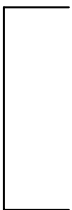
**1.1 Convergence Condition**



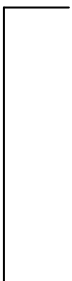
**1.1.1 Implicit Time Integration**



**1.1.2 Max Iterations/Time Step**



**1.1.3 Judging Convergence**





**Figure A2-1-1 Example of Convergence Residual Calculation Results**

**1.2 Algorithm**



**1.2.1 The Pressure-Based Coupled Algorithm**

**Figure A2-1-2 Overview of the Pressure-Based Solution Methods  
( The Right Hand Figure is Coupled Solver )**

### 1.2.2 QUICK Schem



**Figure A2-1-3 One-Dimensional Control Volume**

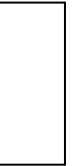


**1.2.3 PRESTO! Schem**



## 2.0 ANSYS AUTODYN

### 2.1 Introduction



### 2.2 Multi-Material Euler Solver Used in Blast Wave Calculation

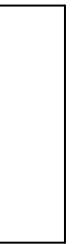
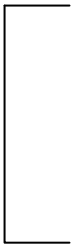
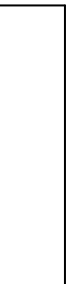
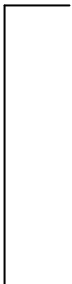
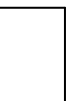
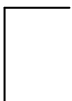


TabelA2-2-1 Multi-Material Euler Solver Used in ANSYS AUTODYN

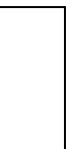
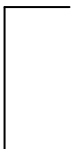


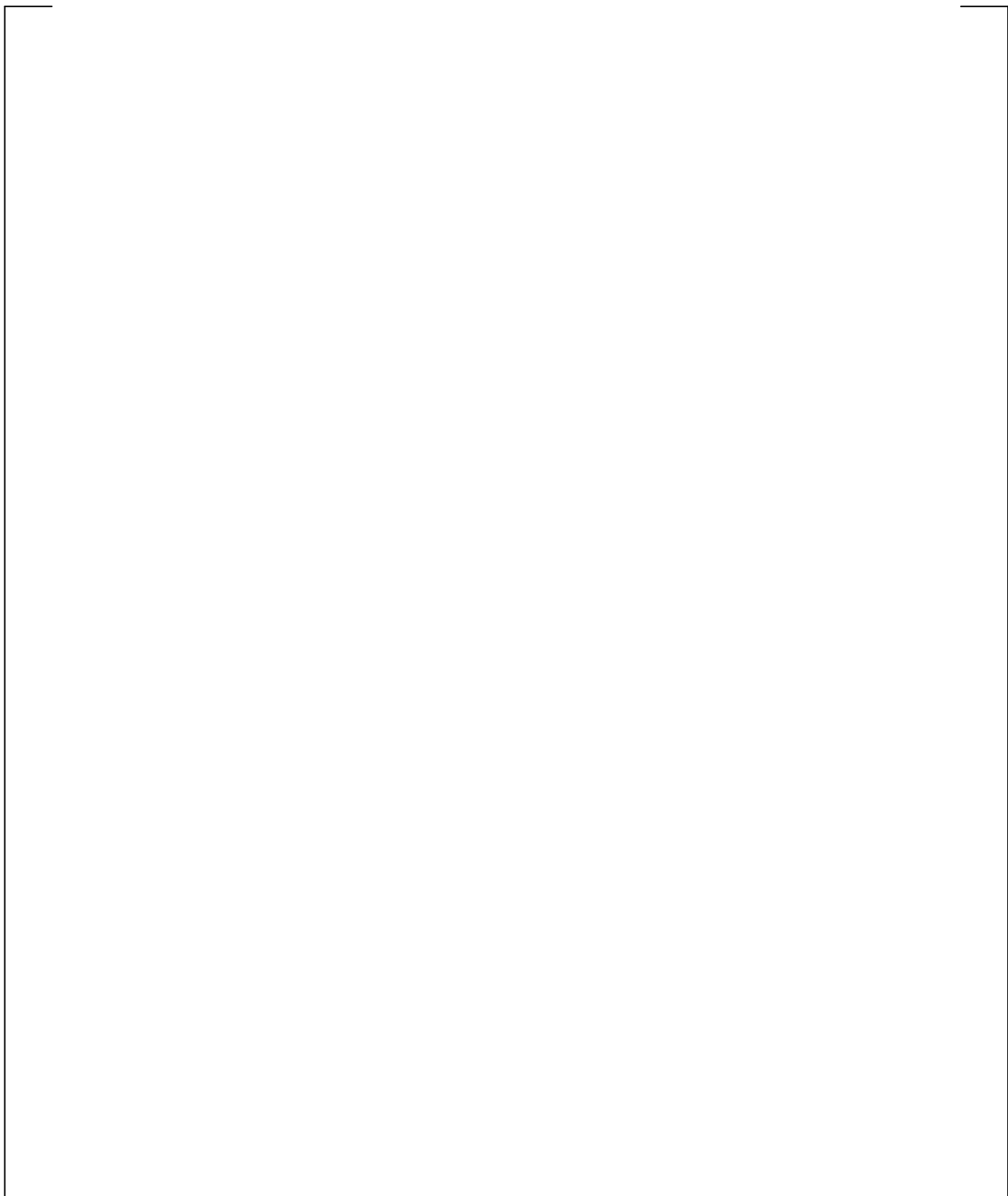
### 2.3 Calculation Algorithms

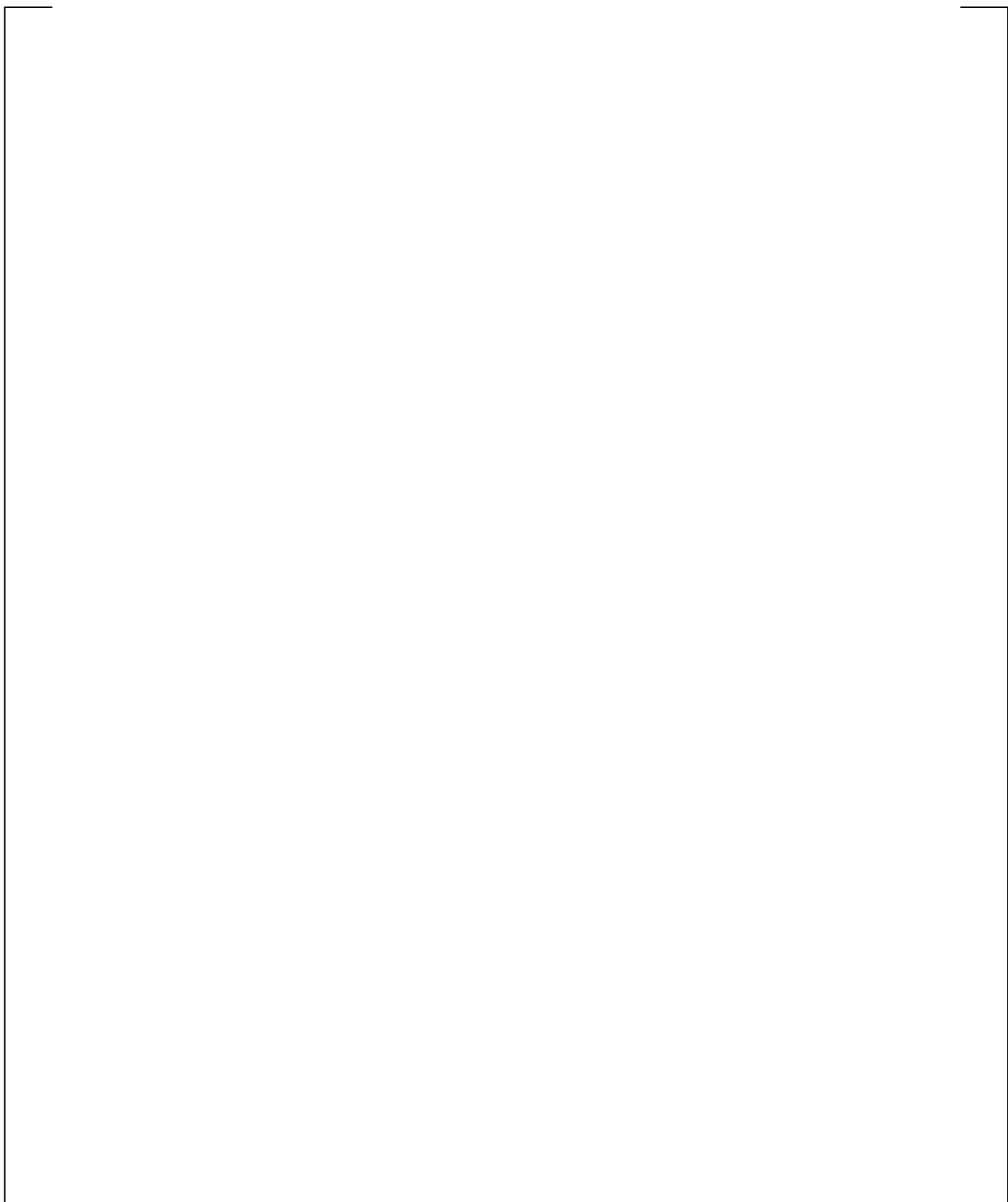
#### 2.3.1 Convergence Calculation



#### 2.3.2 Basic Physical Equations of the Euler Code







**2.3.3 Multi-Material Interface Tracking**

**2.3.4 Pressure Calculation**

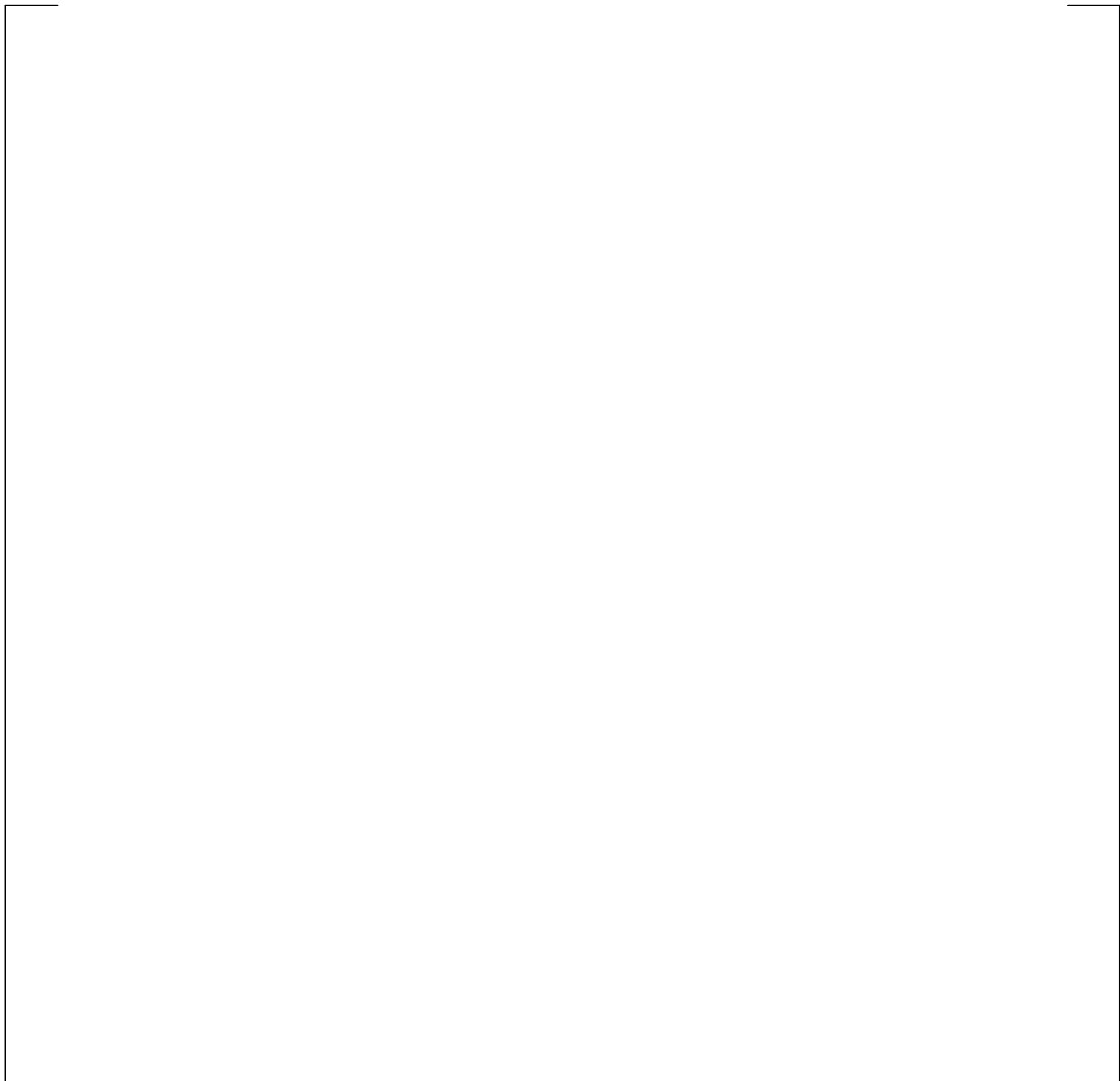
### 2.3.5 Computation Cycle of Multi-Material Euler



FigA2-2-1 Computation Cycle of Multi-Material Euler

### 2.4 Time Step





**3.0 REFERENCES**

- 1-1 ANSYS, Inc., "ANSYS FLUENT 12.0 Theory Guide",2009
- 1-2 ANSYS, Inc., ANSYS FLUENT 12.0 User's Guide, April 2009
- 2-1 S. Hancock, "Finite Difference Equations for PISCES-2DELK", TCAM-76-2, Physics International, 1976.
- 2-2 B. Van Leer, "Towards the Ultimate Conservative Difference Scheme.IV. A new Approach to Numerical Convection", J. Comp. Phys. 23, pp.276-299, 1977
- 2-3 B. Van Leer. "Towards the Ultimate Conservative Difference Scheme.V. A second-order sequel to Godunov's method", J. Comp. Phys. 23, pp.276-299, 1977
- 2-4 W. F. Noh and P. R. Woodward. "SLIC, Simple Line Interface Calculation", Proc. of the 5<sup>th</sup> Int. Symp. on the Numerical Method in Fluid Dynamics, 1976
- 2-5 O. Yu Vorobiev and I. N. Lomov, "Numerical simulation of gas-solid interfaces with large deformations," Advances in Computational Engineering & Sciences 2000, Vol. 1, pp.922-927, 2000



## **Appendix 3**

### **Outline of Blowdown Analysis**

**TABLE OF CONTENTS**

**LIST OF FIGURES ..... A3-3**

**LIST OF TABLES ..... A3-4**

**1.0 OUTLINE OF BLOWDOWN ANALYSIS ..... A3-5**

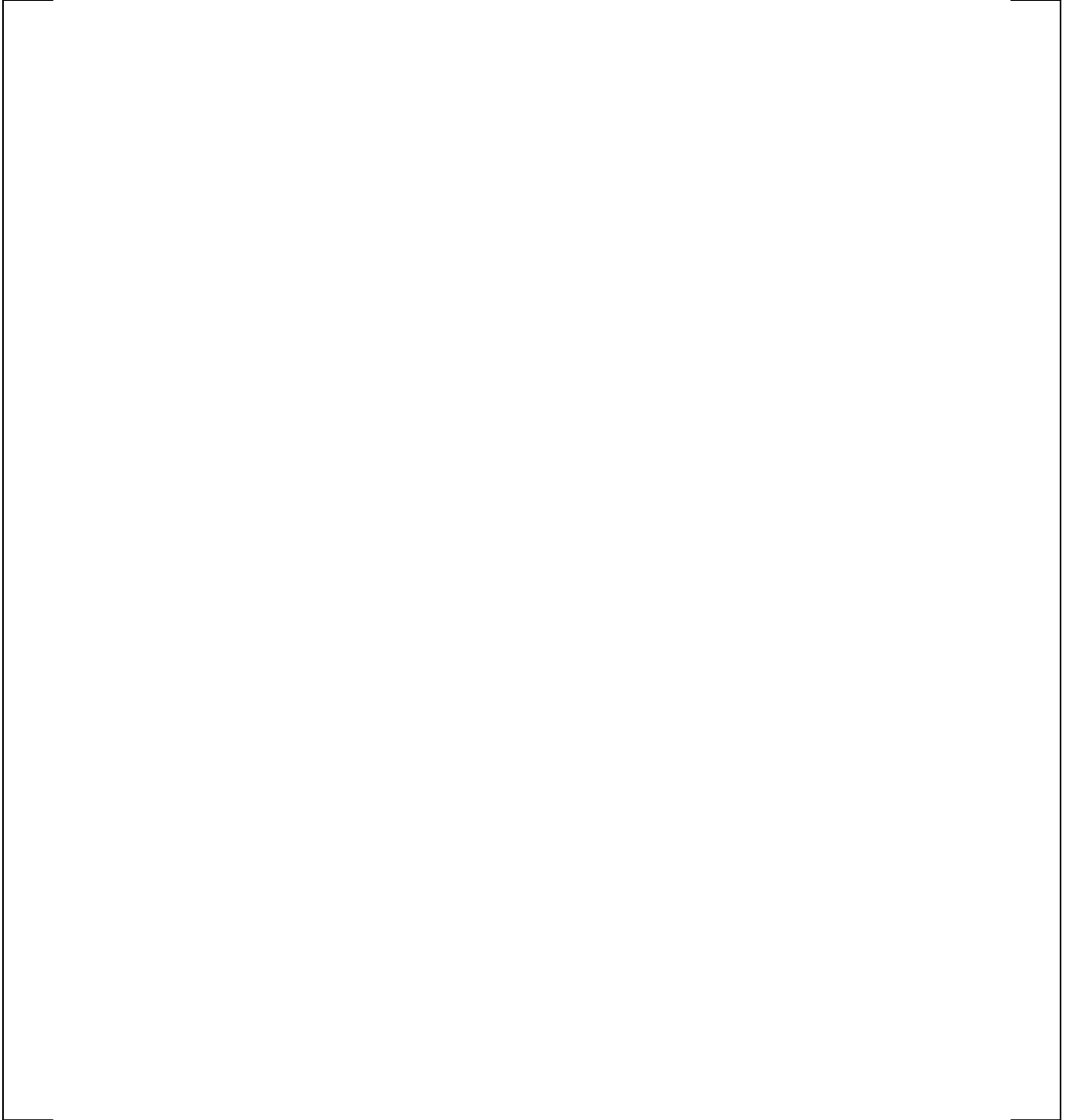
**LIST OF FIGURES**

Figure A3-1	RHRS Hot Leg Branch Line off RCS(Hot Leg 10-inch Break - B Loop)	A3-8
Figure A3-2	RHRS Hot Leg Branch Line off RCS(Hot Leg 10-inch Break - A, C, D Loop)	A3-9
Figure A3-3	RHRS Cold Leg Branch Line off RCS(Cold Leg 8-inch Break - B Loop)	A3-10
Figure A3-4	RHRS Cold Leg Branch Line off RCS(Cold Leg 8-inch Side Break - A, C, D Loop)	A3-11
Figure A3-5	Pressurizer Spray Line(Cold Leg 6-inch Break - B Loop)	A3-12
Figure A3-6	Pressurizer Spray Line(Cold Leg 6-inch Break - C Loop)	A3-13
Figure A3-7	Charging Line(Cold Leg 4-inch Break - A Loop)	A3-14
Figure A3-8	Letdown Line(Cross Over Leg 3-inch Break - D Loop)	A3-15
Figure A3-9	Loop Drain/Excess Letdown Line(Cross Over Leg 2-inch Break - A, C Loop)	A3-16
Figure A3-10	Loop Drain (Cross Over Leg 2-inch Break - B Loop)	A3-17
Figure A3-11	Pressurizer Safety Valve Line (Pressurizer 6-inch Break)	A3-18
Figure A3-12	Pressurizer Safety Depressurization Valve Line (Pressurizer 4-inch Break)	A3-19
Figure A3-13	Pressurizer Safety Depressurization Valve Line (Pressurizer 8-inch Break)	A3-20
Figure A3-14	Seal Injection Line (RCP 1.5-inch Break)	A3-21

**LIST OF TABLES**

Table A3-1	Blowdown Analysis Results	A3-6
------------	---------------------------	------

**1.0 Outline of Blowdown Analysis**

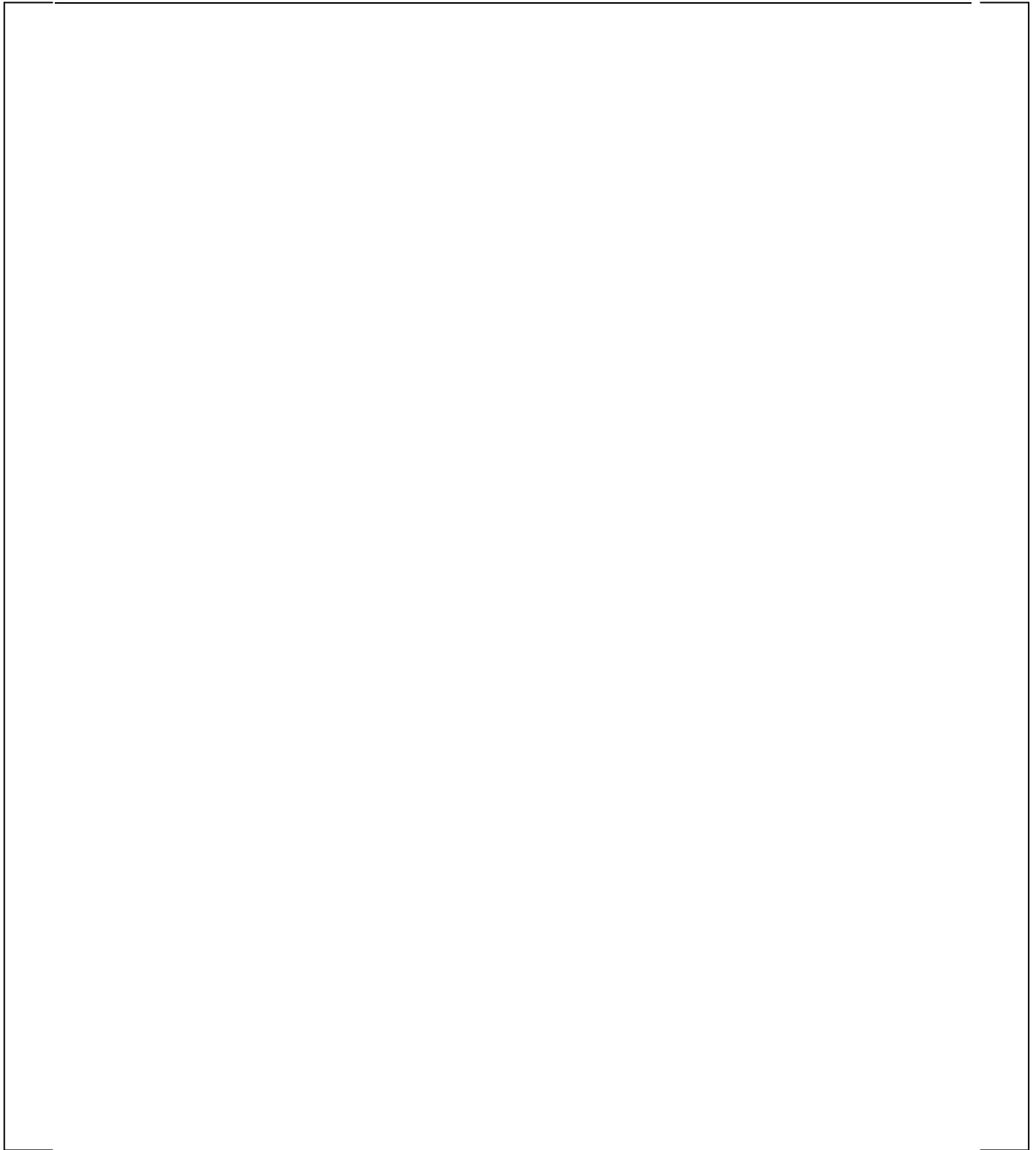


**Table A3-1 Blowdown Analysis Results (1/2)**

Figure No.	System	Subsystem	Nominal Diameter (Inches)	Loop	Break Location	Single Phase Steam Start Time(s)/ Pressure(lb/in <sup>2</sup> )	Single Phase Steam End Time(s)/ Pressure(lb/in <sup>2</sup> )
A3-1	RCS	Residual Heat Removal System (RHRS) Hot Leg Branch Line off RCS	10	B	Hot Leg		
A3-2	RCS	RHRS Hot Leg Branch Line off RCS	10	A, C, D	Hot Leg		
A3-3	RCS	RHRS Cold Leg Branch Line off RCS	8	B	Cold Leg		
A3-4	RCS	RHRS Cold Leg Branch Line off RCS	8	A, C, D	Cold Leg		
A3-5	RCS	Pressurizer Spray Line	6	B	Cold Leg		
A3-6	RCS	Pressurizer Spray Line	6	C	Cold Leg		
A3-7	CVS	Charging Line	4	A	Cold Leg		
A3-8	CVS	Let Down Line	3	D	Crossover Leg		
A3-9	RCS	Loop Drain/Excess Letdown Line	2	A, C	Crossover Leg		
A3-10	RCS	Loop Drain	2	B	Crossover Leg		
A3-11	RCS	Pressurizer Safety Valve Line	6	B	PZR		

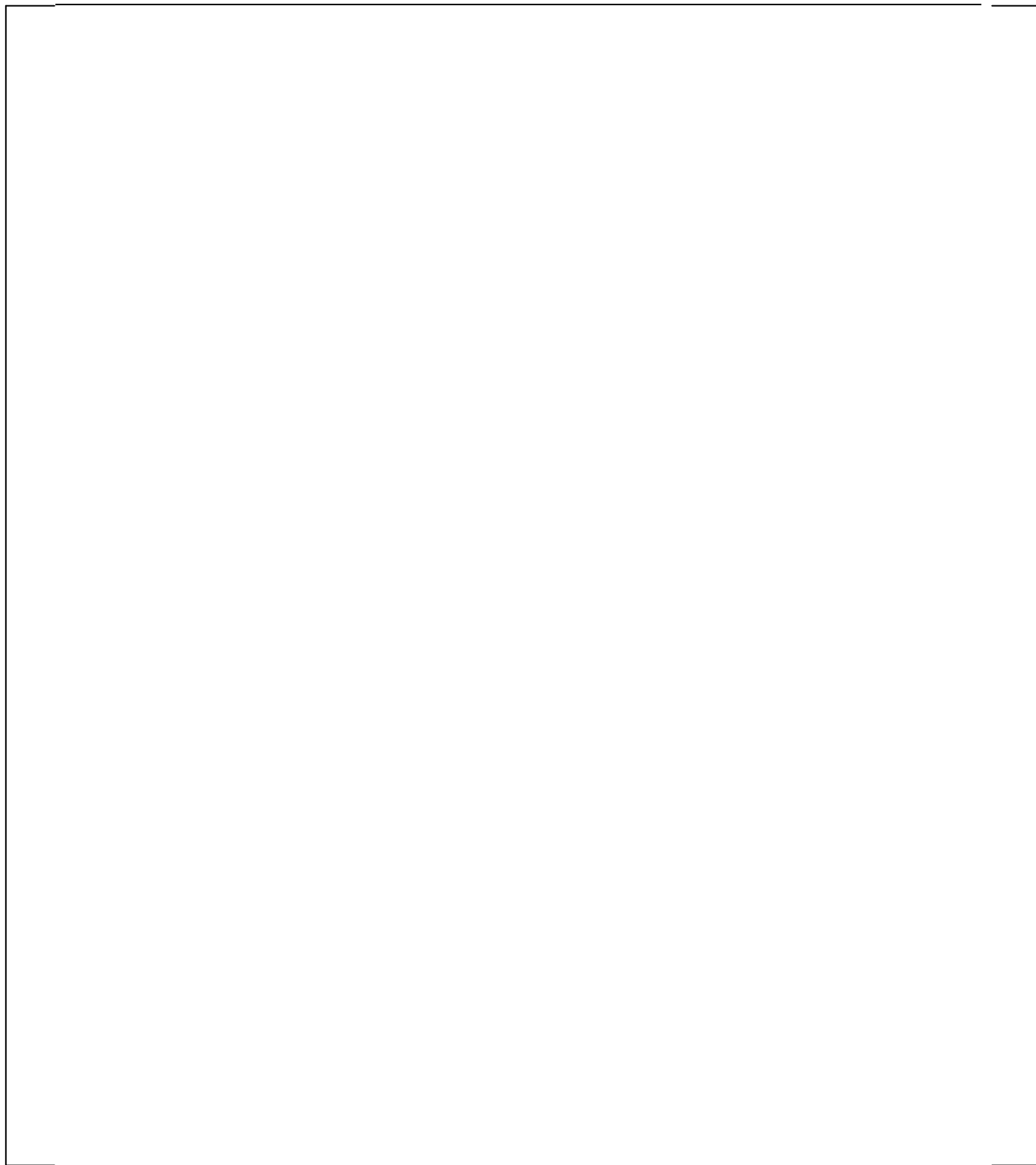
**Table A3-1 Blowdown Analysis Results (2/2)**

Figure No.	System	Subsystem	Nominal Diameter (Inches)	Loop	Break Location	Single Phase Steam Start Time(s)/ Pressure(lb/in <sup>2</sup> )	Single Phase Steam End Time(s)/ Pressure(lb/in <sup>2</sup> )
A3-12	RCS	Pressurizer Safety Depressurization Valve Line	4	B	PZR		
A3-13	RCS	Pressurizer Safety Depressurization Valve Line	8	B	PZR		
A3-14	CVS	Seal Injection Line	1.5	B	RCP		

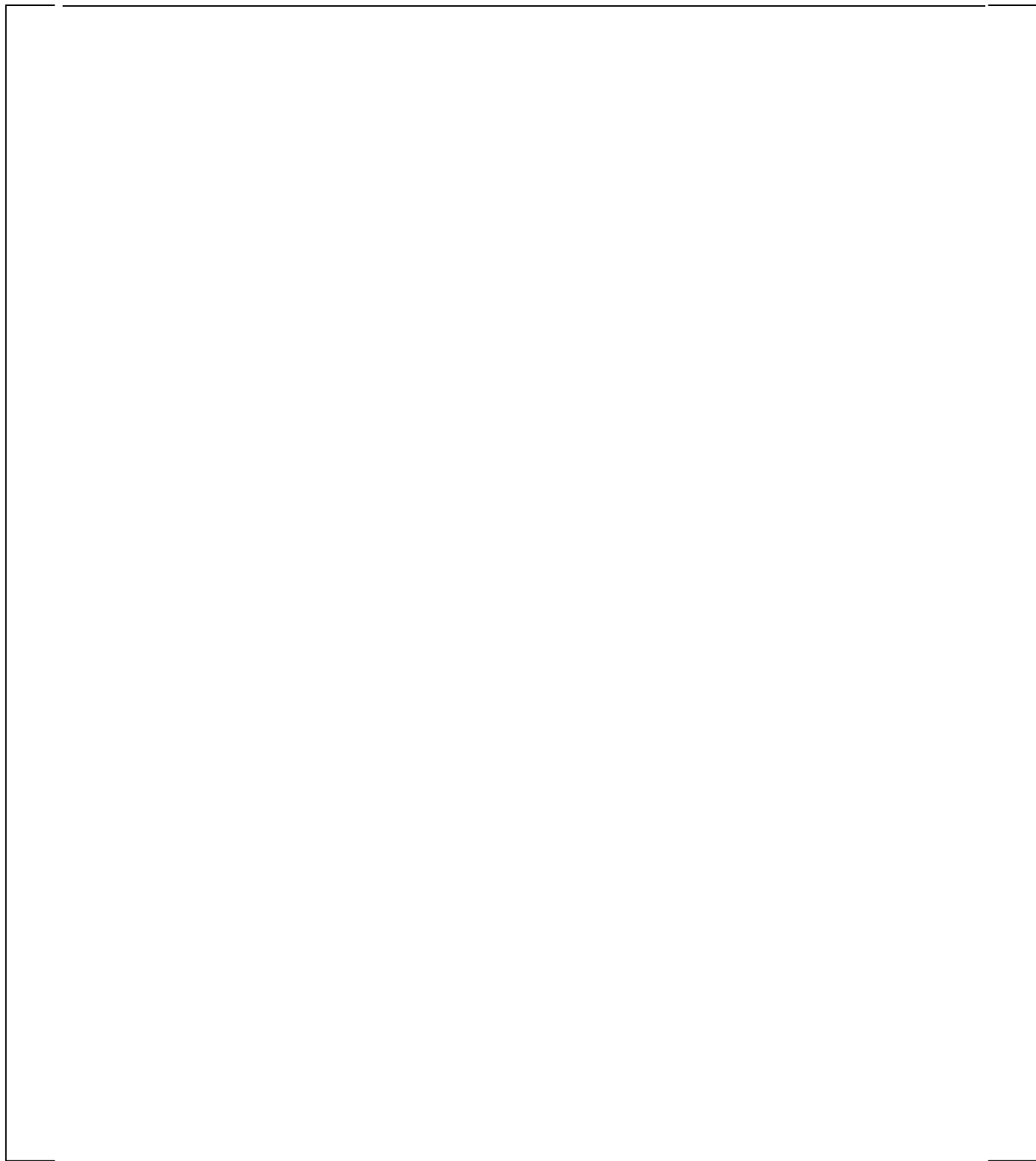


**Figure A3-1 RHRs Hot Leg Branch Line off RCS  
(Hot Leg 10-inch Break - B Loop)**

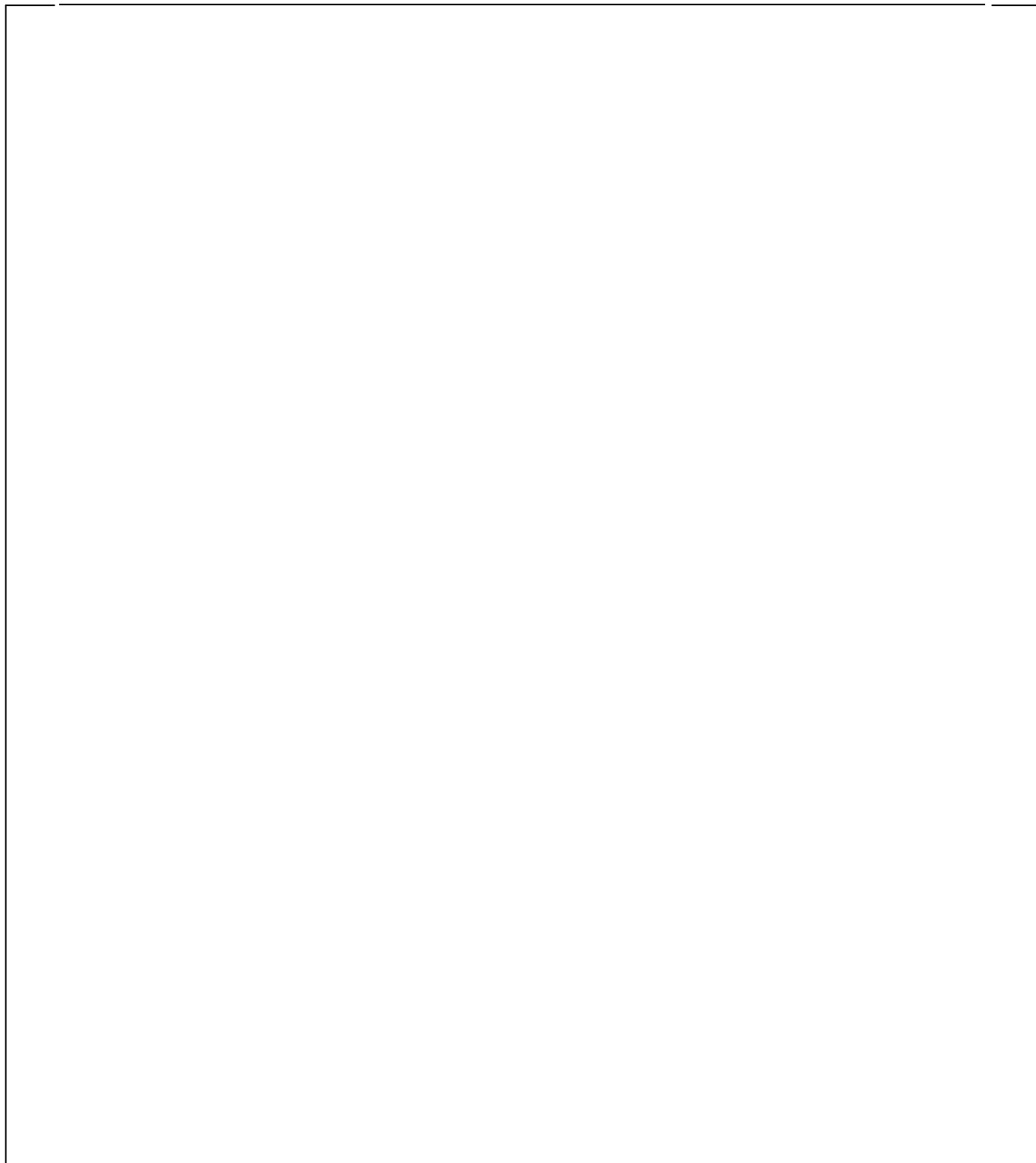




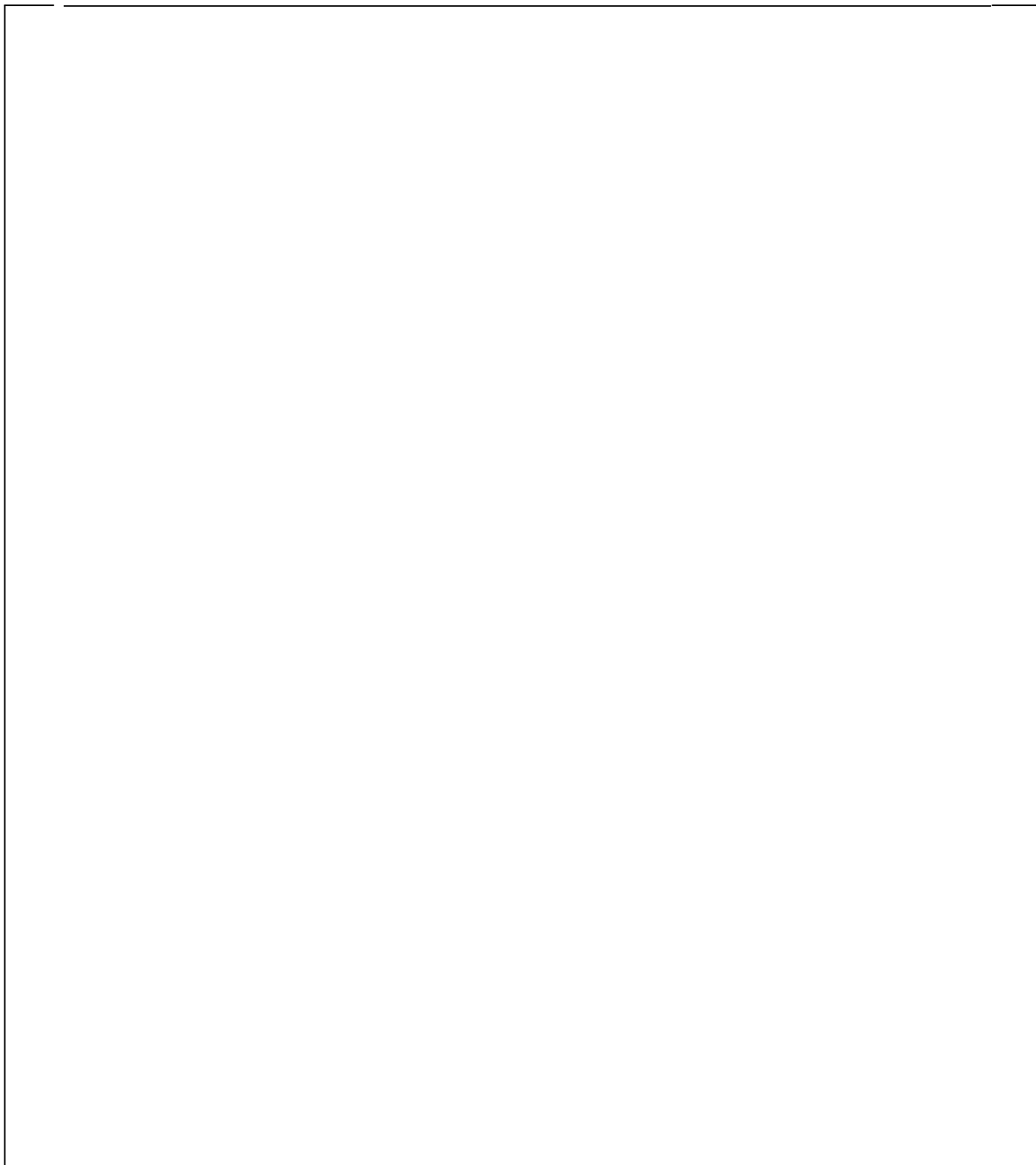
**Figure A3-2 RHRs Hot Leg Branch Line off RCS  
(Hot Leg 10-inch Break - A, C, D Loop)**



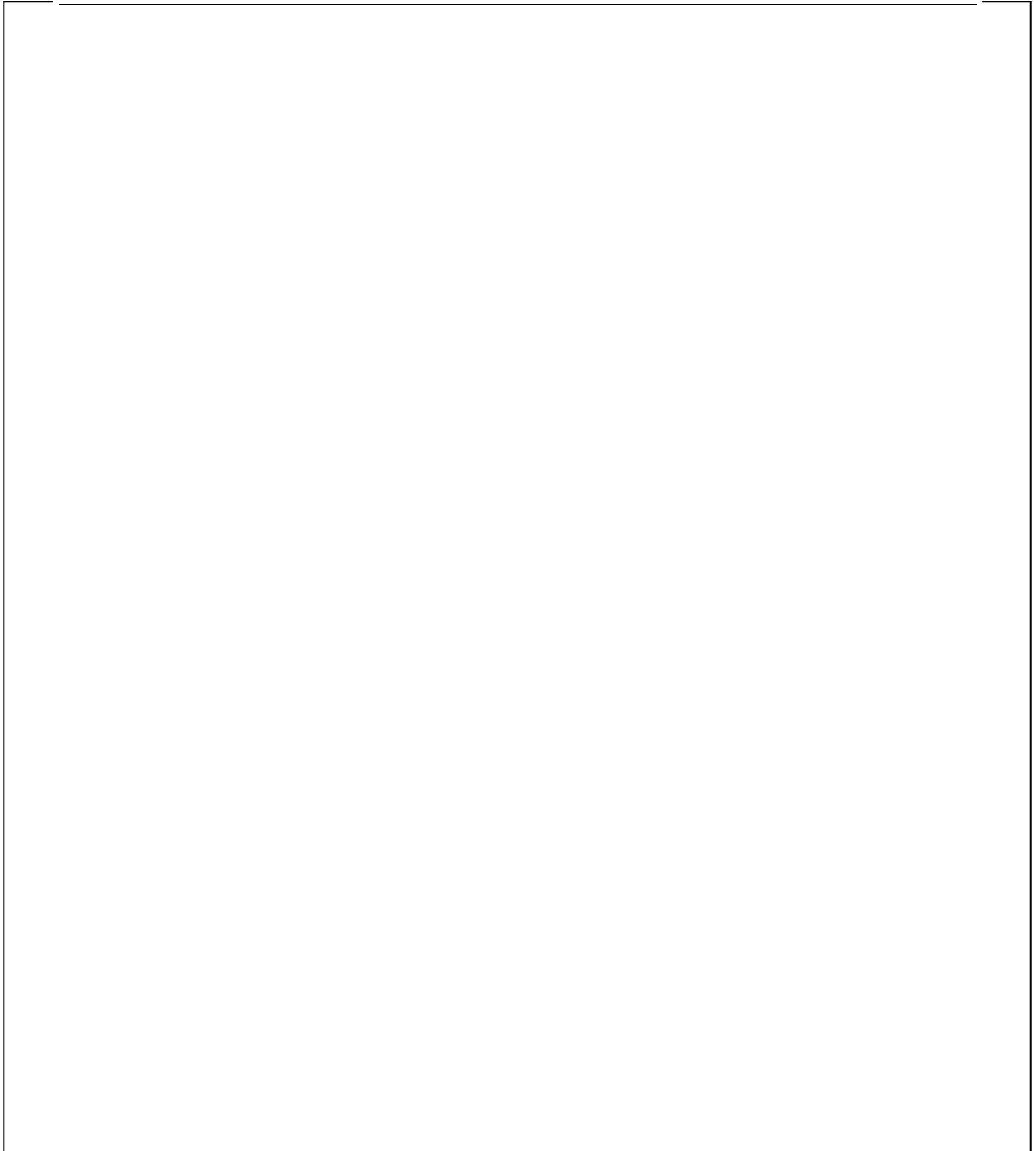
**Figure A3-3 RHRs Cold Leg Branch Line off RCS  
(Cold Leg 8-inch Break - B Loop)**



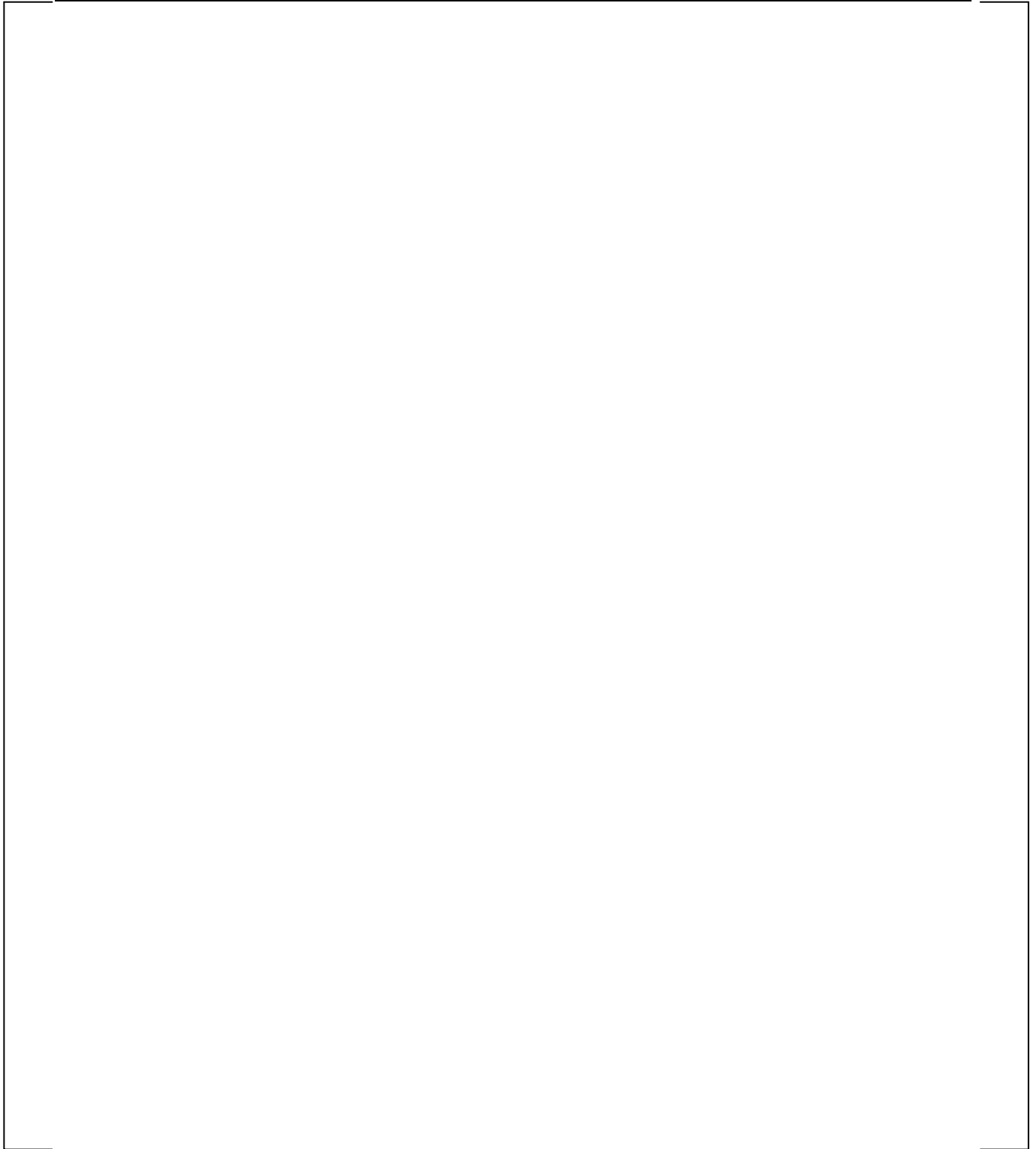
**Figure A3-4 RHRs Cold Leg Branch Line off RCS  
(Cold Leg 8-inch Side Break - A, C, D Loop)**



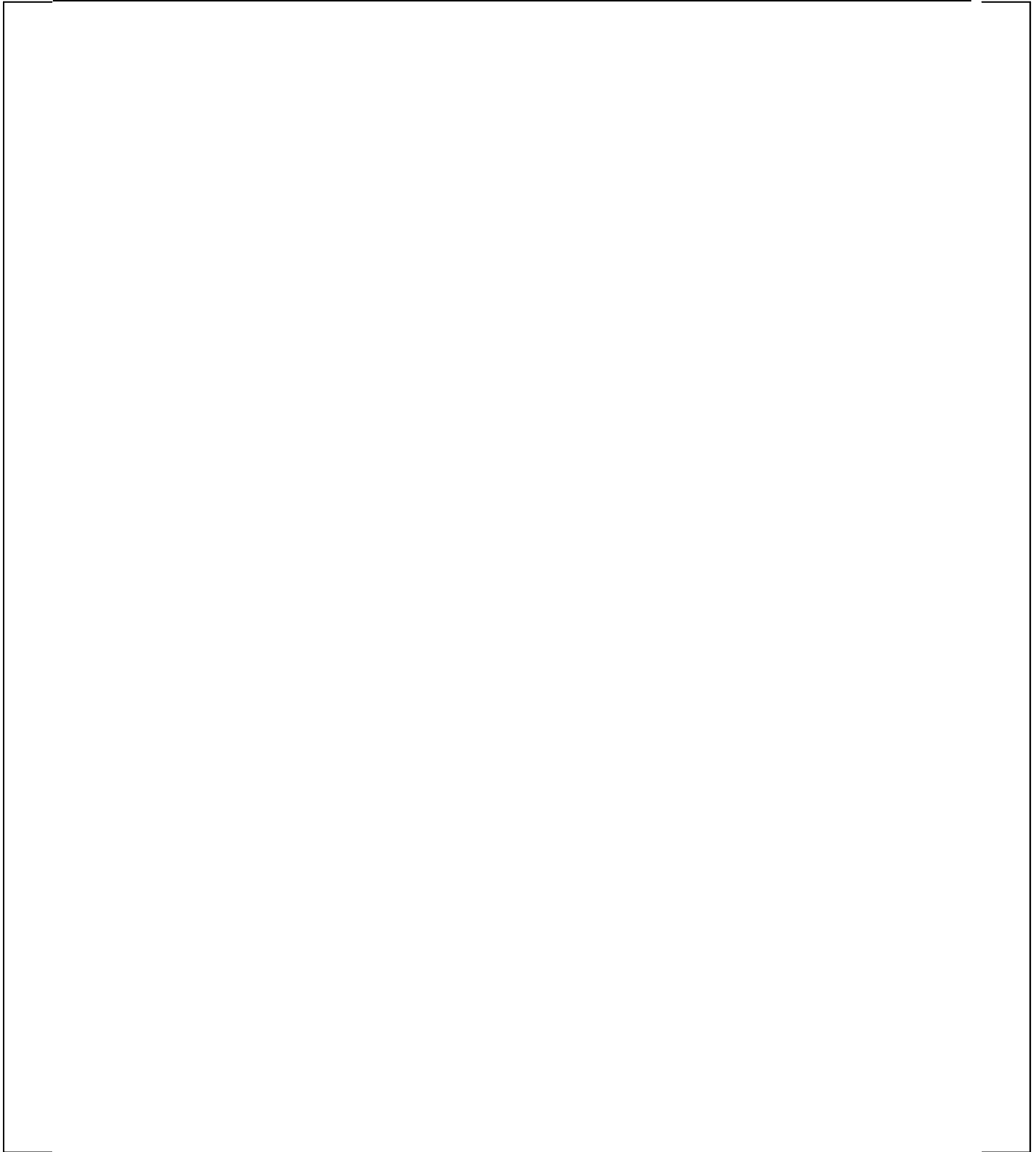
**Figure A3-5 Pressurizer Spray Line  
(Cold Leg 6-inch Break - B Loop)**



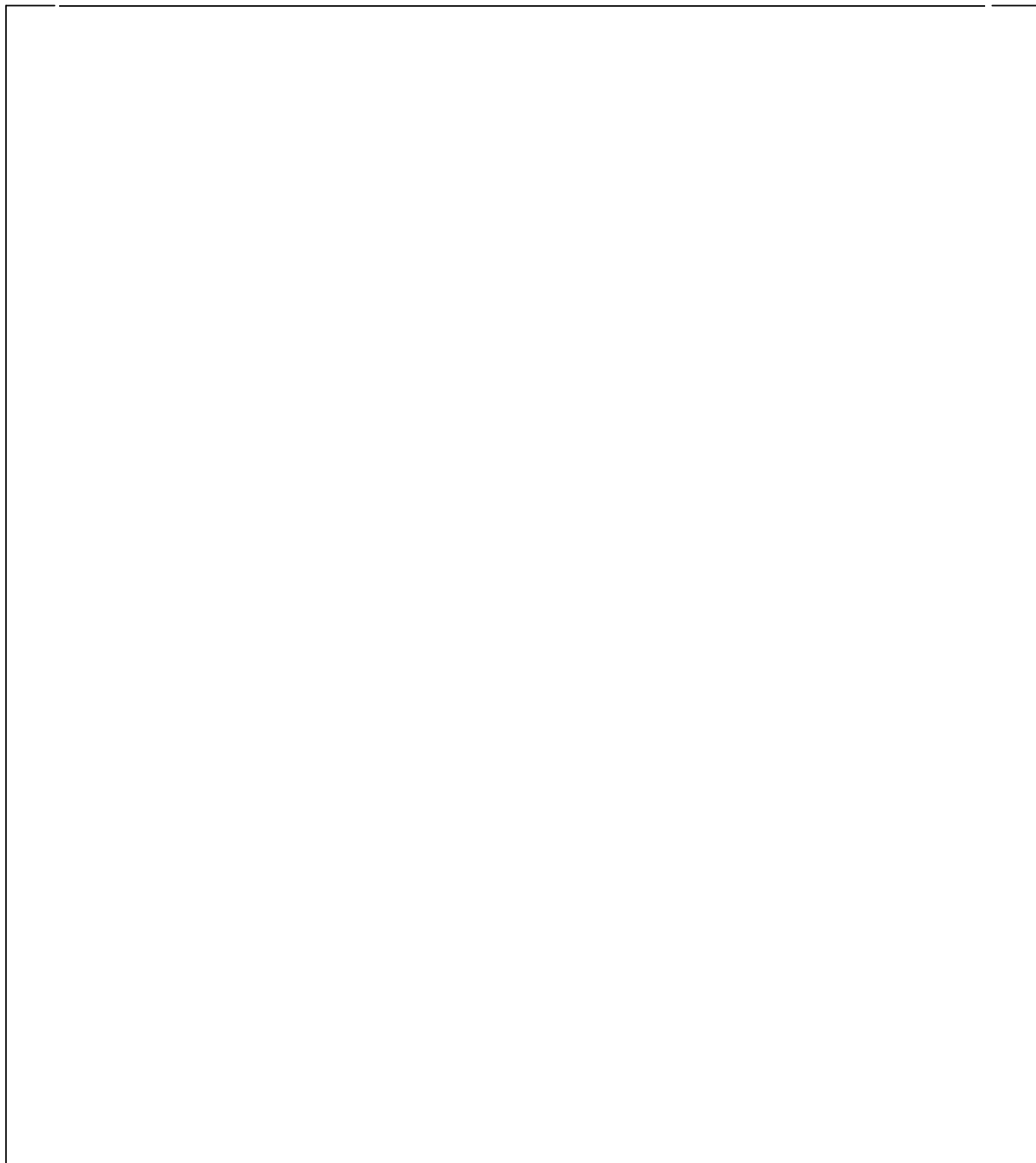
**Figure A3-6 Pressurizer Spray Line  
(Cold Leg 6-inch Break - C Loop)**



**Figure A3-7 Charging Line  
(Cold Leg 4-inch Break - A Loop)**

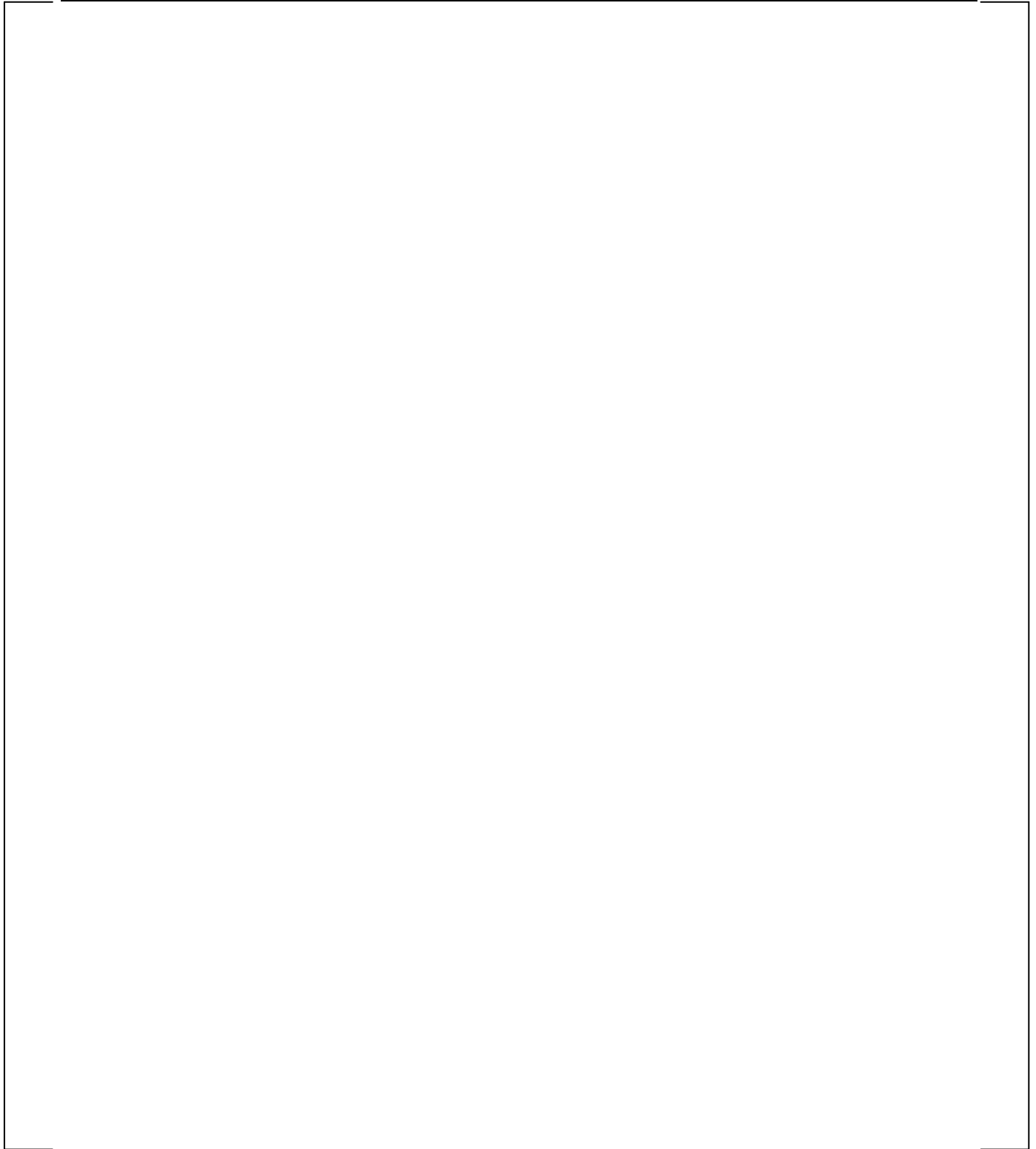


**Figure A3-8 Let down Line  
(Cross Over Leg 3-inch Break - D Loop)**

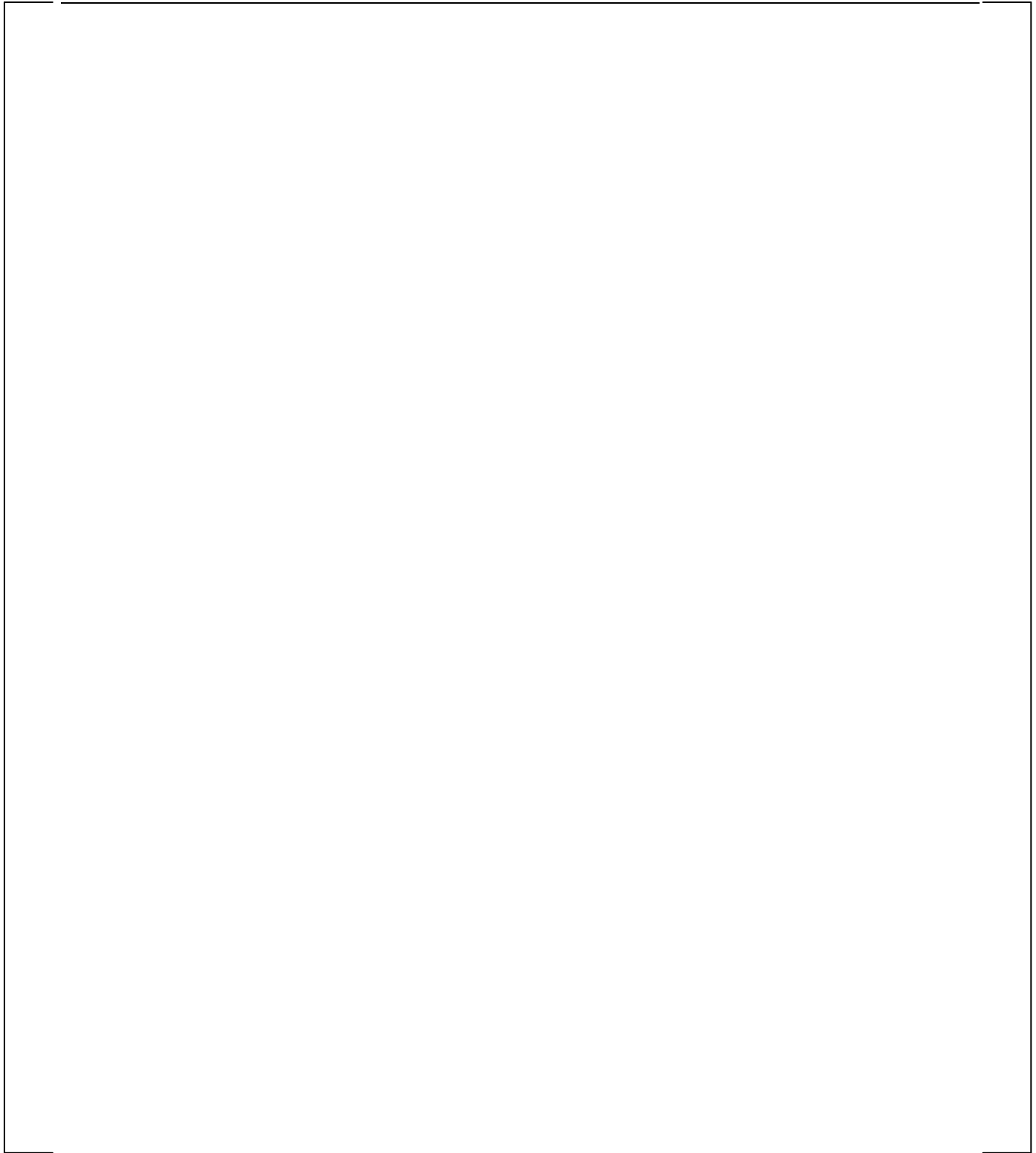


**Figure A3-9 Loop Drain/Excess Letdown Line  
(Cross Over Leg 2-inch Break - A, C Loop)**

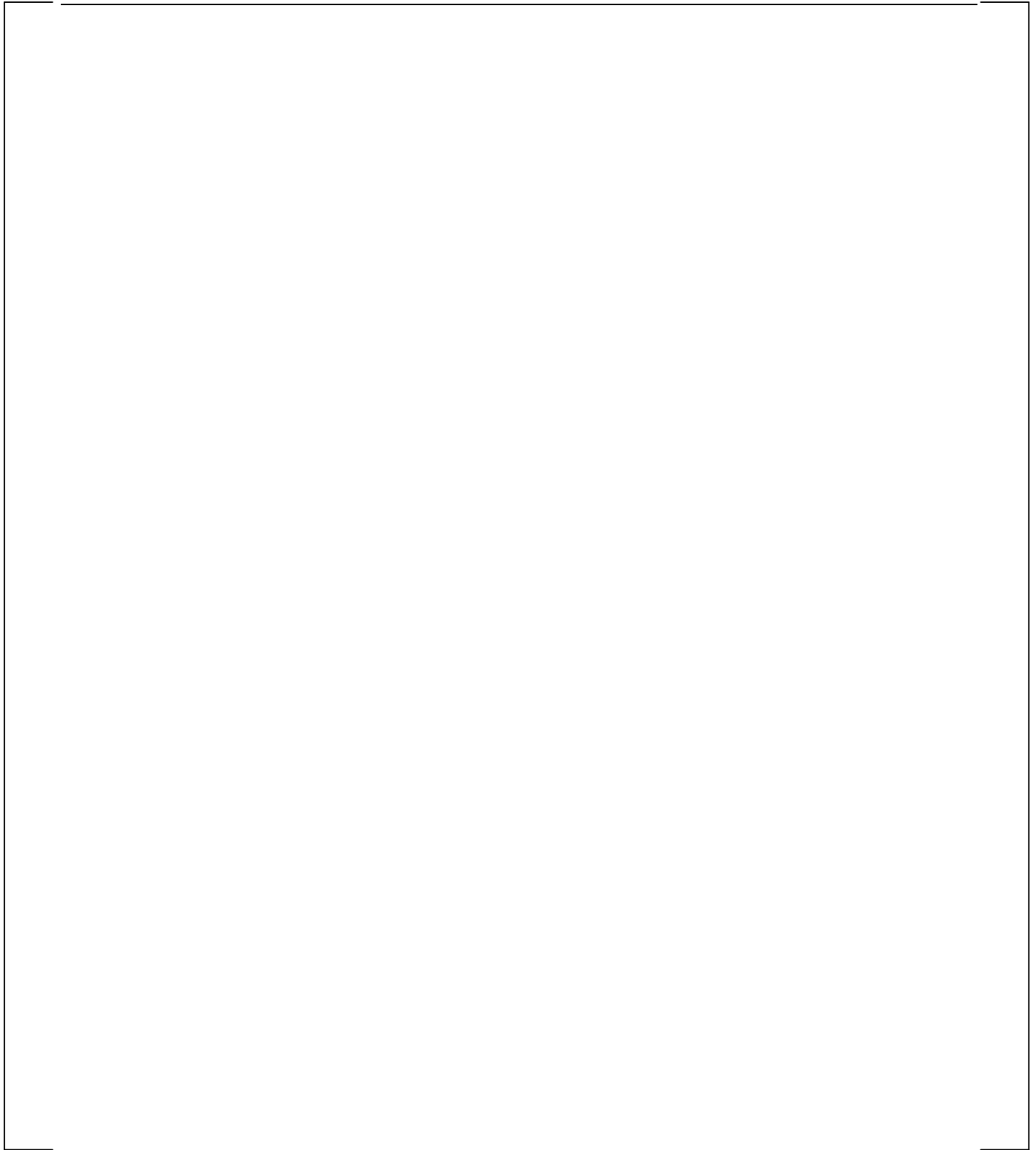




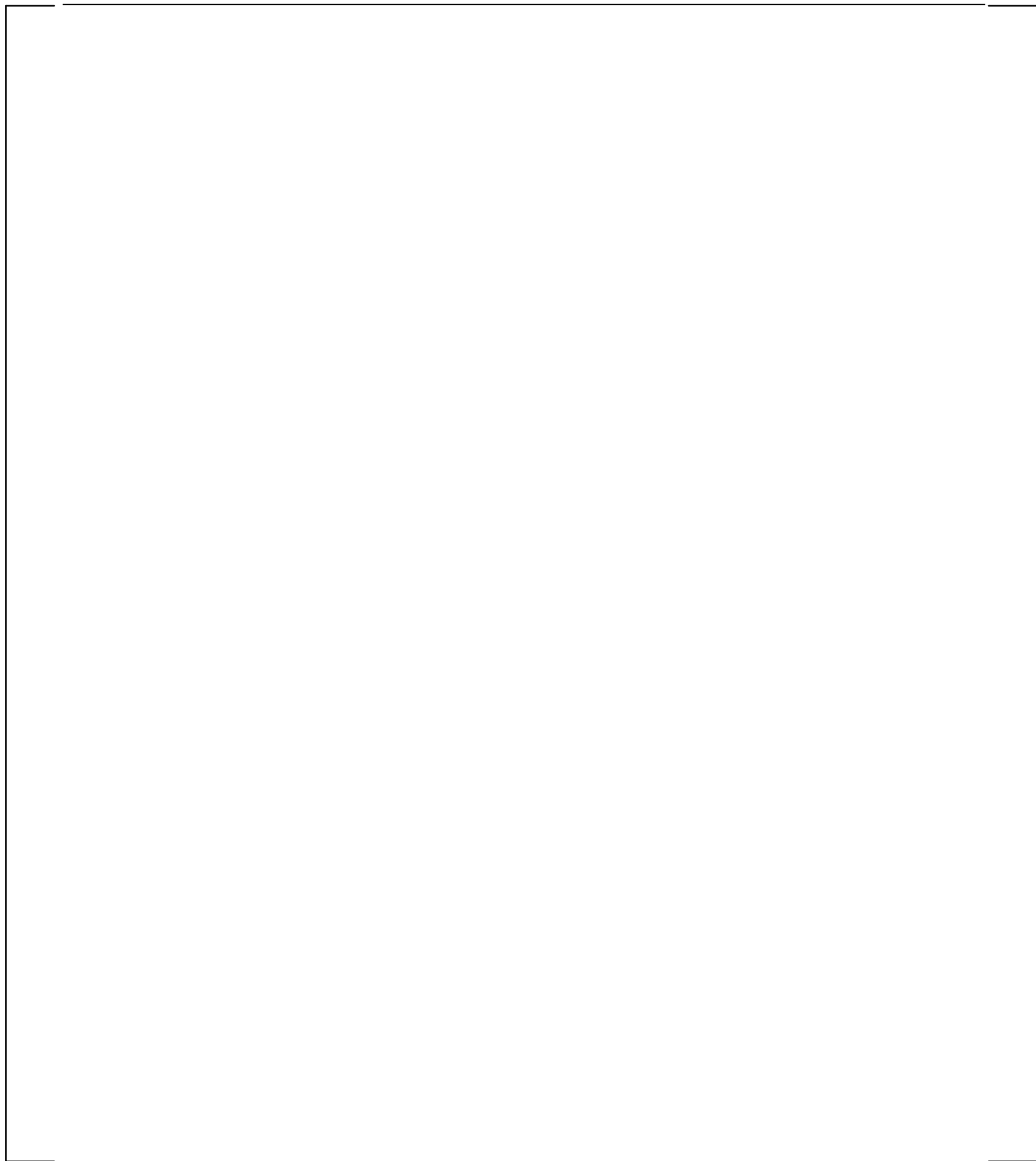
**Figure A3-10 Loop Drain  
(Cross Over Leg 2-inch Break - B Loop)**



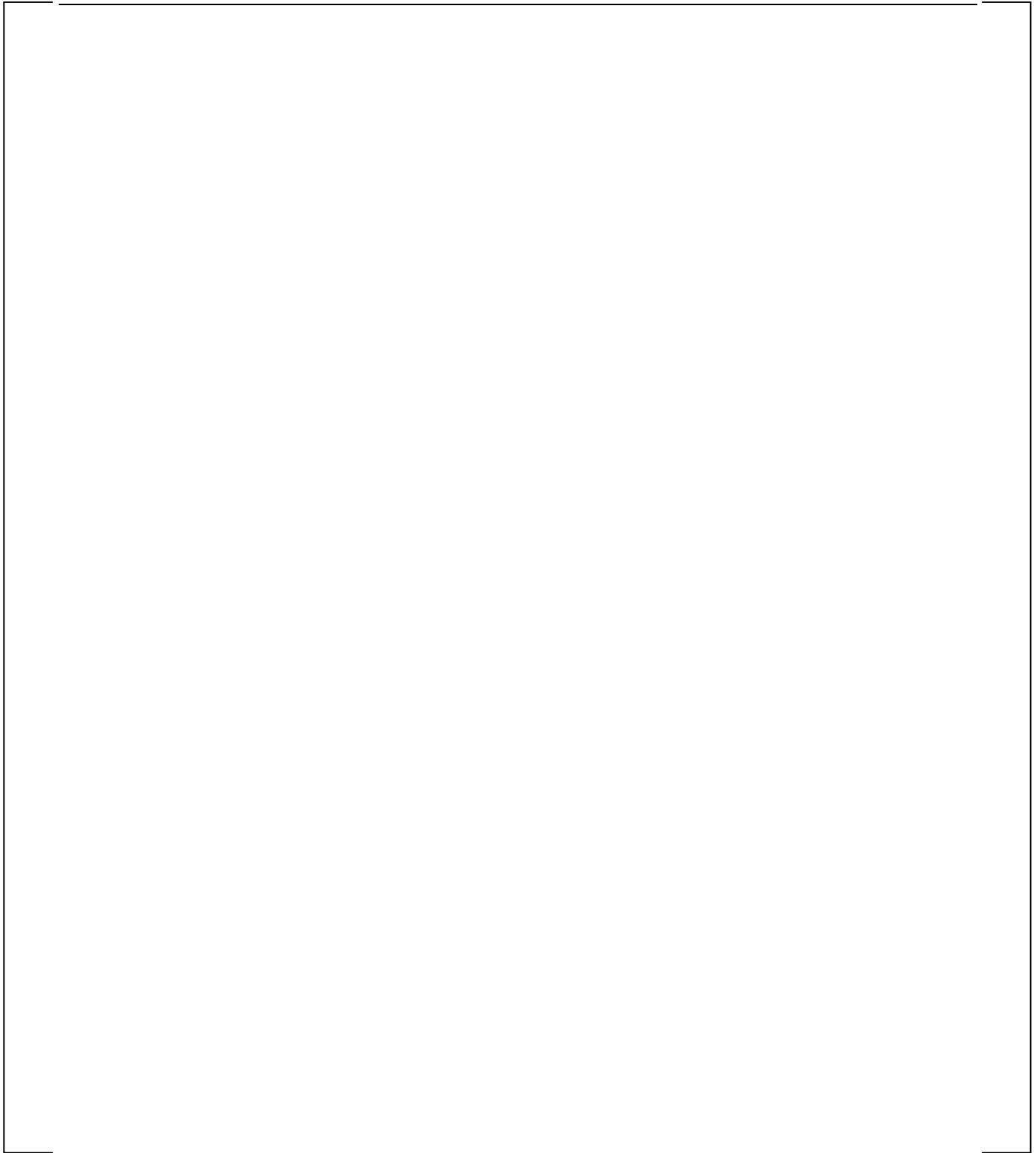
**Figure A3-11 Pressurizer Safety Valve Line  
(Pressurizer 6-inch Break)**



**Figure A3-12 Pressurizer Safety Depressurization Valve Line  
(Pressurizer 4-inch Break)**



**Figure A3-13 Pressurizer Safety Depressurization Valve Line  
(Pressurizer 8-inch Break)**



**Figure A3-14 Seal Injection Line  
(RCP 1.5-inch Break)**

## **Appendix 4**

# **Simple Beam Methodology in consideration of Resonating High Frequency Mode**

**TABLE OF CONTENTS**

**LIST OF FIGURES ..... A4-3**

**LIST OF TABLES ..... A4-4**

1.0 SIMPLE MODE MODEL RESONATING WITH A JET OSCILLATION ..... A4-5

    1.1 JET LOAD ..... A4-5

    1.2 ONE ANTI-NODE SPAN MODEL ..... A4-6

    1.3 EFFECTIVE LOAD FOR HIGH FREQUENCY MODE..... A4-7

    1.4 NUMBER OF ANTI-NODE..... A4-10

**LIST OF FIGURES**

Figure A4-1-1	Vibration Mode of a Pipe Resonating with the Jet Oscillation	A4-6
Figure A4-1-2	Equivalent Partial Model of a Pipe Subjected to a Dynamic Distributed Load that Excites the Vibration Mode	A4-6
Figure A4-1-3	Lumped Mass Vibration System (under loading conditions that excite vibration modes)	A4-8
Figure A4-1-4	Lumped Mass Vibration System (under actual loading conditions)	A4-8
Figure A4-1-5	Effective Load in the Resonance Model	A4-9



**LIST OF TABLES**

Appendix 4 has no tables

**1.0 SIMPLE MODE MODEL RESONATING WITH A JET OSCILLATION**



**1.1 Jet Load**



**1.2 One Anti-Node Span Model**



**Figure A4-1-1 Vibration Mode of a Pipe Resonating with the Jet Oscillation**



**Figure A4-1-2 Equivalent Partial Model of a Pipe Subjected to a Dynamic Distributed load that Excites the Vibration Mode**

**1.3 Effective Load for High Frequency Mode**



**Figure A4-1-3 Lumped Mass Vibration System (under loading conditions that excite vibration modes)**



**Figure A4-1-4 Lumped Mass Vibration System (under actual loading conditions)**



**Figure A4-1-5 Effective Load in the Resonance Model**

**1.4 Number of Anti-Node**



## **Appendix 5**

### **Frequency of Jet Pressure Oscillation**



**TABLE OF CONTENTS**

**LIST OF FIGURES** ..... A5-3

**LIST OF TABLES** ..... A5-4

1.0 CONSIDERATION FROM KIM'S PAPER ..... A5-5

2.0 CONSIDERATION FROM TAM'S PAPER..... A5-9

3.0 REFERENCES..... A5-12

**LIST OF FIGURES**

Figure A5-1-1	Correlation of the Oscillation Frequency with the First Shock Cell, Shock Wave Distance and Pipe Diameter	A5-5
Figure A5-1-2	Contour Diagrams Obtained by Free-jet Analysis	A5-7
Figure A5-1-3	Results of Oscillation Frequency Calculation (Specific Heat Ratio: 1.3)	A5-8
Figure A5-2-1	Type 1 Bessel Function Graph	A5-10
Figure A5-2-2	Velocity Contour from Free-Jet Analysis (Results of Analysis Under Actual Operating Conditions)	A5-10
Figure A5-2-3	Results of the Calculation of the Oscillation Frequency	A5-12

LIST OF TABLES

Table A5-1-1	Calculation Conditions	A5-6
Table A5-2-1	Results of Calculation of Minimum Oscillation Frequency (Jet Diameter :8D)	A5-11

**1.0 CONSIDERATION FROM KIM'S PAPER**



**Figure A5-1-1 Correlation of the Oscillation Frequency with the First Shock Cell,  
Shock Wave Distance and Pipe Diameter**

**Table A5-1-1 Calculation Conditions**



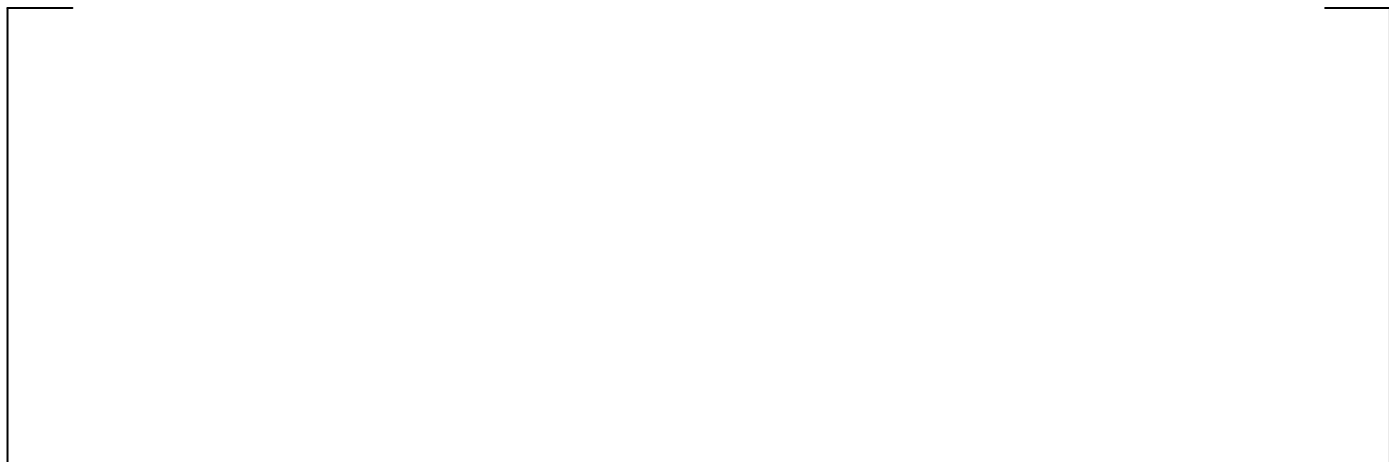
**Figure A5-1-2 Contour Diagrams Obtained by Free-Jet Analysis**



**Figure A5-1-3 Results of Oscillation Frequency Calculation (Specific Heat Ratio: 1.3)**

**2.0 Consideration from Tam's Paper**





**Figure A5-2-1 Type 1 Bessel Function Graph**



**Figure A5-2-2 Velocity Contour from Free-Jet Analysis (Results of Analysis Under  
Actual Operating Conditions)**

**Table A5-2-1 Results of Calculation of Minimum Oscillation Frequency  
(Jet Diameter :8D)**





**Figure A5-2-3 Results of the Calculation of the Oscillation Frequency**

### **3.0 REFERENCES**

- A5-1 Kim, S.I and Park, S.O., "Oscillatory behavior of supersonic impinging jet flows", 2005
- A5-2 Tam,C.K.W and Ahuja,K. K. ,"Theoretical Model of Distance Tone Generation by Impinging Jets", 1990

## **Appendix 6**

# **Example of Structural Analysis for Jet Pressure Oscillation**

**TABLE OF CONTENTS**

**LIST OF FIGURES ..... A6-3**

**LIST OF TABLES ..... A6-4**

1.0 CALUCULATION EXAMPLE OF SIMPLE BEAM (HAND CALCULATION)..... A6-5

    1.1 CALCULATION CONDITIONS..... A6-5

    1.2 CALCULATION RESULTS..... A6-7

2.0 ANALYSIS EXAMPLE OF 3D BEAM MODEL FOR PIPING SYSTEMS..... A6-14

    2.1 ANALYSIS CONDITIONS..... A6-14

    2.2 ANALYSIS RESULTS ..... A6-17

3.0 ANALYSIS EXAMPLE OF FEM MODEL FOR JET BARRIER..... A6-23

    3.1 ANALYSIS CONDITIONS..... A6-23

    3.2 ANALYSIS RESULTS ..... A6-26

---

**LIST OF FIGURES**

Figure A6-1-1	Jet Impingement Model Image	A6-5
Figure A6-1-2	Jet Load of Calculation Model	A6-8
Figure A6-1-3	Calculation of Maximum Moment	A6-9
Figure A6-1-4	Calculation Model of Resonance	A6-11
Figure A6-2-1	The Load Time Histories of Pressure Oscillation	A6-15
Figure A6-2-2	Analysis Load Set Image	A6-16
Figure A6-2-3	Piping System Model	A6-18
Figure A6-2-4	46 <sup>th</sup> Mode Shape	A6-19
Figure A6-2-5 (1/3)	Moment of X- Direction Time Histories	A6-20
Figure A6-2-5 (2/3)	Moment of Y - Direction Time Histories	A6-21
Figure A6-2-5 (3/3)	Moment of Z - Direction Time Histories	A6-22
Figure A6-3-1	Simplified Jet barrier model	A6-24
Figure A6-3-2	Boundary conditions of the analytical model	A6-25
Figure A6-3-3	FE model of Jet barrier	A6-26
Figure A6-3-4	1 <sup>st</sup> Mode Shape (overturning of whole body [240Hz])	A6-27
Figure A6-3-5	2 <sup>nd</sup> Mode Shape (twist of pillar [316Hz])	A6-27
Figure A6-3-6	Transient response maximum stress (Max stress 13.4MPa / Time=0.0216 s)	A6-28

**LIST OF TABLES**

Table A6-1-1	Break Piping Specification	A6-6
Table A6-1-2	Jet Impinged Piping Specification	A6-6
Table A6-1-3	Jet Characteristics	A6-6
Table A6-2-1	Impinged Piping Specification	A6-14
Table A6-2-2	Jet Characteristics	A6-15
Table A6-2-3	Maximum Moment and Stress	A6-17
Table A6-3-1	Specification of jet barrier model	A6-23
Table A6-3-2	Analytical model input list	A6-25

**1.0 CALCULATION EXAMPLE OF SIMPLE BEAM (HAND CALCULATION)**



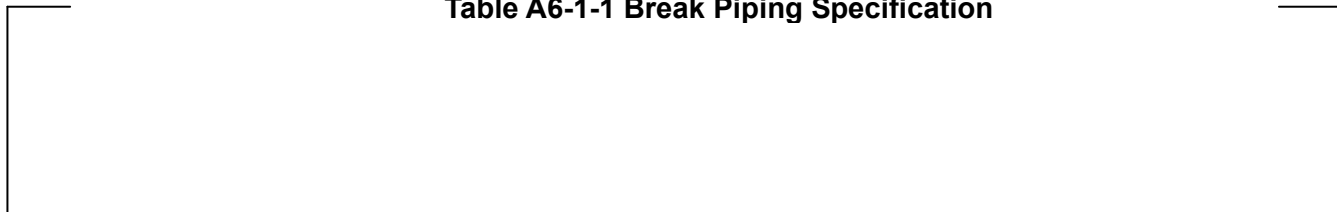
**1.1 Calculation Conditions**



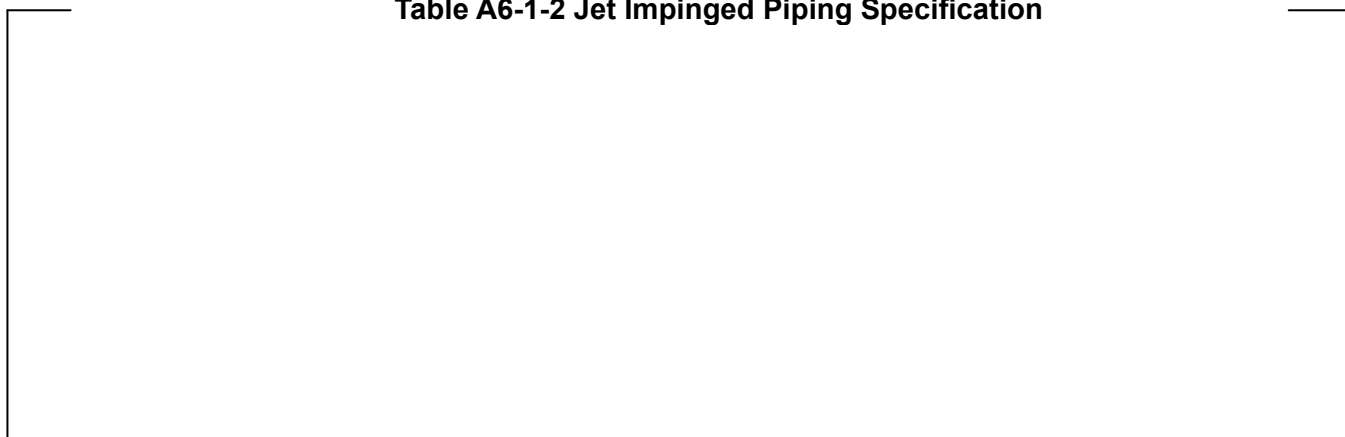
**Figure A6-1-1 Jet Impingement Model Image**



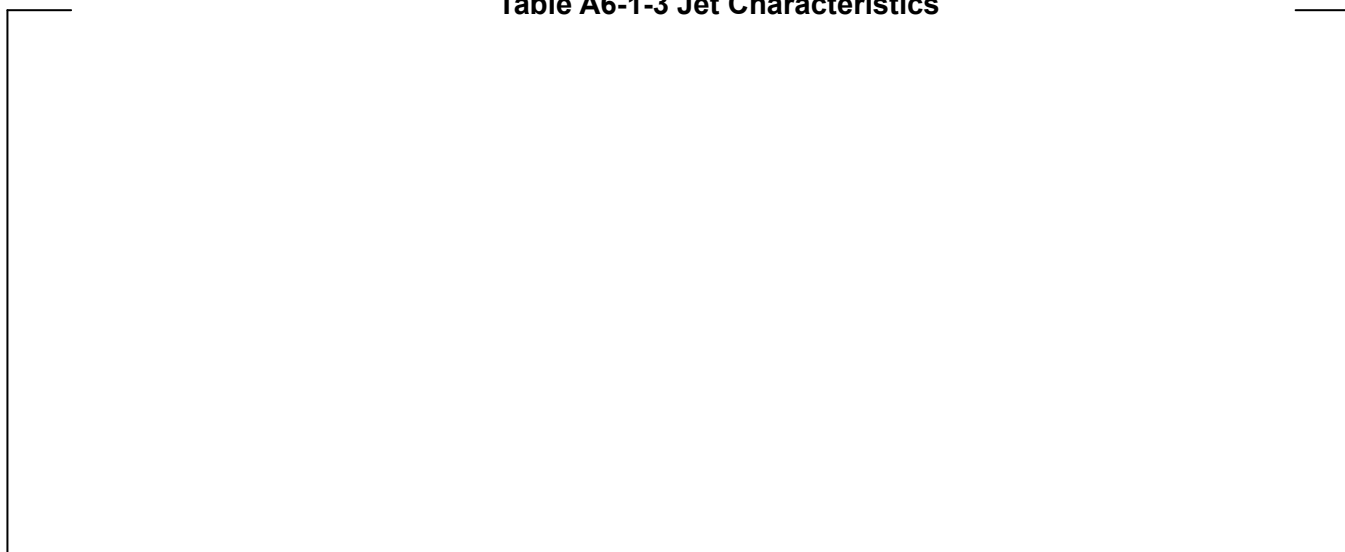
**Table A6-1-1 Break Piping Specification**



**Table A6-1-2 Jet Impinged Piping Specification**



**Table A6-1-3 Jet Characteristics**



**1.2 Calculation Results**

**1.2.1 Calculation for Pipe Stress from Static Steam Jet Load**

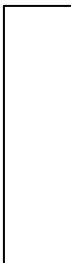
**Figure A6-1-2 Jet Load of Calculation Model**



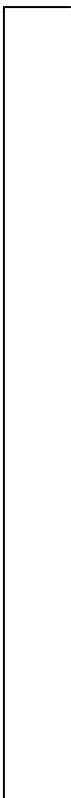
**Figure A6-1-3 Calculation of Maximum Moment**

**1.2.2 Calculation for pipe stress from resonance with the piping**

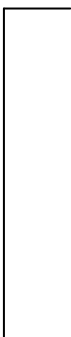
**1) Amplification factor ( $A_f$ ):**



**2) Load :**

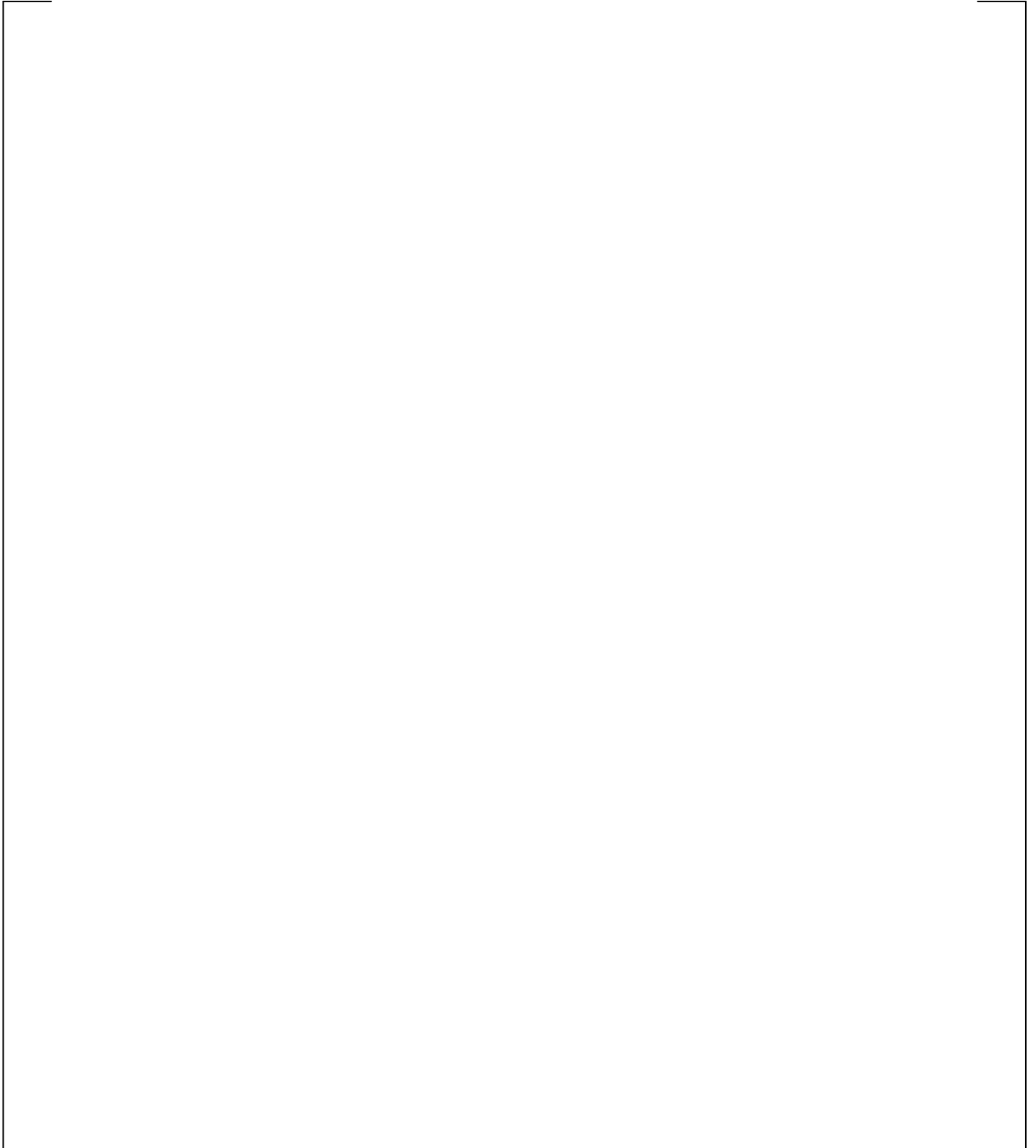


**3) Moment (part center of piping):**



**4) Stress:**

**5) Number of anti-node:**



**1.2.3 Pipe Stress by jet pressure oscillation**





**2.0 ANALYSIS EXAMPLE OF 3D BEAM MODEL FOR PIPING SYSTEMS**

**2.1 Analysis Conditions**

**Table A6-2-1 Impinged Piping Specification**

**Table A6-2-2 Jet Characteristics**



**Figure A6-2-1 The Load Time Histories of Pressure Oscillation**



**Figure A6-2-2 Analysis Load Set Image**

**2.2 Analysis Results**

**Table A6-2-3 Maximum Moment and Stress**

Figure A6-2-3 Piping System Model

Figure A6-2-4 46<sup>th</sup> Mode Shape

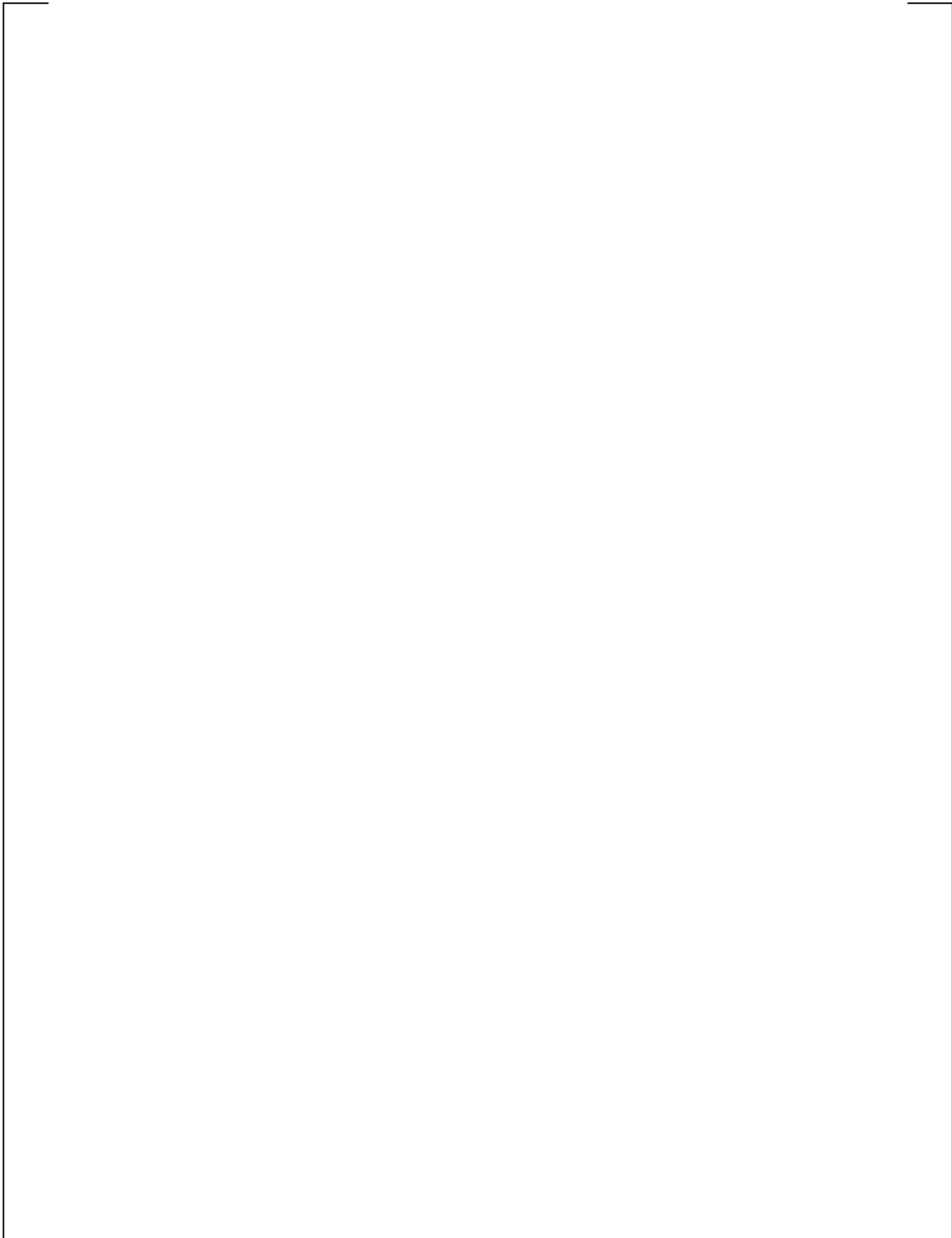


Figure A6-2-5 (1/3) Moment of X- Direction Time Histories

Figure A6-2-5 (2/3) Moment of Y - Direction Time Histories





Figure A6-2-5 (3/3) Moment of Z - Direction Time Histories

**3.0 ANALYSIS EXAMPLE OF FEM MODEL FOR JET BARRIER**

**3.1 Analysis Conditions**

**Table A6-3-1 Specification of jet barrier model**



**Figure A6-3-1 Simplified Jet barrier model**



**Figure A6-3-2 Boundary conditions of the analytical model**

**Table A6-3-2 Analytical model input list**

A large, empty rectangular frame with a thin black border, occupying the lower half of the page. It is positioned below the second caption and above the footer.



**Figure A6-3-3 FE model of Jet barrier**

### **3.2 Analysis Results**





**Figure A6-3-4 1<sup>st</sup> Mode Shape (overturning of whole body [240Hz])**



**Figure A6-3-5 2<sup>nd</sup> Mode Shape (twist of pillar [316Hz])**



**Figure A6-3-6 Transient response maximum stress**  
**(Max stress 13.4MPa / Time=0.0216 s)**