NUREG/CR--5220-Vol.1

TI89 002152

Diagnosis of Condensation-Induced Waterhammer

Methods and Background

Manuscript Completed: August 1988
Date Published: October 1988

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Prepared for
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Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN D1703

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ABSTRACT

This guidebook provides reference material and diagnostic procedures concerning condensation–induced waterhammer in nuclear power plants. Condensation–induced waterhammer is the most damaging form of waterhammer and its diagnosis is complicated by the complex nature of the underlying phenomena. In Volume 1, the guidebook groups condensation–induced waterhammers into five event classes which are have similar phenomena and levels of damage. Diagnostic guidelines focus on locating the event center where condensation and slug acceleration take place. Diagnosis is described in three stages: an initial assessment, detailed evaluation and final confirmation. Graphical scoping analyses are provided to evaluate whether an event from one of the event classes could have occurred at the event center. Examples are provided for each type of waterhammer. Special instructions are provided for walking down damaged piping and evaluating damage due to waterhammer. To illustrate the diagnostic methods and document past experience, six case studies have been compiled in Volume 2. These case studies, based on actual condensation–induced waterhammer events at nuclear plants, present detailed data and work through the event diagnosis using the tools introduced in the first volume.

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PREFACE

Condensation–induced waterhammer is physically complex and extreme events can be very damaging to piping systems. Diagnosis can be difficult without previous experience with condensation and two–phase flow analysis and testing. For this reason the NRC has commissioned this guidebook for diagnosing these complex, troublesome and frequent (10 per year) events. The purpose is to present recommendations and methods for diagnosing condensation–induced waterhammer which can be used by investigators to help determine the cause of a damaging fluid transient. Creare Inc. has been active in this field since 1975, solving problems for the government and the nuclear industry related to multiphase fluid transients. In this guidebook we have tried to distill our experience in a form which is accessible to the non–specialist.

We would like to express our appreciation to the numerous individuals who assisted in the preparation of this guidebook:

- Michael Gahan and Stephen Davis of Balitimore Gas and Electric,
- John Fox and Jim Abel of Commonwealth Edison Company,
- Kenneth Chau of Consumer's Power Company,
- Don Pracht, Bob Hammelmann, and Rick Casella of Niagara Mohawk Power Corporation,
- Peter Quinlan of NUSCo,
- Charlie Williamson of Public Service Electricity and Gas,
- Mark Medford at Southern California Edison,
- Roy Uffer of Quadrex Energy Services Corp.

- Peter Griffith of MIT,

- Charles Troutman, Alec Serkiz, Tony D'Angelo, Duane Danielson, Randall Huey, Kerry Landis, Joe Lenahan and Peter Wen of NRC,

- Frank Dolan, Heidi Krueger and Dodd Stacy of Creare Inc.

DIAGNOSIS OF CONDENSATION–INDUCED WATERHAMMER

1 SUMMARY AND INTRODUCTION

This report is intended to support post–event diagnosis and evaluation of waterhammer events in nuclear power plants. It is written primarily for NRC inspectors and other staff participating in investigation teams, and may also benefit utility personnel who are investigating waterhammer events. This report provides specialized technical material. It does not replace or modify procedures normally followed during investigations.

Based on Licensee Event Reports and published compendia of events (Chapman, 1982; Leeds, 1986; Serkiz, 1987), about 200 waterhammer events at nuclear plants were reported to the NRC in the period 1969 to 1986. Some of these events were due to condensation–induced waterhammer and those were the most physically complex and difficult to diagnose. Furthermore, these condensation–induced events are the ones primarily responsible for significant damage or impact on plant operation. NRC Regional inspectors are sometimes called upon to diagnose these events. This report familiarizes the investigator with condensation–induced waterhammer and provides material to aid in field evaluation of such events.

1.1 PURPOSE

This guidebook has two purposes. The first is to provide training and reference material for the diagnosis of condensation–induced waterhammer events in nuclear power plants. Sections of the guidebook are thus devoted to presenting the basic phenomenology of severe waterhammer events, while other sections review event diagnosis through presentation of cases based on actual waterhammer events. The second purpose is to serve as a field guide for use during and after the investigation of waterhammer events. General procedures are introduced to structure investigations. Checklists and graphical tools are presented to aid during an investigation.

In support of these general purposes, this guidebook has five specific objectives, which are to:

1. illustrate the phenomenology of condensation–induced waterhammer,
2. present a procedure for event diagnosis,
3. present guidelines for evaluating damage from waterhammer events,
4. illustrate event diagnosis through detailed diagnostic cases based on actual waterhammer events, and
5. present graphical tools and information to aid in the analytic aspects of event diagnosis.

The structure of the guidebook is based on these objectives. The following section briefly summarizes the contents of the guidebook.

1.2 SYNOPSIS

This guidebook is organized in two volumes: Methods and Background, and Case Studies. Volume 1 (Methods and Background) proceeds from a review of condensation–induced waterhammer phenomena through diagnostic techniques. Volume 2 (Case Studies) presents detailed information from condensation–induced waterhammer events. Several sections serve primarily as training or background material while others are written as a field guide for use during investigations. The sections which are intended primarily as training material are:

- Chapter 2 ("Condensation–Induced Waterhammer Phenomena" in Vol. 1), and
- Volume 2 ("Case Studies in Condensation–Induced Waterhammer").

Sections to provide support during field investigations into the cause of condensation–induced waterhammers are:

- Chapter 3 ("Diagnostic Techniques" in Vol. 1),
- Chapter 4 ("Evaluation of Waterhammer Damage" in Vol. 1),
- Chapter 5 ("Waterhammer Analysis for Event Diagnosis" in Vol. 1), and
- the Appendices of Volume 1.

Chapter 2 presents background material on the various classes of condensation induced waterhammer. The purpose is to give the reader an understanding of the phenomena involved in condensation–induced waterhammer and define terminology in the diagnostic procedure. Readers who are experienced in the principles of waterhammer may wish only to briefly review this chapter.

Chapter 3 is a general procedure to aid in the diagnosis of condensation induced waterhammer events. The reader may wish to consult this chapter during the diagnosis of a particularly damaging event or one which is difficult to evaluate. The Chapter presents a logical structure for proceeding with an investigation into the cause of a waterhammer event. In addition, checklists and Tables are included to provide the inspector with easily accessible information for use during field investigations.

Chapter 4 presents guidelines for evaluating damage due to waterhammer events. The types of waterhammer damage are reviewed, a detailed methodology for walking down damaged piping systems is presented, and methods for estimating piping loads based on observed damage are reviewed. Post–event piping evaluation to determine the effect of a waterhammer on plant safety is also discussed.

Chapter 5 illustrates analytic techniques useful for event diagnosis. Simple calculations are described and illustrated by examples based on actual waterhammer incidents. These calculations are intended to help determine the plausibility of event scenarios considered during a field investigation.

Volume 2 addresses event diagnosis in depth by providing detailed accounts of several condensation induced waterhammer events and their diagnoses. The purpose is to illustrate the practical application of the procedure introduced in Chapter 3. The cases also show how engineering judgment plays a crucial role in waterhammer investigations, in which the evidence regarding the cause of the event is typically incomplete. All of these cases are based on actual systems and events.

Finally, several Appendices are included at the end of Volume 1. These support field investigations of condensation induced waterhammer events. Summary information is provided regarding past waterhammer events, indexed by event class, level of damage and reactor system in which they have occurred. Graphical calculational aids and material and fluid property data are presented to assist scoping calculations during investigations. Use of these calculational tools is illustrated in the examples presented in Chapter 5.

1.3 REFERENCES

1 Chapman, R.L. et. al.; *Compilation of data Concerning Known and Suspected Water Hammer Events in Nuclear Power Plants (CY 1969 - May 1981)*; EGG–CAAP–5629, NUREG/CR–2059, EG&G Idaho Inc. for U.S. NRC, May 1982.

2 Leeds, E.J.; *Re-Examination of Waterhammer Occurrences*; US–NRC Office for Analysis and Evaluation of Operational Data, EER #AEOD/E608, July 1986.

3 Serkiz, A.W.; *Waterhammer in U.S. Nuclear Power Plants*; Presented at the ASME Pressure Vessel and Piping Conference, San Diego, CA, June 28–July 22, 1987.

2 CONDENSATION–INDUCED WATERHAMMER PHENOMENA

This chapter familiarizes the reader with condensation induced waterhammer. Five event classes are introduced to classify the various forms of condensation–induced waterhammer events. These classes correlate with damage levels and the systems in which they occur, and will provide a useful framework for event diagnosis. Every event class is characterized by a common sequence of stages, which describe the general phenomena leading ultimately to waterhammer. The specific events which can occur during these stages are described as well.

2.1 THE FIVE CLASSES OF CONDENSATION–INDUCED WATERHAMMER EVENTS

A detailed review of documented waterhammer events and other literature identifies five classes of condensation–induced waterhammer. These classes represent the broad, generic types of condensation–induced waterhammer which should be anticipated or considered in diagnosis of new events. The classes do not differ in fundamental phenomena—indeed, all event classes may be described by the same sequence of fundamental stages to be described in Section 2.2. Rather, the event classes are defined by the general configuration of piping and fluid. The event class concept is useful because the identified classes correlate with system of occurrence and level of damage, and thus provide a useful diagnostic tool.

The five classes of condensation–induced waterhammer events are shown in Figures 2.1 through 2.5. These sketches are very simple, but they provide an efficient graphic description of the essential event scenario. The classes are named:

- subcooled water slugs,
- watercannon,
- trapped void collapse,
- saturated water slugs, and
- thermal inversion.

Other workers have introduced similar classifications of events (see Van Duyne and Yow, 1988, for example). The event classes are discussed in turn below.

The <u>subcooled water slug</u> event class is illustrated in Figure 2.1. This event class has occurred in PWR feedwater systems and steam generators, in which it has often been referred to as "steam generator waterhammer." Subcooled water slug events can potentially occur in the main steam lines of PWRs and BWRs following an overfill event in which subcooled water enters these lines. This event class has been responsible for the most severe waterhammer damage to piping systems, including the cracking of main feedwater pipes at Indian Point Unit 2 on November 13, 1973 (Cahill, 1974) and at San Onofre Unit 1 on November 21, 1985 (So. Cal. Edison, 1985).

A subcooled water slug event requires a large area of steam and subcooled water contact, as shown in the first segment of Figure 2.1. Typically this arises due to a small flow of subcooled water into a horizontal pipe leading to a reservoir of high pressure steam. Rapid

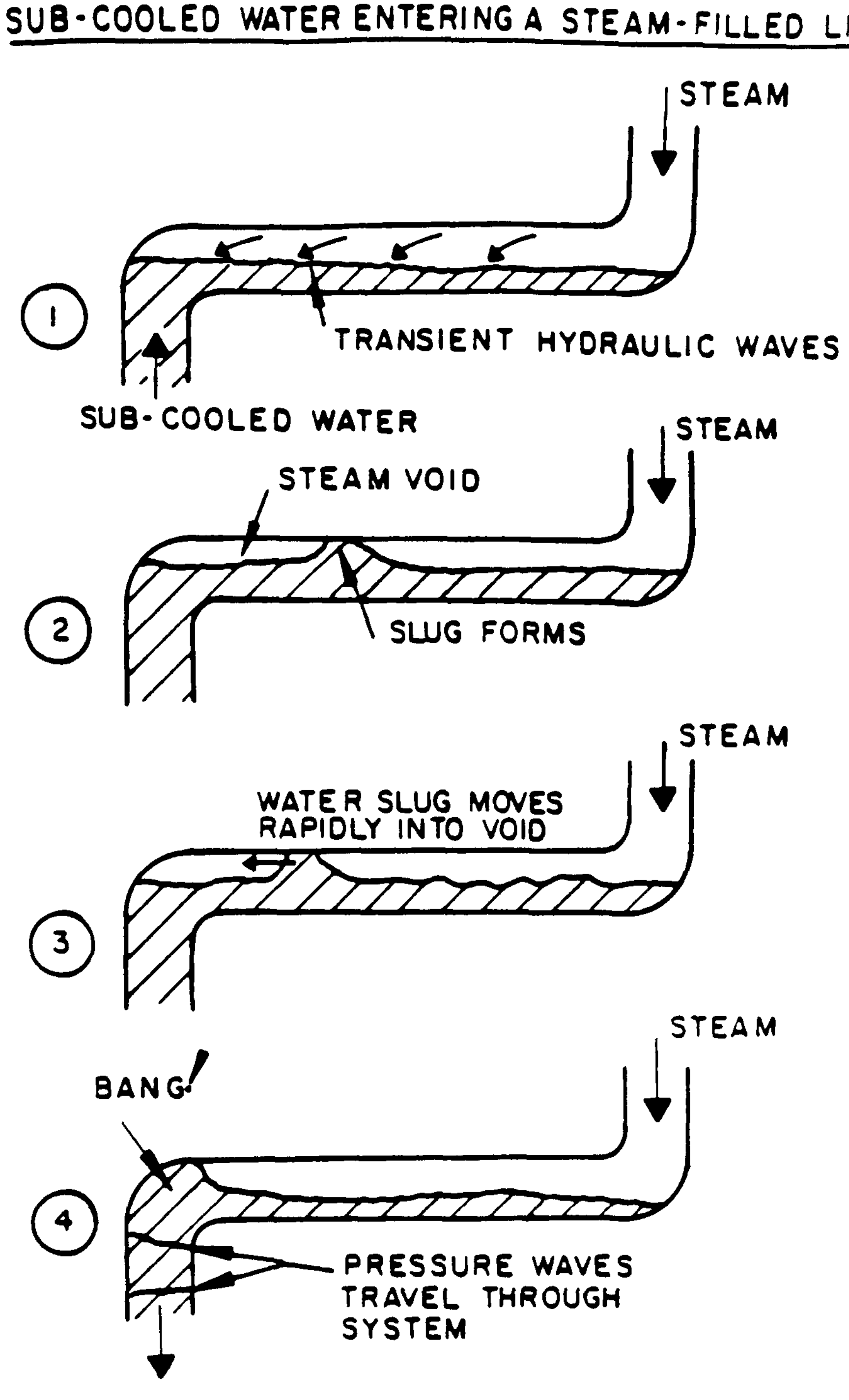


Figure 2.1 A SUB–COOLED WATER SLUG EVENT
(SYSTEMS: PWR STEAM GENERATOR, FEEDWATER, MAIN STEAM LINES)

condensation on the liquid surface induces a high velocity steam flow counter to the direction of liquid water flow. Under the proper conditions this countercurrent flow will generate waves on the surface of the liquid. One of these waves may contact the pipe's upper surface and trap a steam void as shown in the second segment of Figure 2.1. Rapid condensation of the trapped void results in a large differential pressure across the slug of water formed by the trapping wave. This slug is accelerated into the collapsing void as shown in the third segment of Figure 2.1. As the void vanishes and the slug strikes the liquid surface (segment four), pressure waves of great magnitude are generated. These waves propagate through the piping system and can cause severe damage.

The watercannon event class is illustrated in Figure 2.2. This event has occurred in the HPCI systems of BWRs, where the exhaust lines of the turbines which drive the HPCI pumps enter the pressure suppression pool. These events typically result in moderate damage to components such as check valves and rupture discs.

The watercannon event begins as steam exhausts into a pool of subcooled water, as shown in the first segment of Figure 2.2. When the exhaust valve is closed (segment two) a bubble of high temperature steam is trapped above the subcooled liquid surface. Rapid condensation occurs (segment three) and liquid is quickly drawn up into the exhaust line. The water is suddenly stopped by the closed exhaust valve (segment four), giving rise to a large pressure pulse. Watercannon may also occur without valve closure if the steam flows initially through a constriction. Rapid condensation can cause the flow to choke and reduce the pressure above the liquid surface. The liquid can quickly be drawn upwards to impact the constriction at high velocity.

Trapped void collapse is the most common of the event classes, and has occurred in BWR condenser, core spray, process steam, RHR and service water systems, as well as PWR ECCS and feedwater systems. These events typically result in damage to pipe supports and snubbers, though larger components have also suffered moderate damage. This event class is illustrated in Figure 2.3.

A trapped void collapse event begins with the trapping of a steam void, shown in the first segment of Figure 2.3. The numerous ways in which such a void can form will be discussed in more detail later in this Guidebook. Void collapse is initiated by repressurization, which might occur by opening a valve (as in segment two of Figure 2.3) or by several other mechanisms (to be reviewed later). As the void vanishes the slug or column of water is suddenly decelerated, resulting in waterhammer.

Saturated water slug events are also fairly common, and have been reported to occur in the condenser, HPCI, main steam and RCIC systems of BWRs and in the feedwater systems of PWRs. The typical level of damage resulting from these events is moderate and usually will not cause large pipes to rupture. A sequence of events which can lead to a saturated water slug event is illustrated in Figure 2.4.

A slug of water is formed by condensation at a low point in the piping system, as illustrated in the first segment of Figure 2.4. Another method for slug formation is the inadvertent injection of liquid into a steam pipe, some of which may remain in a low point following drainage of the main line. Waterhammer is triggered when the slug of water is suddenly accelerated, perhaps due to the opening of a valve as shown in the second segment of Figure 2.4. Significant loads on the piping may develop as the slug is driven through the normally steam-filled lines.

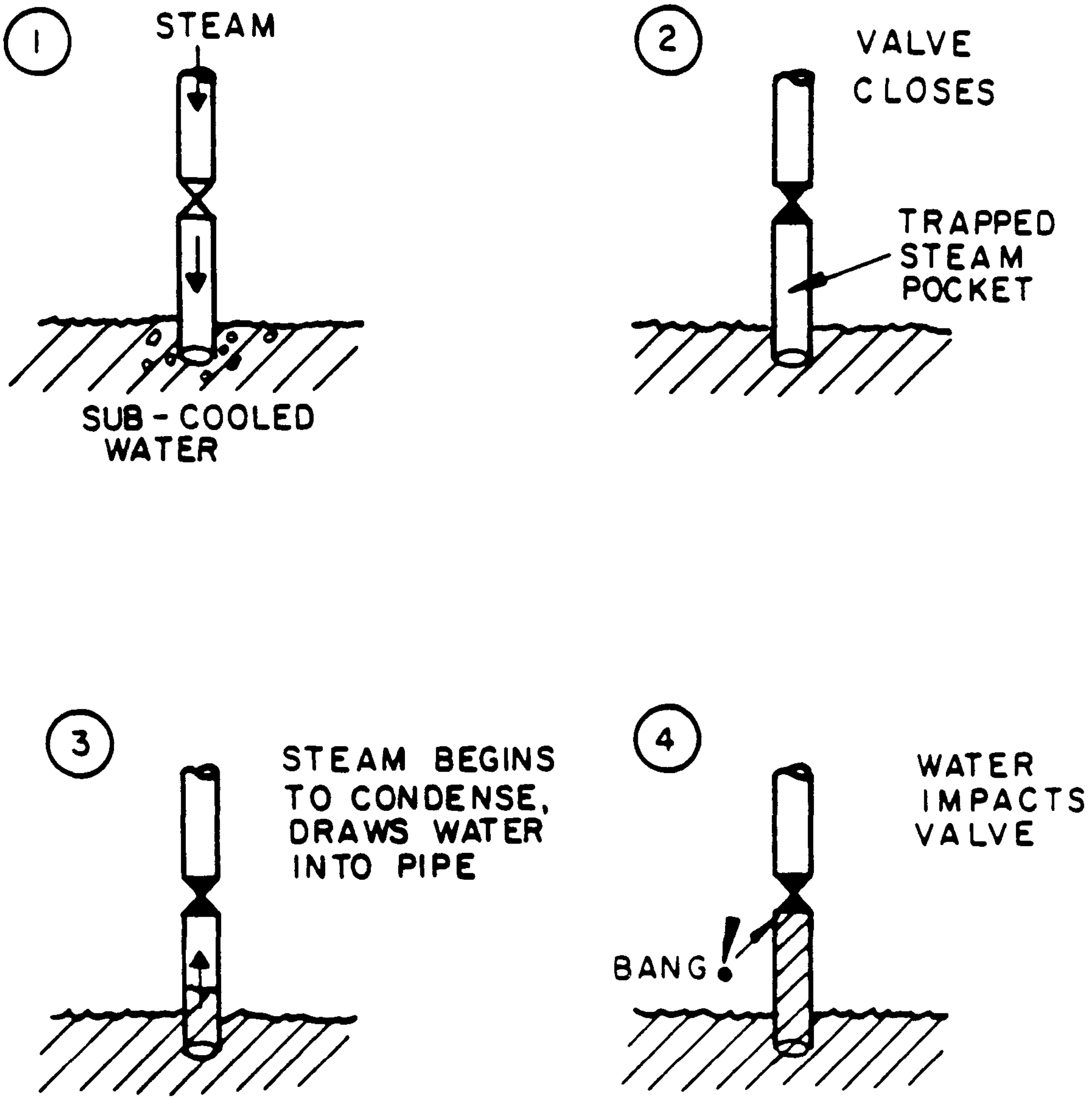


Figure 2.2 WATERCANNON
(SYSTEMS: BWR HPCI)

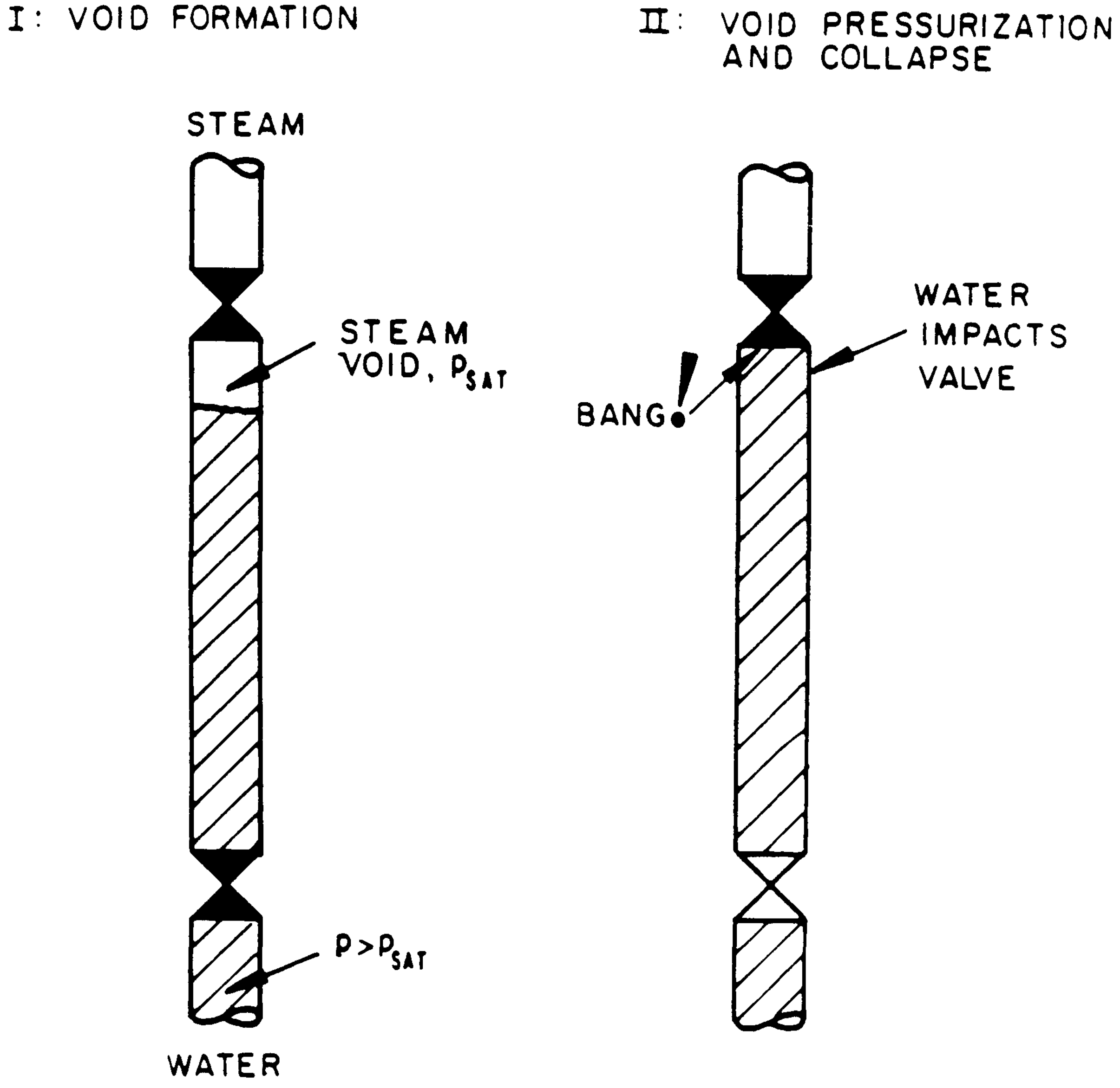


Figure 2.3 COMPONENT-TRAPPED VOID
(SYSTEMS: BWR CONDENSER, CS, PROCESS STEAM, RHR, SCW; PWR ECCS, FW)

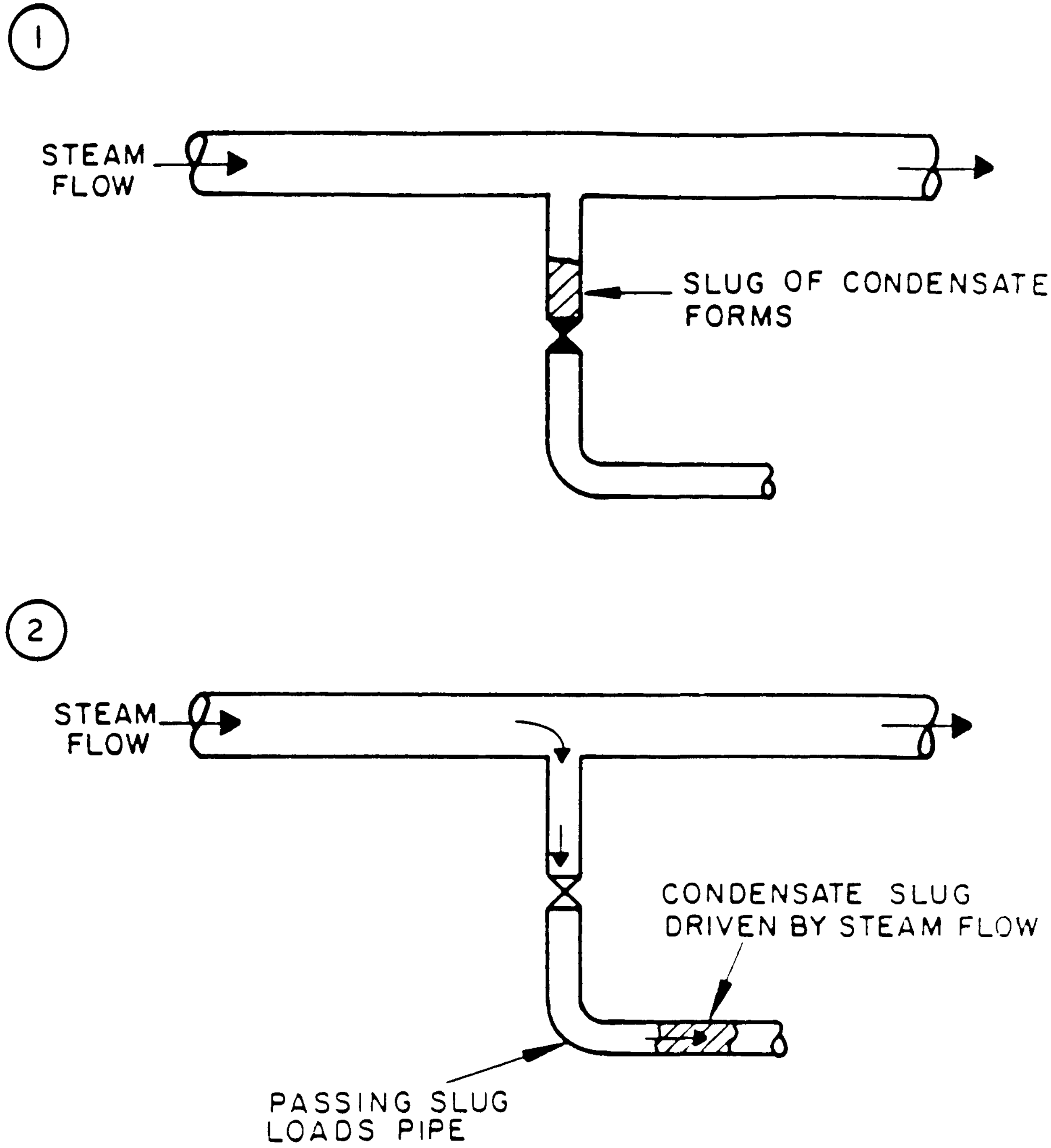


Figure 2.4 SATURATED WATER SLUG
(SYSTEMS: BWR CONDENSER, HPCI, MAIN STEAM, RCIC, RHR; PWR, FW)

The final event class is thermal inversion, which is illustrated in Figure 2.5. These events have been reported primarily in the feedwater systems of fossil plants. However, one such event has been reported to have occurred in the Wylfa nuclear plant in Great Britain, in which a steel pipe was split (Wilkinson and Dartnell, 1980). The typical level of damage in fossil plants has been the fracture of 250 to 500 mm cast iron gate valves.

A thermal inversion event begins with an elevated reservoir of relatively cold water with a bottom–draining outlet pipe. Under normal conditions the outlet pipe is used only for flow from the tank, but during an unusual transient the flow in the pipe may reverse. If the reverse flow consists of fluid which is warmer than that in the reservoir, as in the first segment of Figure 2.5, then a thermal inversion waterhammer may occur. As the hot liquid rises its static pressure drops until it becomes superheated. At this point the liquid flashes and steam begins to form (segment two). The presence of steam voids above the hot fluid column further reduces the pressure and still more liquid flashes, quickly voiding the entire line above the hot fluid (segment three). Cold water then drains from the tank into the voided line, driven by gravity and reduced pressure in the void due to condensation (segment four). When the cold and hot columns strike (segment five) a waterhammer pressure pulse is generated due to the sudden deceleration of the fluid columns.

Waterhammer event classes are correlated with systems of occurrence and levels of damage in Appendix B. The Tables in this Appendix may be used during investigations to suggest possible event scenarios based on historical data. The Tables are based on a survey of previously published event compendia, journal articles, NRC staff reports and Licensee Event Reports. The large number of entries in the "unknown damage" and "unknown event class" columns reflects the unavailability of sufficient information to classify these events.

There is an additional class of events which we mention for completeness and call "conventional waterhammer." These events are initiated by abrupt valve closures, unsteady oscillations of components such as valves, pump starts or stops, and other dynamic fluid–structure interactions that do not involve condensation as the event trigger. Typically the damage due to conventional waterhammer is less than that due to condensation–induced waterhammer. This Guidebook treats the five classes of condensation–induced waterhammer events which can cause significant damage, and thus does not address conventional waterhammer.

2.2 THE COMMON STAGES OF CONDENSATION–INDUCED WATERHAMMER

All of the basic waterhammer event classes described in Section 2.1 involve the following sequence of events, or stages:

1. void formation,
2. slug formation,
3. slug acceleration,
4. void collapse, and
5. impact

Each individual stage can happen in several ways, as detailed below.

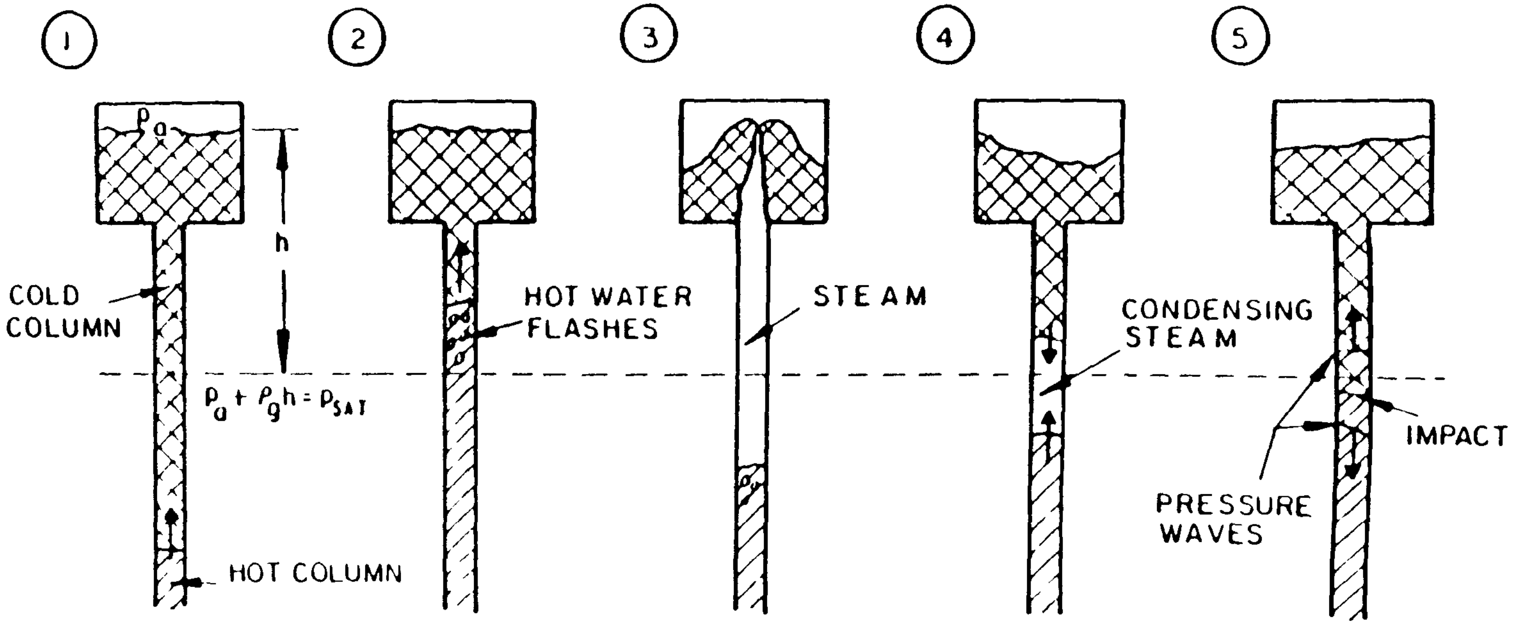


Figure 2.5 THERMAL INVERSION
(SYSTEMS: FOSSIL PLANT AFW AS DESCRIBED BY WILKINSON AND DARTNELL (1980))

2.2.1 Void Formation

Condensation–induced waterhammer can only occur if a steam void is present to be condensed. Voids may form in several ways:

a) The void may already exist. For instance, a pipe may be initially steam–filled as a result of previous events.

b) A line may drain. This could be the result of flow due to gravity or imposed pressure differences, or an applied steam flow could flush out the line.

c) Flashing or boiling may create voids. Steam will tend to form spontaneously in regions where the pressure falls below the saturation pressure corresponding to the local temperature. Alternatively, application of heat from hot pipe walls or nuclear heating may raise the temperature above the local saturation temperature. These effects could also occur in combination.

d) Steam may be introduced into the line from a source usually at a higher pressure. For example, an open or leaky valve, a contiguous steam reservoir or a cavitating pump could be the source of steam.

2.2.2 Slug Formation

A slug of liquid is found in all condensation–induced waterhammer events. The slug may arise in the following ways:

a) The slug may already exist. It might result from condensate pooling in the lower parts of a pipeline, water draining into the region, or simply be the result of prior history that has left the lower part of a (vertical or inclined) pipe full of water.

b) The slug may be introduced to the system. This could occur as a result of flow into the pipe from a reservoir, pump or piping system containing water. The slug could also form as a result of injection of water from a tee or an emergency coolant injection system. In this case it may not form directly at the injection point but some distance away, after the initial momentum of the water has been exhausted.

c) The slug may be created by interfacial instability. The most common mechanism is the creation of a wave in stratified flow, which is picked up and eventually fills the pipe as a result of lift forces from steam flowing above it. A more complicated interaction occurs in countercurrent flow in bottom–discharge feedrings. Slugs may also form when a mixture of steam and water flows around a bend.

2.2.3 Slug Acceleration

Since waterhammer results from the conversion of the kinetic energy of moving water into acoustic pressure energy, the water must first be set in motion. This can occur in several ways:

a) Pressure may rise on one side of the slug, as a result of a valve opening, pump starting, hot water flashing to form steam that acts like a piston (see example 4 in Chapter 5), or rapid heat transfer that causes boiling.

b) Pressure may fall on one side of the slug, as a result of a valve opening, a pump starting, or condensation of steam on subcooled water or cold metal surfaces.

c) Rather than being a separate individual slug, the water may be part of a continuous column set in motion by system transients resulting from valve adjustments, pump startups, etc., in remote regions.

2.2.4 Void Collapse

Waterhammer occurs when moving water suddenly changes its velocity by striking a non–compliant surface such as steel or other water. In order for this to occur, the intervening steam or gas must disappear. This can occur in several ways:

a) Venting through a pipe connection, fitting or valve (including the valve about to be hit). Since the pressure drop for the same volumetric flow rate of steam is less than for water, particularly at lower pressures, the area of this vent may be relatively small compared with the pipe cross–section.

b) Condensation on subcooled water or pipe walls. This may be the continuation of the process that set up slug motion in item 2.2.3 above. As the water interface approaches the end of the void there is a race between compression and condensation of the steam. Compression may mitigate the severity of the event, particularly if air is present.

2.2.5 Impact

When a moving slug of water hits a solid surface or changes direction, its velocity is changed very rapidly and the resulting pressures and loads can be large. Several types of impact are possible:

a) Striking the end of a pipe or the face of a closed valve. In this case the water is essentially brought to rest.

b) Striking another slug or column of water. Both of the water regions change their velocity as waves propagate out from the region of impact.

c) Striking a region of area reduction or a partly–open valve. Some of the water "squirts through" the smaller area but the main slug is forced to change its velocity.

d) Passing through a pipe elbow. The liquid slug rapidly changes velocity causing reaction forces on the surrounding piping.

In all of the above cases, acoustic compression waves propagate away from the point of impact, sometimes traveling many (i.e. hundreds) of feet away through the piping and perhaps causing damage in remote areas.

2.3 REFERENCES

1 Van Duyne, D.A. and Yow, W.; *Water Hammer Prevention, Mitigation, and Accommodation Task 1 - Plant Water Hammer Experience*; Prepared for Electric Power Research Institute, Palo Alto, California, January 1988.

2 Cahill, W.J.; *Feedwater Line Incident Report - Indian Point Unit No. 2.*; Consolidated Edison Co., AEC Docket No. 50–247, January 14, 1974.

3 Southern California Edison Co.; *Investigation Report: San Onofre Unit 1 Water Hammer Event of November 21, 1985*; NRC Docket No. 50–206, April 1986.

4 Wilkinson, D.H. and Dartnell, L.M.; *Water Hammer Phenomena in Thermal Power Station Feed Water Systems*; Proceedings of the Inst. of Mech. Engineers, Vol. 194, March 1980.

3 DIAGNOSTIC TECHNIQUES

Diagnosis is defined as the investigation of the cause or nature of a condition, situation or problem. This chapter contains guidelines for conducting a diagnostic investigation to determine the causes of complex and damaging condensation–induced waterhammer events. An overall structure is provided to guide diagnostic and information activities. This procedure emphasizes determination of the cause of an event.

3.1 WHEN AND HOW TO USE THESE GUIDELINES

These diagnostic tools may be useful whenever a particularly complex or severe waterhammer event has occurred. The waterhammer investigator may initially face any of a large number of potential situations. Plant personnel may have already diagnosed the event or they may still be trying to determine what happened. The event itself may be quite simple to understand or physically complex. The exact time of occurrence may be known, or damage may have gone undetected for an unknown period of time. Rather than consider each possible situation separately, this section provides generic guidance.

This Chapter suggests specific diagnostic activities intended to supplement standard NRC procedures for conducting an incident investigation. These activities fit within the overall context of an event investigation as detailed in NUREG–1303, "Incident Investigation Manual" (AEOD, 1988). The specific waterhammer–related activities in this section can be performed by themselves or as part of the general procedure. To help the investigator use the two procedures concurrently, sections of this waterhammer diagnosis procedure are referenced to sections of the general investigation procedure in NUREG–1303.

An overview of the waterhammer diagnosis procedure is given in Section 3.2. Experienced investigators may wish to skip directly to Section 3.3, in which specific diagnostic actions are recommended.

3.2 A STRUCTURE FOR DIAGNOSIS

Although there is no single sequence of actions for all investigations, it is helpful to think of an investigation in three stages, as outlined in Table 3.1.

1) preliminary assessment,
2) detailed evaluation, and
3) confirmation.

Within each stage there are two kinds of activities, information and diagnosis, leading to an output from each stage. The diagnostic techniques in this chapter are organized based on the activities and outputs listed in Table 3.1. Each of these elements is discussed in turn below.

Preliminary Assessment Stage

Within the first few hours of a waterhammer investigation, it is usually possible and desirable to complete an overall assessment of the situation. The main objectives of this stage can be satisfied by determining: 1) Is the physical cause of the event readily apparent and known

Table 3.1 OVERALL PLAN FOR A WATERHAMMER INVESTIGATION

STAGE IN INVESTIGATION	INFORMATION	DIAGNOSIS	OUTPUT
1. PRELIMINARY ASSESSMENT (Section 3.3)	• simple system schematics • plant damage • initial conditions • event sequence outline	• level of diagnosis • critical event data	• level of investigation • diagnosis plan
2 DETAILED EVALUATION (Section 3.4)	• line walkdown and damage survey • interviews • detailed records • timetable of events	• determine the event center • determine the fluid state • deduce an event scenario • scoping calculations	• event scenario
3. CONFIRMATION (Section 3.5)	• test results • analysis results • evaluation results	• confirmatory tests • confirmatory analysis • comparative evaluations	• close diagnostic investigation

with confidence?, and 2) If not, what information is needed and what form should further diagnosis activities take? At the end of this stage the investigator has either decided to proceed directly to confirmation (no further diagnosis activities are necessary), or determined a broad plan of action for continued diagnosis during the evaluation stage.

Detailed Evaluation Stage

Many condensation–induced waterhammer events are sufficiently complex and uncertain that evaluation and/or confirmation stages are required. The purpose of the evaluation stage is to determine the cause of the event with sufficient confidence to proceed with confirmation and mitigation. Activities include a plant walkdown, interviews, and event analysis. At the end of this stage, the investigator has developed high confidence in a diagnosis.

Confirmation Stage

Complex diagnoses may require replication of the event in a test laboratory or verification of redesigns or revised operating procedures by suitable plant tests. Detailed analyses and comparative evaluations are also recommended for complex events. These activities provide a confirmation of diagnosis that goes beyond a confident evaluation.

Information and Diagnosis Activities

During each stage of the investigation, the efforts to determine the cause of the event are of two distinctly different kinds. On the one hand, there is gathering, development and review of facts such as piping diagrams, sequences of operator actions and timewise instrument readings. Often this effort can be frustrating and tedious. Memories are short, information may be unavailable or require considerable effort to develop, key people may not be on duty again for some time. Sometimes, it is hard to justify why particular information is needed, particularly early in an investigation. Yet if the cause of an event were already known, information would not be required. Time and again some seemingly minor fact has provided the turning point in an investigation. Consider the following example:

During investigation of a suspected condensation–induced waterhammer event in a system that had been damaged by condensation a year before, we interviewed a man who had been working inside containment during the event. He described a steady "banging" and said,

> "I thought someone was hammering on something. But when it didn't let up after several minutes, I went to take a look. The pipe was swinging along its entire length every time there was a bang."

This interview was only one of the many we had held, in addition to review of hours of flow data, operator logs, and piping diagrams. Yet it provided the first definite clue and insight that condensation was not involved at all. Condensation–induced waterhammer is generally a short–lived event involving a few distinct impacts, not a sustained periodic hammering lasting several minutes with no sign of letting up. (We diagnosed an unstable flow control valve.) The point of this example is that information gathering is a useful activity even when you are not sure of what you need to know.

The second kind of activity is diagnosis. It involves expert evaluation of information relying on both experience and deduction. Sometimes diagnosis is structured, relying on generation of a large number of alternative hypotheses and a systematic process of elimination. More often diagnosis is intuitive, employing a few central clues, prior experience, and quick checks on insights.

The following sections contain guidelines for each of the three stages of a waterhammer investigation. The organization of these sections is indicated in Table 3.1.

3.3 PRELIMINARY ASSESSMENT

The goal of this stage is to quickly assess the situation and decide on a general course of action. Information is most readily obtained from a responsible plant or utility engineer. Following the preliminary assessment stage the investigator should have a general knowledge of the event and a plan for further diagnosis. This activity should occur during the entrance meeting outlined in Section 2.7 of NUREG–1303.

3.3.1 Information Activities for Preliminary Assessment

The goal in the preliminary assessment is not to develop new information but to assess what is currently known about the event in order to perform the diagnostic activities discussed in Section 3.3.2. Information requirements are limited to items which can be obtained through discussions with knowledgeable utility or plant engineers. As indicated in Table 3.1, the information requirements at this stage regard the damage, the sequence of events preceding the waterhammer, and simple schematics of the damaged system.

3.3.1.1 Simple System Schematics

With the aid of plant personnel construct simple schematics showing the essential features of the system in which the waterhammer occurred.

3.3.1.2 Plant Damage

Information is necessary to determine both the magnitude of the waterhammer and the safety significance of the event. It is important to find out how the damage was discovered. Did it occur in a system crucial to plant safety? Was the event of great magnitude, involving severe damage to large pipes and components? Or was the damage less severe and limited to smaller lines, pipe hangers and supports, instrument lines, etc.?

3.3.1.3 Initial Conditions

Determine the state of the plant before the waterhammer event. Specific information useful at this stage includes:

- plant mode
- operation of pumps, heat exchangers, and other components
- valve lineups
- fluid temperatures and pressures

3.3.1.4 Event Sequence Outline

Construct a rough timetable of the sequence of events leading up to the waterhammer. Include any available quantitative information regarding the plant state. Important elements of the initial timetable might be:

- valve realignments,
- pump starts or stops,
- liquid levels in tanks or steam generators,
- flow rates,
- fluid temperatures, and
- fluid pressures.

Reports of eyewitnesses which fix the time and/or location of the waterhammer should also be included.

3.3.2 Diagnostic Activities for Preliminary Assessment

Diagnostic activities aim at quickly determining a plan of action for continued diagnosis.

3.3.2.1 Level of Diagnosis

The task is to determine:

- what is the safety significance of the observed damage?
- can the event already be explained with confidence?

and based on this determination decide how to proceed with the investigation.

Most waterhammer events are easily diagnosed by plant engineers. The less common event is a damaging waterhammer due to complex causes which cannot be diagnosed with as much certainty. However, even if the licensee has a confident diagnosis in hand, an independent detailed evaluation (Section 3.4) may still be warranted if the safety implications of the event are significant. If the event is not well understood, a detailed evaluation is necessary to determine the cause of the event.

3.3.2.2 Critical Event Data

The goal is to determine information which is key to the detailed investigation. Key information should be selected based on the location of damage in the plant, adjacent piping, and connecting systems and components.

The result should be a list of items which are key to evaluating the event. Examples are: water and steam temperatures, pressures and flowrates; operating procedures; isometric drawings, etc.

3.3.3 Output from the Preliminary Assessment

At the conclusion of this stage the investigator should have an overall knowledge of plant state before, during, and after the event; the type and extent of damage from the event; and the completeness of any previous event diagnosis.

3.4 DETAILED EVALUATION

The goal of the detailed evaluation is to determine a credible event scenario which is consistent with the waterhammer damage and other evidence. This stage has been outlined in Table 3.1, and begins immediately following the preliminary assessment with a walkdown of the damaged areas of the plant. Information activities involve extensive data collection from witnesses, instruments and damaged components. Diagnosis focuses on recognizing important data, integrating the evidence and proposing the cause of the event.

3.4.1 Information Activities for Detailed Evaluation

The detailed evaluation of a complex waterhammer event may require extensive amounts of information. Key evidence has already been identified during Step 3.3.2.3 of the preliminary assessment. In addition, there are four major sources or categories of information which are available, as listed in Table 3.1: a plant walkdown, detailed plant records, interviews with plant staff and a detailed timetable of events. The key evidence identified in the preliminary assessment provides an initial structure to the investigation and perhaps a quick solution to the problem. The four sources of data are discussed below to give general guidance in the event that extensive additional evidence must be collected during the diagnosis.

3.4.1.1 Line Walkdown and Damage Survey

A line walkdown should be the first activity of the detailed evaluation. A walkdown involves a physical inspection of affected piping, components and supports to collect data and document the kinds and extent of damage that has occurred, and to provide evidence for evaluating the cause of the event. Section 4.3 contains detailed guidelines for preparing and conducting a walkdown, and Section 2.8 of NUREG–1303 provides general guidance. Activities that should be included in the walkdown are summarized in List 3.1. This list is supported by List 3.2 which gives some indications for identifying damaged components and Table 3.2 which defines qualitative damage levels that may be useful in reporting and correlating with a waterhammer event class. A qualitative damage level should be assigned to the event. Some photographic examples of waterhammer damage appear in the case studies (Chapter 6). Table 3.2 also lists the waterhammer event classes which might be responsible for each level of damage.

3.4.1.2 Interviews

Interviews with plant personnel should be held as soon as possible following the preliminary assessment and plant walkdown to minimize information lost from the memories of the interviewees. Guidelines for interviews are found in Section 2.9 of NUREG–1303. The interviews should include representatives from the following categories of licensee personnel, if available:

List 3.1 LINE WALKDOWN AND DAMAGE SURVEY

1. Walk the line confirming damage reported in the preliminary assessment.
2. Search for unreported damage (see List 3.2).
3. Mark all damage locations in piping isometric.
4. Take or arrange for photographs of damaged parts.
5. Ensure that damaged parts will be saved for possible future gauging or metallurgical analysis.
6. Measure permanent deformations and motion indicators. Record on sketches of "as found" dimensions relative to immobile reference points.

List 3.2 INDICATIONS OF WATERHAMMER DAMAGE

- "scratch marks" which indicate pipe motion during the transient
- elongated bolts and/or extruded gaskets in valve bonnets
- bulges in pipe indicating overpressure and plastic deformation
- pipe supports which are bent, torn or have been loosened from the plant wall
- spalled or cracked concrete
- loosened or missing bolts
- broken cables or instrument lines
- pipe motion indicated by insulation damage or visible support wear marks
- pipe axial motion indicated by pipe saddles slipped out of supports

Table 3.2 **DEFINITIONS AND EXAMPLES OF QUALITATIVE WATERHAMMER DAMAGE LEVELS**

DAMAGE LEVEL	TYPICAL INDICATIONS (heaviest damage caused by the event)	CAUSED BY THE FOLLOWING WATERHAMMER EVENT CLASSES*
SEVERE	Rupture of pressure boundary Significant plastic deformations Significant motion of large, seismically supported pipes	– subcooled water slug
MODERATE	Small pipe deformations Valve or small component damage Rupture of instrument line Significant motion of un–supported piping	– subcooled water slug – component trapped void – thermal inversion – saturated water slugs
MINOR	Pipe hanger or support deformation Failed rupture discs Failed instrument No damage (but operation interrupted)	– subcooled water slug – component trapped void – water cannon – saturated water slugs

*Based on historically reported events (see Table B–1)

1. event witnesses: obtain information about observed line motion, noises, steam leaks, etc.,
2. operators: obtain briefings on the plant condition prior to and during the event, and the control room operations during this period,
3. engineering staff: obtain briefings on system history, explanations of any previous similar problems, justifications of operational procedures, etc.

The interviewer should direct the interview by asking specific questions. For example: "So you heard some banging. Was it rap, rap, rap or rap (pause) rap (pause) rap?" Planning is necessary to conduct the interviews systematically. Predetermined questions concerning suspect areas should be asked of all interviewees. Further guidance on the conduct of interviews during an investigation may be found in NUREG 1303.

3.4.1.3 Detailed Records

Evidence to support the diagnosis can come from many sources, some of which appear in List 3.3. An extensive list of issues which should be resolved through detailed data review or through interviews with plant staff is given in List 3.4. This list can serve as a guide to data collection activities by indicating areas which remain to be investigated. In additon, Section 2.19 of NUREG–1303 has general suggestions for collection of information.

When they are available, transient instrument data are much more useful than observations by people because an entire history is retained and because finer time scales can be more accurately resolved. For these reasons it is invariably worth the time and effort to obtain instrument records.

3.4.1.4 Timetable of Events

On the basis of information gathered from the plant and during interviews construct a detailed timetable of events leading up to the waterhammer. The timetable should include:

- a list of plant initial conditions,
- relevant operator actions,
- automatic control actions,
- transient events,
- reports from event witnesses, and
- values of important plant state variables (e.g. liquid levels, temperatures, flow rates, etc. which are important to the event).

Examples of such a timetable are found in Sections 6.1 and 6.2. Section 2.10 of NUREG–1303 provides additional guidance.

List 3.3 SOURCES OF DETAILED PLANT RECORDS

- __ piping and instrument diagrams
- __ process diagrams
- __ maintenance records
- __ surveillance records
- __ design reviews
- __ engineering changes and modifications
- __ as–built drawings
- __ vendor information and manuals
- __ quality assurance records
- __ operating procedures
- __ emergency procedures
- __ technical specifications
- __ Plant Safety Oversight Committee meeting minutes
- __ transcripts of NRC Operations Center notifications
- __ post–trip reports
- __ strip/trend recorder charts
- __ operating logs
- __ process computer output
- __ Technical Support Center computer output
- __ plant security computer output (provides times/locations of plant personnel)

List 3.4 INFORMATION CHECKLIST FOR DETAILED EVALUATION

1. PLANT
   a) Status – operating or down at present?
   b) Prior Operation – describe generally, for example to indicate whether startup tests were underway, or to state operating power level or to describe a transient the operators were performing.

2. DAMAGE AND WATERHAMMER INDICATORS
   a) What components were damaged?
   b) What motions were observed?
   c) What noises were heard?
   d) Describe or quantify damage, motions, or noises.

3. SYSTEM ASSESSMENT
   a) Which system was primarily involved? (e.g., RHR, feedwater, etc.)
   b) Were other systems possibly also involved?
   c) Obtain the relevant P&IDs, isometrics and process diagrams.
   d) What is the prior experience with waterhammer in this system at this plant? Comparable plants?

4. EVENT ASSESSMENT
   a) What was the prior condition or operation of the affected system?
   b) What were the operators attempting to do?
   c) Obtain or sketch valve alignments, pump states, and generally the component state before, just before and during the event.
   d) Identify passive components and other elements (check valves, water levels) and consider their possible state.
   e) Quantify the thermal hydraulics including initial estimates of flow, pressure and subcooling where feasible.
   f) Was there structural degradation from prior operation present in the vicinity of damage (e.g. from intergranular stress corrosion cracking, "hung up" snubbers, etc.)
   g) What caused the waterhammer? Was this occurrence design related, or induced by plant operations or maintenance activities?
   h) Was a new system (or component) involved? Were new operating procedures being utilized; were either of such changes implemented within past 12–18 months?
   i) Were new design or control features being tested?

5. PLANT DESIGN FEATURES AND OPERATION PRECAUTIONS (to minimize waterhammer)
   a) What design features and/or operational precautions have been previously implemented to minimize or avoid this type of waterhammer occurrence?
   b) Why did this waterhammer occur now and not before?
   c) What guidance or procedures (for avoidance of waterhammer) have been provided previously by either the NSSS vendor or the A–E?

(continued)

List 3.4 INFORMATION CHECKLIST FOR DETAILED EVALUATION (CONCLUDED)

6. DATA SOURCES
   a) List and acquire licensee event reports and other documents describing or analyzing the event.
   b) List people who may have useful information.
   c) Conduct preliminary interviews if easy to do so.
   d) List related instruments (pressures, flow rates, state sensors, water levels).
   e) Assess data availability (logs, transient records, computerized plant data). If necessary, act promptly to secure data before routine erasure of computer tapes.
   f) Obtain post–accident examination data (e.g. metallurgical examination data).

7. CORRECTIVE ACTION TAKEN
   a) What repairs and corrective actions have been taken to repair damage sustained and to prevent recurrence of similar waterhammers? To what extent have operators been trained to recognize the potential for waterhammer occurrence and which systems (or components) are most susceptible to waterhammer occurrence?

3.4.2 Diagnostic Activities for Detailed Evaluation

Diagnosis for a detailed evaluation begins by locating sections of the plant where the waterhammer might have originated. Evidence collected from instruments, damaged components and event witnesses is then used to reconstruct the fluid state near these locations. Potential event sequences are proposed based on this information, and scoping analyses using the graphical tools provided in this guidebook permit quick evaluation in many cases. These activities are summarized and shown in the context of the entire investigation in Table 3.1.

A successful diagnosis involves compelling insight. There is no way to anticipate in general when in this process that insight will come. The steps outlined below provide a structure to the investigation and indicate activities to hasten such insight. There may be substantial iteration among the steps outlined below. That is, they may not be executed sequentially in the order presented, although it is useful to explain them in this way.

These diagnosis activities correspond to the "analysis and integration" phase of an investigation described in Section 2.23 of NUREG–1303.

3.4.2.1 Determine the Event Center

The first step in determining the cause of an event is to identify locations where steam voids and liquid slugs might have formed and interacted to cause a waterhammer. The location where this actually occurred is termed the "event center."

The event center is the point or region where the main thermal hydraulic action occurred. It is generally a region of two–phase flow and condensation. In most cases the event center will also contain the point of slug impact.

The event center often is not the location of damage or pipe motion. Pressure waves can travel long distances with little attenuation. Pipes move according to whether they are flexible, not due to being at the event center. Pipes and components rupture and deform because they cannot withstand a load, not because they are at the event center. In some cases damage locations and the event center will be the same, but in most cases they will differ. However, the event center always communicates with damage locations through liquid–filled pipes.

The piping configuration between the event center and damage locations must allow transmission of waterhammer pressure waves without excessive attenuation. Junctions tend to reduce the pressure wave amplitude, while constrictions can increase it. Guidelines for estimating transmission effects are found in Example 8 in Chapter 5.

An important indicator of a potential event center is the detailed sequence of events. Many waterhammer events are immediately preceded by the opening of a valve, starting of a pump, or some other operation which clearly indicates a location in the plant. In addition, there are certain plant components which are more likely than others to be an event center. Such components in a typical nuclear plant appear in List 3.5. Subcooled water reservoirs are often closely coupled to the event centers, or are event centers themselves. Typical subcooled water reservoirs in BWRs and PWRs appear in Lists 3.6 and 3.7, respectively.

List 3.5 COMMON EVENT CENTERS

Horizontal pipe sections
High points in the piping system
Steam discharge lines into liquid
Condensate drainage lines
"T" configurations
High elevation auxiliary or emergency FW tanks
Moisture separator drain tanks
Direct contact heat exchangers

List 3.6 TYPICAL SUBCOOLED WATER RESERVOIRS IN BWRs

SCRAM accumulator
Condensate storage tank
Suppression pool or torus
Fuel pool, upper containment pool, etc.
Waste collection or surge tank
Cooling water supply
Standby liquid control storage tank

List 3.7 TYPICAL SUBCOOLED WATER RESERVOIRS IN PWRs

Condensate storage tanks
Volume control tank
Refueling water storage tank
Containment sump
ECCS accumulators
Emergency FW tank
Containment spray storage tank

3.4.2.2 Determine the Fluid State

The fluid state near the event center determines whether a waterhammer could have occurred and is essential evidence to support the diagnosis. At this point one or perhaps several potential event centers have been identified for further consideration. The fluid "state" consists of such information as the pressure, temperature, and flow rate of the steam and liquid water in the vicinity of each potential center. Review the available information and obtain data to complete knowledge of the fluid states. Even if actual instrument readings are not available, most diagnoses can proceed without precise information. Rough estimates are often acceptable substitutes for recorded data.

3.4.2.3 Deduce an Event Scenario

An event scenario is a sequence of thermal hydraulic occurrences which might have caused a waterhammer and led to the plant damage. A scenario consists of the five stages of waterhammer introduced in Section 2.2:

1. void formation,
2. slug formation,
3. slug acceleration,
4. void collapse, and
5. impact.

These steps should be part of any proposed event scenario. A scenario may be obvious based on fluid states at a particular center. The event's damage level is an important clue in determining an event scenario. Table 3.2 correlates waterhammer event classes with qualitative damage levels.

If a scenario is not obvious, Table 3.3 is provided to suggest possible scenarios. The Table is a matrix of event center configurations and fluid states. In each section of the matrix is the type of condensation–induced waterhammer that is typically associated with that combination. This matrix is not meant to be exclusive of other combinations and is presented only as an aid in "brainstorming" an event scenario.

Section 2.2 can be consulted to review the various ways in which the waterhammer stages can occur. Table 3.4 summarizes the mechanisms for each stage of waterhammer. As a further aid in deducing event scenarios, Table 3.5 is provided. This Table lists the nuclear plant systems in which each of the waterhammer event classes have been reported. These Tables can help in the systematic investigation and/or elimination of event scenarios.

Hardware and design flaws which have contributed to past waterhammer events appear in List 3.8. Operational and procedural errors which have contributed to past waterhammers are arranged by event class in List 3.9. These Lists support diagnoses by suggesting likely parts of an event scenario.

Table 3.3 WATERHAMMER EVENT CLASSES TYPICALLY ASSOCIATED WITH VARIOUS PLANT COMPONENTS AND FLUID STATES

FLUID STATE	CONFIGURATION		
	STEAM RESERVOIR	SUBCOOLED WATER RESERVOIR	NO RESERVOIR
STEAM FLOW		WATER CANNON	SATURATED WATER SLUG
SATURATED WATER FLOW		THERMAL INVERSION	COMPONENT TRAPPED VOID
SUBCOOLED WATER FLOW	SUBCOOLED WATER SLUGS		COMPONENT TRAPPED VOID
NO FLOW			COMPONENT TRAPPED VOID

Table 3.4 SPECIFIC PHYSICAL MECHANISMS ASSOCIATED WITH WATERHAMMER EVENT STAGES*

EVENT STAGE	TYPICAL MECHANISMS
1. VOID FORMATION	• exists prior to event • line drains • flashing or boiling • steam flow into line
2. SLUG FORMATION	• exists prior to event • introduced by flow • interfacial instability
3. SLUG ACCELERATION	• pressure rise • pressure drop • acceleration by hydraulic components
4. VOID COLLAPSE	• venting • condensation
5. IMPACT	• striking a solid obstruction • striking another slug or water column • striking a partial obstruction • passing through a pipe elbow

* See Section 2.2 for more complete explanations of these mechanisms.

Table 3.5 NUCLEAR PLANT SYSTEMS TYPICALLY ASSOCIATED WITH WATERHAMMER EVENT CLASSES

EVENT CLASS	BWR SYSTEMS	PWR SYSTEMS
SUBCOOLED WATER SLUG	MAIN STEAM	STEAM GENERATOR FEEDWATER MAIN STEAM
WATERCANNON	HPCI	—
COMPONENT-TRAPPED VOID	CONDENSER CORE SPRAY PROCESS STEAM RHR SERVICE WATER	FEEDWATER ECCS
SATURATED WATER SLUG	CONDENSER HPCI MAIN STEAM RCIC RHR	FEEDWATER
THERMAL INVERSION	—	FEEDWATER

List 3.8 HARDWARE/DESIGN FLAWS CONDUCIVE TO WATERHAMMER

1. Subcooled water slug
   - check valve failures in subcooled water feed lines
   - long horizontal pipe runs
   - downward–draining feed rings
   - mistaken subcooled water injection

2. Watercannon
   - inadequate vacuum breakers or turbine outlet pressure relief

3. Saturated water slug
   - failed heat tracing
   - failed or inadequate condensate drainage

4. Component trapped void
   - leaky isolation valves
   - heat soakback
   - inadequate venting provisions
   - sudden valve closure inducing column separation
   - failed void detection system
   - failed keep–full systems
   - large elevation difference

List 3.9 OPERATIONAL/PROCEDURAL ERRORS CONDUCIVE TO WATERHAMMER

1. Subcooled water slugs
   - initiate subcooled water flow without first checking water level in destination tank
   - valve misalignment leading to unintentional subcooled water injection

2. Watercannon
   - deactivating equipment (such as a pump turbine which exhausts to a subcooled water reservoir) before it has warmed up

3. Saturated water slug
   - initiation of liquid flow into an active steam line (improper valve alignment)
   - blocked condensate drain line (improper valve closure)

4. Component trapped void
   - improper valve sequencing
   - sudden valve closure leading to column separation
   - improper venting/filling procedures
   - reduction in HX coolant flow induces boiling in hot line

5. Thermal inversion
   - reverse flow into a high elevation subcooled water storage tank

An event scenario may be so obvious and so well backed up by the available plant data that no further work is necessary. However, it is also possible that the postulated event scenario is not completely convincing, or that more than one such scenario has been proposed. In such cases it is often useful to perform some simple scoping calculations to quickly determine if the postulated scenario is consistent with the available evidence. The graphical calculation tools in Appendix C of this Guidebook are provided to support this activity.

The key components of a postulated event scenario are often such quantitative statements as:

> "the flow rate of water was insufficient to fill the pipe," or
>
> "the observed damage is the result of a pump startup which collapsed a void."

The Figures in Appendix C provide simple methods to determine if such key statements can be supported by the evidence. The Figures have been selected to aid in calculations which are common in event diagnosis. Use of these Figures is illustrated by the Examples in Chapter 5 of this Guidebook. The graphical calculations presented in Appendix C are summarized in the Table of Contents and explained more fully within the Appendix itself.

To use the graphical tools to evaluate a proposed event scenario, first refer to the example in Chapter 5 which corresponds to the event class under consideration. The example will illustrate how to use any relevant calculation tools.

3.4.3 Output From the Detailed Evaluation

The detailed evaluation stage ends when a credible event scenario has been identified. This scenario must explain the observed damage and be consistent with the evidence from instruments and interviews. The key phenomena in the event scenario should be consistent with scoping calculations.

When the detailed evaluation is complete, proceed to the next stage of the investigation discussed in Section 3.5: Confirmation.

3.5 CONFIRMATION

The third stage of the waterhammer diagnosis is confirmation. The goal is to verify the event scenario diagnosed during the preliminary assessment or the detailed evaluation. Confirmation ensures that the steps taken to prevent recurrence address the true cause of the waterhammer. Confirmation activities also help ensure that additional plant damage does not go undetected. Verification is accomplished by testing, analysis, and demonstration that the proposed event scenario is consistent with the plant's operation before and during the waterhammer. These activities still fall within the analysis and integration phase of the investigation described in Section 2.23 of NUREG–1303. Some confirmation activities may require assistance from outside specialists as discussed in Section 2.14 of NUREG–1303. Rothe and Izenson (1988) summarize how waterhammer testing has been used for event confirmation.

The amount of effort spent to confirm a diagnosis can vary widely depending on the damage caused by the event and/or its generic implications. This section assumes that the event is significant enough to warrant a complete and thorough confirmation. For lesser events it is not necessary to perform all the activities discussed here.

Finally, confirmatory activities are very event specific and are difficult to discuss in general. For many events of lesser magnitude, confirmation consists only of a successful fix. Specific examples of confirmation tests are described in the case studies in Sections 6.1 and 6.2 of this Guidebook.

3.5.1 Diagnostic Activities for Confirmation

Diagnostic activities in the confirmation stage aim to answer the following questions:

1. What tests are necessary to confirm the event scenario?
2. Do the test results confirm the event scenario?

The following paragraphs elaborate on the types of tests which may be performed and how the test results may affect the event diagnosis.

3.5.1.1 Confirmatory tests

There are two types of tests which may be necessary to confirm a diagnosis: in–situ tests and laboratory tests.

Most diagnoses can be challenged in–situ before any repairs or modifications have been made. Mild events can be systematically replicated, usually by varying a flow or thermal condition to escalate a flow oscillation or behavior. Special instruments can be introduced to detect and confirm elements of the event scenario while avoiding recurrence of excessive loads.

The thermal and hydraulic phenomena associated with condensation–induced waterhammer are complex, and the understanding of these processes is sometimes incomplete. In some circumstances a laboratory model test will be useful to establish whether a suspected behavior can in fact occur at all. Such tests also provide a quantitative basis for hydraulic and load calculations.

Examples of how testing has been used to aid in the confirmation of event diagnoses are presented in Sections 6.1 and 6.2.

3.5.1.2 Confirmatory analysis

It is usually desirable to perform some detailed calculations based on the proposed event scenario. Such analyses can have several purposes:

1. to scale the results of laboratory tests,
2. to show that the actual plant response during the event is consistent with the proposed event scenario,
3. to investigate loads on piping due to pressure wave propagation, and
4. to show that the waterhammer event is bounded by accepted design basis events.

Scaling laboratory data may require special analyses derived for the particular thermal hydraulic phenomena in the proposed event scenario. Such analyses may attempt to derive scaling factors by which the results of confirmatory laboratory tests may be used to predict the pressures, flowrates and loads due to the actual waterhammer, or to design a test based on the plant configuration. Plant response and piping loads are typically investigated using well established computer models of reactor and piping systems. Comparison with design basis events is warranted if the waterhammer event had a direct effect on the reactor primary system. In this case calculations with established reactor system analysis codes may be necessary to demonstrate that the effects of the waterhammer are within the bounds set by the plant's design basis accidents.

Examples of how analysis has been used for confirming actual waterhammer event diagnoses may be found in Chapter 6.

3.5.1.3 Comparative Evaluations

Comparative evaluations provide a third measure of confirmation by showing that the proposed event scenario is consistent with the system and plant's operational history prior to and during the event. A comparative evaluation answers the following questions:

1. If the waterhammer occurred in a particular system loop or component, why didn't it occur in other loops or components?
2. Why did the waterhammer occur at the particular time that it did and not before?

The proposed event scenario should provide reasonable answers to these questions by defining the conditions which were necessary for the waterhammer. Other locations in the plant, as well as the waterhammer site at times prior to the event, should not have met these conditions. Section 6.2 is an example of comparative evaluation used in diagnosis.

3.5.2 **Information Activities for Confirmation**

The diagnostic tests and analyses selected in Section 3.5.1 determine the information activities for confirmation. Also, performance of the comparative evaluations may suggest additional plant data to review. The case studies in Chapter 6 illustrate the types of information obtained in confirmation tests.

3.5.3 Output from Confirmation

The confirmation stage ends when the proposed event scenario has been demonstrated consistent with the results of tests, analyses and comparative evaluations. This concludes the diagnostic portion of the investigation.

3.6 CONCLUSION OF THE INVESTIGATION

Conclusion of the investigation requires documentation and mitigation activities. Mitigation techniques, though dependent on an accurate diagnosis of the event, are not truly part of the diagnostic process. Furthermore, these techniques have been well documented in previous NUREG documents. Mitigation is briefly reviewed in Appendix A. Chapter 5 and Section 2.25 of NUREG–1303 contain procedures for documenting and concluding investigations.

3.7 REFERENCES

1 Office for Analysis and Evaluation of Operation Data; *Incident Investigation Manual*; U.S. Nuclear Regulatory Commission, NUREG–1303, February 1988.

2 Rothe, P.H. and Izenson, M.G.; *Waterhammer Testing*; Presented at the EPRI Workshop on Waterhammer, Boston, MA, June 14, 1988.

4 EVALUATION OF WATERHAMMER DAMAGE

(Prepared by Quadrex Energy Services Corporation)

4.1 INTRODUCTION

This chapter provides guidelines for evaluating damage caused by waterhammer events. Observed damage generally provides the most significant and often the only data available to evaluate the causes and effects of a waterhammer event. Waterhammer damage and/or the lack of damage can be used to approximate the magnitude of the event, its cause and the long term effect on the piping system and its associated components. Therefore, it is important to be able to properly evaluate waterhammer damage.

This chapter will provide an engineer reviewing a waterhammer event with the appropriate background to use waterhammer damage observations to approximate the magnitude of waterhammer pressures and loads. Section 4.2 will provide general background material on waterhammer damage. Guidelines for performing a damage evaluation walkdown will be discussed in Section 4.3, which will also include walkdown checklists. Section 4.4 will provide methodologies for estimating waterhammer pressures and piping loads. Methods for evaluating the effects of waterhammers on piping and component life will be provided in Section 4.5.

4.2 BACKGROUND

4.2.1 Purposes and Limits of Waterhammer Damage Evaluation

The purposes of evaluating waterhammer damage are to determine:

- the magnitude (pressure and piping loads) of the event,
- the cause of the event, and
- the effects of the damage on the system.

Damage evaluation will only provide an approximation of the event magnitude. Generally, loads will be bounded by being large enough to cause the observed damage, but small enough so that damage did not occur in other locations. The accuracies with which damage can be estimated and the ability to calculate loads required to cause the estimated damage limit the accuracy with which loads can be estimated.

4.2.2 How Damage Occurs

Waterhammer damage occurs because of either local overpressure or pressure imbalance in a piping segment.

OVERPRESSURE DAMAGE

When the pressure inside a pressure retaining component such as a pipe, valve body, tank or heat exchanger is increased, the stresses on the pressure retaining boundary increase, causing the boundary to expand. If the stresses are within the elastic limits of the material, the deformation is not permanent and the component returns to its original condition. Thus, there is no observed damage. However, if the stresses exceed the elastic limit of the material, the component does not return to its original condition. This condition is called plastic deformation and, depending on the magnitude of the event, may result in observable damage. Some plastic deformations may not be readily observable.

PRESSURE IMBALANCE DAMAGE

When a pressure wave is passing through a piping segment, the pressures will be different at each end of the piping segment. The pressure imbalance will result in a net force imbalance on the piping segment, as shown in Figure 4–1. The net force imbalance, called a segment force, will cause the piping segment to move in the direction of the higher pressure. The piping motion is restrained by other segments of the piping, anchors, attached equipment, piping supports, or structures and equipment in the path of the motion. Figure 4–2 shows examples of pipe motion. Pipe motion can cause damage by either impact or bending. When a pipe impacts a structure or component, damage can occur to the pipe, including attachments such as valve operators and insulation, and/or to the target that it strikes. When a pipe is restrained from motion, damage may occur to the pipe and its supports.

4.2.3 Where Damage Occurs

Damage can occur in:

- any section of piping through which the waterhammer wave travels,
- sections of piping attached to a section of piping moved by a waterhammer wave,
- any structure or component that can be impacted by waterhammer caused pipe motion, and
- pipe supports, structural anchors and equipment nozzles attached to the piping.

Waterhammer pressure waves travel through all open and partially open sections of piping, including piping branches and open flow path components such as heat exchangers and valves. They are neither stopped nor affected by containment walls or pipe restraints.

4.2.4 Types of Damage

For the purposes of this discussion, damage will be divided into three types:

- Observable,
- Non–observable, and
- Evidence.

Most damage will be caused by piping motion. The types of observable damage caused by piping motion include:

- insulation damage, generally in the form of dents or insulation powder in the area,

- supports and snubbers, (Support damage can include missing supports, failed supports, bent supports, failed or rotated pipe clamps, cracks in supports or support attachments, partially or failed anchor bolts, cracked welds, broken lugs, and inoperative or leaking snubbers.)

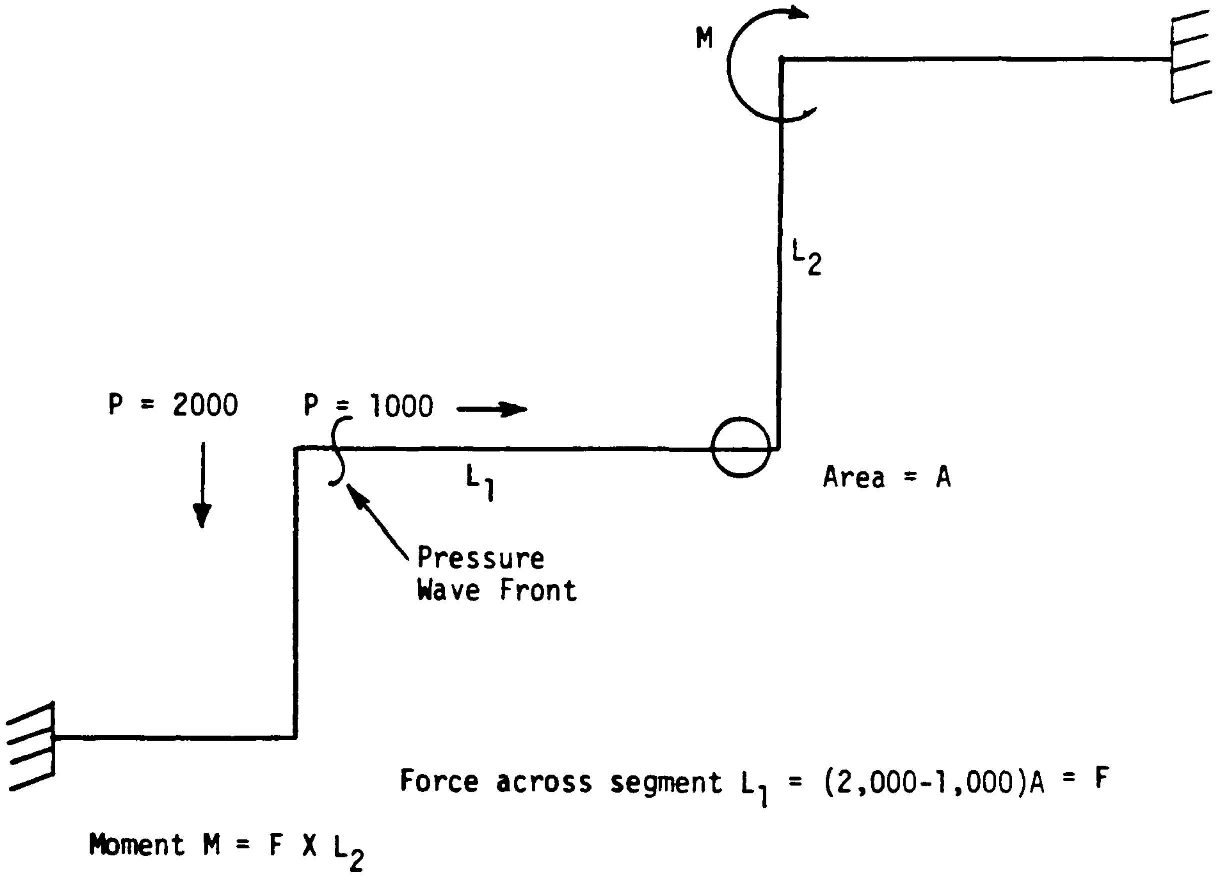
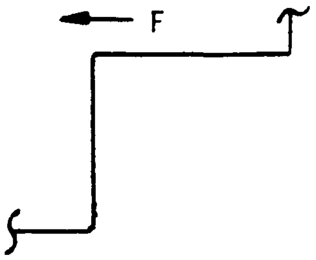
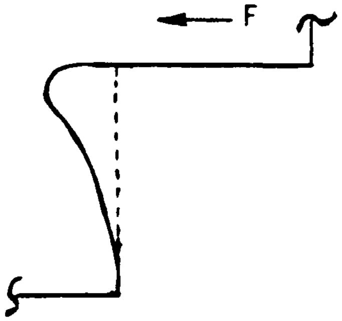


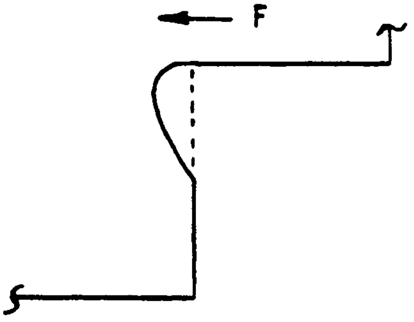
Figure 4.1 PIPING SEGMENT FORCE



(a) Unbent Pipe



(b) Pipe Hinges at Adjacent Elbow



(c) Pipe Hinges in Adjacent Segment

Figure 4.2 EXAMPLES OF PIPE BENDING

- bent piping,
- damage to adjacent structures, components and decking,
- concrete damage at wall and floor penetrations and near piping supports,
- piping cracks near restrained ends, such as anchors, guides or tees, and
- damage to small attached lines such as drain, vent and instrument sensing lines.

Observable piping damage caused by overpressure includes:

- piping bulges, (Piping bulges generally occur at the point of event origin, but can also occur near a closed valve where the magnitude of the pressure wave is increased by reflection.)
- elongated bolts (generally on valve bonnets), and
- leaking gaskets and seals.

Non–observable damage includes fatigue damage and cracks below the piping surface. Sub–surface cracks can be detected by non–destructive examination (NDE), as dicussed in section 4.5.

Some waterhammer damage has no adverse effects, but provides useful evidence to evaluate the event. As examples, impacts can cause insulation dents and minor dents, scratches or paint scrapes on adjacent components or structures. These occurrences, while not harmful damage, provide evidence of piping motion that can be used to estimate pipe deflections and segment forces.

4.3 WALKDOWN METHODOLOGY

Most, and in many cases all, information defining waterhammer damage is obtained by walking down the affected lines. The effectiveness and efficiency of the walkdown are functions of the walkdown methodology and preparation. See also Section 2.8 ("Plant Tour of Equipment and Systems") in NUREG–1303.

4.3.1 Walkdown Preparation

The steps described below will improve the efficiency and effectiveness of waterhammer damage walkdowns.

1. Find out as much information as possible from plant personnel and/or reports about the type of damage incurred and which lines were affected. This will provide a general understanding of where the event occurred and its magnitude, prior to performing detailed reviews.

2. Review the Piping and Instrumentation Drawings (P&ID) or flow diagrams for the piping system involved. When reviewing the system, note the areas of influence of a waterhammer as discussed in 4.2.3 of this document. Completing this review should:

    - define all lines and attached components of interest and

    - provide an understanding of the affected system and how it works.

3. Review the piping layout or isometric drawings for the lines defined in step 2. This review will define the locations of the lines and components of interest. The reviewer should now be familiar with the piping layout of concern as well as understanding the system.

4. Develop an itinerary for performing the walkdown. The itinerary should define the walkdown route and lines and major components of interest.

5. Develop checklists to document the walkdown. Checklists are a prime means of assuring completeness.

6. Bring appropriate equipment to view, document, and measure damages. Such equipment can include:

    - flashlights,
    - tape measures,
    - clipboards,
    - tape recorders, and
    - cameras (where permitted).

4.3.2 What to Observe

The areas of damage to be observed include:

- insulation,
- pipe supports,
- piping,
- attached components and lines, and
- adjacent structures and components.

Each of these topics will be discussed separately. However, the walkdown observations should be made by following the lines in a logical physical order, looking for all of the items as they occur.

INSULATION

The most obvious waterhammer damage often occurs to insulation. Insulation damage generally occurs in the forms of dents in the insulation or insulation powder below the lines. Insulation damage requires very little force. Therefore, insulation damage cannot be used to estimate loads directly. The presence of damage, however, can be used to determine piping deflections. Piping pressures and forces can be estimated from deflections.

Insulation dents are generally caused by impact with a target. The distance from observed dents to their targets and the depths of the dents should be measured or estimated to determine the piping deflection at that point. The absence of dents in lines that are in close proximity to targets indicates insufficient deflection to strike the target. It may be desirable to note the distances between targets and undamaged insulation at certain locations. Information regarding lack of damage can be used to provide an upper bound on the piping loads. In general, only a limited amount of lack of damage information is required.

The presence of powder often indicates that the line vibrated violently enough to damage the insulation or that the line impacted a target. The presence of powder in combination with the absence of dents may indicate that the powder was caused by line vibrations, but impact did not occur.

PIPE SUPPORTS

Pipe supports are generally more prone to damage than piping. Therefore, support damage is far more common than piping damage. Supports and their attachments should be observed for damage. Support damage can include:

- bent supports (Bending is especially common with rod hangers and struts.),
- rotated or displaced pipe clamps, failed clamp welds, cracked or distorted spherical bearings (hyme joints), and cracked or failed pipe lugs,
- broken supports (If the support failed and is missing, it may be difficult to determine that it existed and was damaged. Therefore, structures near the pipe should be observed. If an accounting is not made of each support, it may not be obvious that supports are missing. It often is not worthwhile on an initial walkdown to try to account for each support. This may be a worthwhile step if major damage is observed elsewhere.),
- support attachments to structures, (Attachment damage can include weld cracks, bent members, and broken or loose bolting, particularly expansion anchor bolts. The type and location of the damage as well as the size, location and type of damaged attachment should be noted.)
- oil below a snubber or a snubber which will no longer displace along its axis, and
- cracked concrete near support and restraint attachments.

PIPING

Observable damage to piping is rare, but should be looked for, if it appears that a significant event has occurred. Observable forms of piping damage are:

- bends,
- bulges,
- cracks, and
- ruptures (extremely rare).

Bends. Insulated piping can appear to be bent when insulation is damaged. Bend observations are only valid on uninsulated piping. If insulated piping appears to have a bend, the insulation has to be removed to confirm the presence of the bend. The location and the degree of a bend and the locations of supports and adjacent components and structures that could restrain piping motion should be noted.

Bulges. The exact locations and descriptions of piping bulges should be noted.

Cracks. The most likely locations for piping cracks are near terminal ends. Piping should be checked for cracks near tees, containment penetrations, structural anchors, and at nozzles attaching to fixed components such as pumps, vessels, and heat exchangers. Cracks do not generally occur in the middle of straight runs. Subsurface cracks can be detected by NDE.

Ruptures. Piping ruptures are extremely rare. Any ruptures should be documented in detail.

ATTACHED COMPONENTS AND LINES

Internal Component Damage. Damage to internals can be caused by excessive pressures. Internal damage is often not apparent on a plant walkdown and may require disassembly to observe. Exceptions to this occur when a component, such as a check valve, isolating a high pressure system from a low pressure component fails. In such a case, the pressure boundary of the low pressure components may fail due to the valve failure.

Components attached to a line that can fail also include gaskets and valve bonnet bolts. Gaskets and other seals forming part of the piping pressure boundary and/or the general area below the seal should be observed, where practical, for evidence of overpressure damage. Bolts securing valve bonnets or flanges should be checked for permanent elongation, if a large waterhammer occurred. Smaller events that result in minor damage or deflections elsewhere, generally do not create sufficient pressure increases to cause overpressure damage.

Motion Caused Damage – Valves and Instruments. Valves and instruments attached to lines may have relatively large masses cantilevered off of the main piping. This is particularly true for remotely operated valves. The attachments of these components to the lines should be checked. Severe events have completely detached large motor–operated valves from piping. All damage should be recorded, noting locations, including distances from the lines and types of damage.

Motion Caused Damage – Attached Lines. Small lines such as instrument sensing tubing, drain, vent, and low flow bypass lines attached to large lines are highly susceptible to damage caused by the motion of the larger line. If the smaller lines do not have sufficient flexibility to move freely with the larger line, they are even more susceptible to damage and should be examined carefully. Cantilevered lines with weights at their ends such as vent and drain lines have high damage susceptibility near their terminals with the main run, and should be examined carefully.

Large lines attached to small lines are generally not affected by waterhammers in the small lines and do not usually require detailed examination.

ADJACENT COMPONENTS AND STRUCTURES

Impact Damage. Impacts resulting from waterhammer induced piping motion can damage adjacent structures and components. Damage can range from severely bent structural members or failed valve operators, to minor paint scrapes. However, all damage should be recorded. Even a minor scratch can be used to document deflections.

When recording damage, the following should be noted:

- the location of the damage,
- the distance from the target to the pipe, (If the target has been deformed, the amount of deformation should be noted so that both the deflection of the piping to the original and to the deformed target can be calculated.)
- the type of damage, (It is important to note whether or not the damage required a significant force to be imposed on the target. Examples of damage requiring significant forces include deformed and broken structural members, gratings, and hand rails and chipped concrete. Paint scrapes and minor scratches do not require significant forces, except to cause the deflections required for the pipe to reach the target.)

Structures and components that should be observed for impact damage include:

- walls, floors and ceilings, (The reverse side of the concrete slab should also be checked for spalling if there is evidence of impact.)
- columns and beams,
- gratings and handrails,
- penetrations through walls, floors and decks, including areas adjacent to penetrations, and
- piping (including inline components and pipe supports), and
- conduit, cable trays, and ducting.

REACTION FORCE DAMAGE

Structures can be damaged by reaction forces transmitted through the piping supports. Such damage can include cracks and other damage to concrete and occurs near penetrations, restraints, stanchions, and other supports strong enough to transmit a structurally damaging load.

4.4 ESTIMATING FLUID LOADS AND PRESSURES

Observed damage and evidence may be used to estimate piping loads and waterhammer pressures. The forces and pressures estimated from observed damage should generally be regarded as approximations rather than exact or highly accurate values. Waterhammers are very rapid transients in which pressure pulses and their resulting piping segment loads are cyclically applied to piping for short durations. Pressure pulses and piping segment forces lasting for a few milliseconds have less effects than steady state pressures and forces of the same amplitude. For analysis beyond diagnosis (to determine piping integrity, for example) it is important to consider the duration and frequencies of waterhammer pressure pulses and segment forces when relating the amplitudes of these pressures and forces to observed deflections and damage.

These activities fall within the analysis and integration phase discussed in Section 2.23 of NUREG–1303.

4.4.1 Direct Pressure Estimation

Pressures may be estimated in two ways, directly or indirectly, depending on the type and cause of damage. If damage has been caused by overpressure, the amplitude of the pressure wave can be estimated directly. When damage has been caused by piping motion, it is first necessary to estimate the segment forces that caused the motion. The amplitude of the pressure wave can then be estimated from the segment forces.

Overpressure in piping can result in ruptures, bulges in the piping, leaking or blown out gaskets, and elongated bolts.

PIPING BULGES

The minimum pressure that can cause a bulge in piping is the pressure required to plastically deform the piping due to excessive hoop stress. This pressure may be calculated by:

$$P = \frac{S_y t}{R} \qquad (4\text{–}1)$$

where: S_y = yield strength,
t = pipe wall thickness,
R = pipe radius.

Using a value equal to the code minimum yield strength in equation 4–1 will provide the minimum pressure. The actual pressure may be several times larger, depending on the duration of the pulse and the amount of plastic deformation that occurred. It should also be noted that the actual yield strength of the piping may be considerably higher than the minimum code yield strength.

The pressure calculated by equation 4–1 provides the minimum amplitude of the spike that occurred at the point of damage. Because plastic pipe expansion reduces the amplitude of the pressure wave, a lesser value is transmitted through the system. The amplitude of the pressure wave transmitted through the system is also given by equation 4–1. It should be noted that the pressure amplitude may be higher than calculated by equation 4–1, because the actual yield strength of the pipe may be higher than the code minimum value.

BOLT ELONGATION

Bolt elongation occurs when the pressure on the pressure retaining component, such as a valve bonnet, causes the stresses in the retaining bolts to exceed their elastic limits. The pressure required to cause bolt elongation can be estimated by first calculating the pressure required to cause plastic deformation of the bolts. When calculating the load required to cause bolt deformation, account must also be made of the load required to relieve the bolt torque. The loads required to relieve bolt torque are discussed in ASME III (reference 3), sections NB, NC, ND 3658 and Appendices XI and XII. Note that bolt release torques are often different than bolt tightening torques.

The minimum Pressure (P) required to cause bolt deformation can be approximated by:

$$P = S_y \times N \times A_{bolt}/A_{bonnet} \qquad (4\text{–}2)$$

where:

A_{bolt} = bolt cross sectional area
A_{bonnet} = bonnet area
N = number of bolts
S_y = bolt material yield strength

It should be noted that the actual yield strength of the bolt material may be higher than the code minimum and depends on the system operating temperature. The Metals Handbook (ASM, 1978) provides data for threaded steel fasteners.

In some cases the bolts are not permanently deformed but gaskets are blown out or there is joint leakage. The minimum load that can cause joint leakage or gasket loss is that required to relieve the bolt preload. The maximum value is the bolt yield load deformation as calculated by summing the loads to relieve bolt preload and elongate the bolt, accounting for the fact that actual bolt material strengths are higher than minimum code allowables.

Bolts may also be subject to bending moments, if there is significant weight, such as a valve operator attached to the pressure retaining surfaces or if the opposite sides of a flange respond differently, as would be the case when piping is attached to a fixed component. For such cases, the effects of bending moments can cause bolt deformation at lower pressures than those calculated using equation 4–2.

4.4.2 Forces and Indirect Pressure Estimation

Waterhammer damage is more often caused by pressure imbalances in the lines than by excessive line pressures. The waterhammer pressures that caused these imbalances can be indirectly estimated from estimates of the piping segment force. The axial force on a piping segment is:

$$F = (P_{in} - P_{out})\,A \tag{4–3}$$

where:
P_{in} = Pressure at the start of the pipe segment
P_{out} = Pressure at the end of the pipe segment
A = Pipe flow area.

Rearranging equation 4–3 yields:

$$(P_{in} - P_{out}) = F/A \tag{4–4}$$

The amplitude of the pressure wave is the absolute value of $P_{in} - P_{out}$. The maximum line pressure will be the sum of the initial line pressure and the pressure wave.

The most difficult portion of this task is the estimation of the segment forces that caused the damage. The degree of damage is affected by both the amplitude and the duration of forces.

4.4.3 Estimation of Segment Forces from Damage

There are two factors that can be used to estimate segment forces, namely piping deflection and target damage. Order of magnitude approximations can be performed manually by a highly experienced structural or piping analyst or with greater accuracies using dynamic piping or structural computer codes. The following sections discuss general methodologies to be used for performing these estimates.

PIPING DEFLECTIONS

Manual Analysis. A highly experienced piping analyst can often provide an order of magnitude approximation of waterhammer segment forces by using static equivalent methods to estimate the forces necessary to cause the observed piping deflections. While this method is less accurate than the use of dynamic piping analysis computer codes, it may be desirable as an interim measure, to obtain approximations, or to evaluate the reasonableness of a computer solution.

Computer Analysis. An estimate of the amplitudes of waterhammer loads may be performed using a dynamic piping stress analysis computer code. While such an analysis is still an approximation, it will be considerably more accurate than a manual static equivalent analysis. The additional accuracy comes from the ability to analyze transient effects without having to use factors to relate them to steady state loads and from the ability to model nonlinear behavior of the piping and pipe supports.

The dynamic stress analysis requires a time history of piping segment forces. Piping deflections calculated by the stress analysis can be compared with measured deflections to estimate piping pressures and segment forces.

COMPONENT DAMAGE

Impact Damage. Components can be damaged by impact from a deflected pipe. The impact required to cause the damage can be estimated by an experienced structural analyst. There are too many types of structures and damage modes to provide detailed procedures for calculating the load required to cause the damage. This section will provide the general procedures and information required to estimate the loads that caused the observed damage.

The first step is to estimate the impact load required to cause the observed structural damage. Descriptions of the damaged component and the damage will be required to perform this analysis. Generally, these analyses will be manually performed estimates. The extensive costs and time required to obtain additional accuracy through detailed dynamic finite element analyses of the damaged structure generally cannot be justified because of other inaccuracies in the calculational procedures and the data.

Estimates are then made of how the impact load occurred. This estimate requires calculating the effective mass and velocity of the impacting pipe. These estimates may be made performing either manual or computer piping deflection analyses.

Estimates of segment force amplitudes and pressures can be obtained from these analyses in the same manner as for analyses based solely on piping deflections.

Reaction Load Damage. Damage to supports and structures can be caused by the reaction loads that occur when piping is restrained. The damage may be in the form of damaged supports or cracked concrete. An estimate of the reaction load required to cause such damage can be made by an experienced structural engineer.

Manual or computer piping analyses may be performed to determine the segment force amplitudes and piping pressures that caused the reaction loads.

Failed Piping Supports. Failed piping supports are a particular type of damage that can be used to estimate the magnitude of waterhammer loads. However, it should be noted that the load required to fail a pipe support is generally in the range of 2 to 20 times its manufacturer's load rating. (References 1 and 2 at the end of this Chapter).

4.4.4 Accuracy of Estimates

The estimates, discussed above, do not provide exact values, but rather bound pressures and loads as being large enough to cause observed damage, but not large enough to cause damage that was not observed. The accuracies of the estimates are limited by:

- the ability to estimate the magnitude of observed damage or evidence,

- the ability to define the force or pressure required to cause the observed damage, (Variances in material properties and the need to make approximations to model effects contribute to calculational uncertainties.)
- uncertainties in the loads required to fail pipe supports, (Pipe supports can often react dynamic loads far in excess of their dynamic rating.)
- the dynamic aspects of the event, (The forces and pressures created by waterhammers are rapid transients. The ability to calculate the effects of such rapid transients on piping systems and components is limited.)
- fluid structure interactions, (Rapid pipe motion and plastic deformation of piping effect the magnitudes of the pressure waves. Calculation of the fluid–structure interactions occurring during a waterhammer event is difficult and often cannot be performed with a high degree of accuracy.)

4.5 EFFECTS ON PIPING AND COMPONENTS

It is necessary to determine the effects of a waterhammer on plant safety and continued operation and whether or not hardware repair or replacements are required. For a small event, it may be obvious that there were no adverse effects and no remedial action is required. For a large event, analyses of the effects on piping and other components may be required. This section discusses the evaluation of the effects of waterhammer damage on piping and components.

There are two general concerns about waterhammer damage that should be addressed. The first is what repairs and replacements, if any, are required before it is safe to return the plant to service. The second is what effect the waterhammer event had on piping life.

4.5.1 Component Damage

Overpressures, impacts and piping deflections can damage components attached to the piping system as discussed in section 4.2.2. Additionally, adjacent components and structures can be damaged by waterhammer caused impact. The types of damage that can occur are discussed in section 4.2.2. The decision on whether repair, including replacement, is required is based upon whether the component can perform its safety–related function in its current state. As examples, damaged valve trim or instrument lines must be repaired or replaced, if they have a safety–related function. Hand rails and floor decking may often suffer extensive damage without affecting any safety–related functions. Thus, repair and replacement of such items might not be required.

It often is not possible to determine analytically if a damaged component will perform its function. In many cases, it is obvious from visual inspection whether or not the damaged component will perform its intended function. For other components, such as seals and internals of active components, in situ functional testing may be required. Such testing is often performed as part of the normal startup procedure, when the system is returned to service.

Pipe supports are the most commonly damaged components and are repaired or replaced when damaged. Specific types of support damage are discussed in section 4.3.2.

4.5.2 Structural Damage

All structural damage, such as chipped or cracked concrete and dented beams, reduces the load bearing capability of the structure to some extent. However, the effects in many cases are either insignificant or less than the design margin of the structural component. An experienced structural engineer can often evaluate the damage as insignificant without either performing detailed analysis or considering the design basis of the structure. In other cases, more detailed analyses may be required to determine how much the structural capacity has been reduced by the damage. Such analyses are generally performed manually and must be performed by an experienced structural engineer. If the structural capacity has been reduced significantly, it will be necessary to compare the remaining structural capacity of the damaged component with its design basis. If the capacity of the damaged component exceeds its design basis, repair is not needed.

It is often less costly to perform some minor repairs, such as regrouting a support attachment, than to analyze the damaged structure.

4.5.3 Piping

Generally, the area requiring the greatest attention following a large waterhammer is piping. It is obvious that ruptured piping requires replacement. There are, however, other forms of piping damage, such as fatigue damage, whose effects are less obvious. Evaluation of such damage requires stress analyses and/or non– destructive examinations (NDE).

PIPING ANALYSIS

Piping stress analyses are performed following a waterhammer event for two reasons. One is to estimate the actual stress levels that occurred in the piping during the event. The other reason is to compare the relative stress levels at various portions of the piping that occurred during the event. The calculation of the actual stress levels is limited by the ability to estimate the waterhammer forcing function time history. Estimates of the amplitudes of the piping segment forces are generally not very accurate. However, if a conservative estimate can be obtained, it can be used to estimate the effects on piping. A relative stress level comparison is important to determine where NDE should be performed, and is generally not affected significantly by errors in estimating the amplitude of the segment forces.

Piping is designed to certain safety codes. Nuclear safety–related piping is generally designed in accordance with the provisions of ASME III (reference 3). The piping is designated as Class 1, 2, or 3, depending on its safety function. Piping classes and applicable codes are generally defined in Chapter 3.2 of the plant's Final Safety Analysis Report (FSAR). Generic requirements for classifying piping by system is provided in Regulatory Guides 1.29 and 1.26 (references 4 and 5). Nonsafety–related piping is generally designed in accordance with the provisions of ASME/ANSI B31.1 (reference 6).

In all cases, piping is designed to have stresses below certain limits, called allowables, under all design basis conditions. Design basis conditions include normal operation, transients, and even certain accident conditions. In some cases, where water or steam hammer is expected when a component performs its normal function, waterhammer loads are part of the design bases. Examples of such anticipated waterhammers are turbine stop valve (TSV) closure and control rod drive (CRD) insert. Because piping associated with such events is designed for water (steam) hammer loads, the occurrence of such events should not result in damage.

Of greater concern from a damage evaluation standpoint are the "unanticipated" waterhammers. These are events that occur due to operator error or component malfunction. Examples of such events include steam generator bubble collapse waterhammer (SGWH) and filling of voided lines. The loads from such events are not included in the design bases of their associated piping systems. Evaluations (references 7 and 8) have shown that these events occur infrequently and have not had significant safety effects. Accommodating them requires massive and cumbersome support systems that would be costly and could have negative safety effects.

Therefore, when an unanticipated waterhammer occurs, there is a possibility that the piping could have exceeded its allowable stress limits. However, there is considerable conservatism in the allowable stress limits of power piping. A pipe may exceed its allowable limits under certain conditions and still be suitable for use.

The evaluation of piping stress levels that occurred during a waterhammer can be accomplished by performing an analysis that considers a time history analysis of the waterhammer forces and combining the results with dead weight, thermal, and pressure loads. The thermal loads should be based upon the operating temperature of the piping at the time of the event. It is not appropriate to include seismic or thermal transient loads in these analyses because they did not occur concurrently with the waterhammer. The piping stress levels calculated during the analyses should be reviewed to determine the effects of the waterhammer on the piping. Details on piping stress analysis requirements may be found in the appropriate sections of ASME III (reference 3) for nuclear piping and B31.1 (reference 5) for nonnuclear piping. The appropriate editions of ASME III and B31.1 for the plant may be found in chapter 3 of the plant FSAR.

The effects on piping that has undergone a large waterhammer can be divided into three general categories:

- The piping did not exceed its allowable stress limits. In this case, no damage has been done and the piping may be returned to service without restriction.
- The piping exceeded its allowable stress limits. In this case, the piping must be evaluated in more detail.
- The piping grossly exceeded its yield limits. In this case, the affected piping section must be replaced.

Only the second condition, which relates to fatigue, requires further evaluation. The fatigue or loss of piping life caused by the waterhammer event can be calculated by using the fatigue curves in Appendix I of ASME III (reference 4), as described below.

Determine the maximum stress level for the piping node of interest from the stress analysis. Estimate the number of alternating stress cycles that occurred. Generally, each waterhammer cycle will result in lower stress levels than the previous cycle. However, rather than consider them to be a series of single cycles occurring at different stress levels, an equivalent number of cycles at the maximum stress level is generally determined. The allowable number of alternating stress cycles for the calculated stress level are determined using Appendix I. The fatigue usage factor is determined by dividing the calculated number of cycles by the allowable number of cycles.

Fatigue curves are not provided for B31.1 piping. However, it is appropriate to use ASME III fatigue calculations for B31.1 piping.

Cautions must be exercised in using stress analyses to evaluate piping life. If the stress analysis shows acceptable effects, the waterhammer forcing functions used in the analysis should be conservative, considering the inaccuracies with which they can be estimated. It should be recognized that the calculated fatigue usage factor should either be very small or combined with the design usage factor for comparison with the allowable of 1.0. An experienced dynamic piping analyst should evaluate the accuracy and conservatism of the analysis. Stress analyses conservative enough to account for uncertainties in estimating segment forces may be so conservative that their results are not realistic. Therefore, it is often desirable to supplement stress analyses with NDE.

NON-DESTRUCTIVE EXAMINATION (NDE)

Because of uncertainties in determining the waterhammer forces and the response of the piping to these forces, stress analyses are not always sufficiently accurate to determine the effects of the waterhammer event on the piping. NDE can be performed on piping to more accurately determine the effects of the waterhammer event. NDE is generally performed on the piping locations calculated to have the highest relative stresses. Even when the absolute magnitudes of piping stresses can not be calculated accurately, their relative magnitudes can. Therefore, it is desirable to perform a piping stress analysis to select points for NDE. However, if plastic hinges formed in the piping, an experienced piping analyst should review the piping stress analysis results to determine if the relative stress ranking of the piping nodes is valid.

NDE can be divided into three general categories:

- visual,
- surface, and
- volumetric examinations.

Visual Examination. Visual examination is used to determine the general condition of the component and in the case of piping, can detect surface cracks, deformations, leakage, and physical damage. Visual inspection can be performed directly or remotely using special tools such as boroscopes, telescopes or cameras. To some extent, visual examination is similar to the walkdown inspection, except that it is carried out in greater depth and performed by trained personnel.

Surface Examination. Surface examinations are performed to detect surface discontinuities, such as cracks. Surface examination methods include magnetic particle and liquid penetrant methodologies.

Volumetric Examination. Volumetric examinations are performed to detect voids, internal cracks and other internal piping flaws. Ultrasonic methods are generally used where there are no gross discontinuities. This includes locations such as butt welds, piping surfaces, elbows, and tees. Radiographic methods are used where there are gross discontinuities.

A general discussion of NDE inspection and examination is provided in article IWA – 2000 of ASME Section XI (reference 9).

It is desirable, but not always possible, to compare inspection results against base data taken prior to the event. Inspection results should be reviewed by a certified inspector trained in the appropriate inspection techniques. The inspector will evaluate the flaws against code allowable flaws as defined in ASME Section XI (reference 9). ASME XI provides a discussion of acceptable piping flaws.

4.6 REFERENCES

1. English, W. F., *Piping and Fitting Dynamic Reliability Program, Fourth Semi-Annual Progress Report, November 1986-April 1987*; General Electric Report NEDC–31542, General Electric, San Jose, CA, January 1988.

2. Howard, G.E., et. al.; *Dynamic Response of Pressurized Z-Bend Piping Systems Tested Beyond Elastic Limits and With Support Failures*; EPRI Report NP–3746, Electric Power Research Institute, Palo Alto, CA, December 1986.

3. American Society of Mechanical Engineers; *Nuclear Power Plant Components*; ASME Boiler and Pressure Vessel Code, Section III, New York, NY.

4. U.S. Nuclear Regulatory Commission; *Seismic Design Classification*; Regulatory Guide 1.29, Washington, DC.

5. U.S. Nuclear Regulatory Commission; *Quality Group Classifications and Standards for Water-, Steam-, and Radioactive-Waste Containing Components of Nuclear Power Plants*; Regulatory Guide 1.26, Washington, DC.

6. American Society of Mechanical Engineers; *American National Standard Code for Pressure Piping, Power Piping*; ANSI/ASME B31.1, New York, NY.

7. Serkiz, A. W.; *Evaluation of Waterhammer Occurrence in Nuclear Power Plants*; NUREG–0927, Revision 1, U.S. Nuclear Regulatory Commission, Washington, DC.

8. A. W. Serkiz; *Regulatory Analysis for USI A-1, Waterhammer*; NUREG–0993, Revision 1, U.S. Nuclear Regulatory Commission, Washington, DC.

9. American Society of Mechanical Engineers; *Rules for Inservice Inspection of Nuclear Plant Components*; ASME Boiler and Pressure Vessel Code, Section XI, New York, NY.

10. ASM Handbook Committee; Metals Handbook Ninth Edition; Volume 1 Properties and Selection: Irons and Steels; American Society for Metals, 1978.

5 WATERHAMMER ANALYSIS FOR EVENT DIAGNOSIS

Waterhammer diagnosis should be quantitative. Ideally, the investigator will be able to show that the diagnosis is consistent with plant data and damage. Precise calculation of waterhammer loads is not necessary or even very useful for this. The goal is simply to demonstrate that the event scenario which has been diagnosed:

- is physically possible, and
- can produce piping loads large enough to account for observed damage.

This chapter introduces simple analytic techniques useful during waterhammer field investigations. These calculations are useful in evaluating the plausibility of a proposed waterhammer event scenario. The use of each calculation method is illustrated by examples based on actual waterhammer events. Most calculations are presented graphically in Appendix C.

5.1 Approximate Condensation–Induced Waterhammer Analysis

Each of the event stages described in Chapter 2 can be analyzed at various levels of sophistication, depending on the accuracy required. However, for many applications, including event diagnosis, it should be sufficient to perform an approximate analysis to estimate if the waterhammer is even possible, and if so, how significant the loads resulting from a waterhammer could be. The following steps are recommended.

5.1.1 Void Formation

Estimate the overall size of the initial void that is trapped by the water slug which is about to accelerate into the void. Corresponding to the categories in 2.2.1 the approach might be:

a) If the void already exists its size will probably be determined by the geometry of the piping that it occupies.

b) If draining has occurred, estimate the average rate of draining and multiply by the elapsed time to obtain the volume drained. If the line has been flushed out and refilled, estimate the volume of water added and subtract from the total volume.

c) If flashing or boiling has occurred, use an energy balance to estimate the amount of steam that was formed.

d) If steam has been introduced, estimate the mean flow rate and multiply by the time, or use some other conservation law, such as mass conservation when a known mass of steam has been transferred from a known source, such as the length of pipe between two valves.

Express the void volume as an equivalent length of pipe, $L_V = 4V_v/\pi D^2$, where V_v is the void volume and D is the pipe inner diameter.

5.1.2 Slug Formation

a) If the slug exists, use past history and the pipe geometry to estimate its volume.

b) If the slug consists of water that was injected, estimate the flow rate and duration of injection up to the time when the slug starts to move to close the void. Some judicious averaging may be necessary. If the slug is drawn in from a reservoir its initial length is zero. If it is part of a long column leading all the way back to a tank or pump, the entire length is to be counted.

c) If the slug forms due to instability of a stratified flow, its initial length is zero.

In each of the above cases, record the initial slug length L_{S1}.

5.1.3 Slug Acceleration

The important parameters which determine the waterhammer loads are the slug velocity, V_s, and length of the slug upon impact (L_{S2}). The velocity is calculated from an approximate equation of motion, and the length is derived from conservation of mass.

a) If the pressure, P_1, on the side of the slug away from the void, rises or stays constant, estimate its mean value. In many cases this will be the imposed pressure from some reservoir. It may also be the saturation pressure corresponding to the temperature of flashing or boiling water.

b) Estimate the mean pressure, P_2, in the void. This may be approximated by the saturation pressure corresponding to the water temperature, or it may be set by some communicating reservoir.

c) If the "slug" is really a long column driven by the entire system, try to simplify the system scenario to get an idea of the major dynamics. For instance, the slug may be driven by an approximately constant pressure determined by the normal flow characteristics of the main piping. Or, the maximum slug speed may be governed by the flow capacity of a pump or major valve.

In the cases where the slug can be identified, estimate its total length, L_{S2}, at the time of impact. In some simple cases this is either the initial slug length or the total length of the pipe. If the slug scoops up water lying on the bottom of a pipe, the final length can be determined by using the principle of conservation of mass.

The approximate analysis now proceeds as follows:

The mean slug length is:

$$L_S = \frac{L_{S1} + L_{S2}}{2} \tag{5.1}$$

The mean acceleration is:

$$A = \frac{P_1 - P_2}{\rho_f L_S} \tag{5.2}$$

where ρ_f = the fluid density (see Fig. D.2).

The impact velocity after traveling a length, L_V is:

$$V_s = \sqrt{\frac{P_1 - P_2}{\rho_f} \frac{2L_V}{L_S}}$$

$$= 2\sqrt{\frac{P_1 - P_2}{\rho_f} \times \frac{L_V}{L_{S1} + L_{S2}}} \tag{5.3}$$

Equation 5.3 usually overestimates the velocity by a factor between 1 and 2. More complicated formulas are given in Appendix C, corresponding to specific situations.

If the slug is moved as part of an entire system transient it may be necessary to replace (5.3) by an estimate from the arguments in (c) above.

In cases where L_V, L_{S1} and L_{S2} are all scaled by the overall pipe length, and perhaps each is not known very well, a rough estimate from (5.3) is

$$V_s = \sqrt{\frac{P_1 - P_2}{\rho_f}} \tag{5.4}$$

5.1.4 Void Collapse

This is one of the more difficult phenomena to represent analytically. It is easiest if the water in the slug or surrounding the void is highly subcooled, in which case the void may realistically be assumed to disappear entirely due to rapid condensation. However, assuming that $P_2 = 0$ will have only minor effects on calculated slug velocities as long as $P_2 << P_1$, and will provide a conservative overestimate of the loads.

5.1.5 Impact

The impact overpressure depends primarily on the slug velocity prior to impact. Therefore, the most severe waterhammers occur when large pressure differences are able to accelerate relatively small slugs to high velocities.

The maximum impact overpressure when a liquid slug strikes a non–compliant surface is:

$$P_H = \rho_f \, a \, V_s \tag{5.5}$$

If the slug hits another water slug, the appropriate value of velocity to use in (5.5) is one half of the relative velocity of the two slugs before impact. "a" is the speed of wave propagation in the pipe. For steel pipes "a" is close to the speed of an acoustic wave in water, or around 4500 ft/s for most conditions of interest (see Figure D.4). Equation (5.5) then predicts an impact pressure of about 60 psi per foot per second of impact velocity, which may be used for quick estimation. If $(P_1 - P_2)$ were a modest value of 10 psi in (5.4), V_s would be 27 ft/s and the maximum impact pressure would be about 1,600 psi. On the other hand, if $(P_1 - P_2)$ were 1,000 psi, as in many nuclear applications, V_s would be 270 ft/s and the impact pressure could be of the order of 16,000 psi, which is usually excessive.

Estimates of P_H can be obtained from Figure C.4 in which P_H is plotted as a function of slug velocity and liquid temperature.

The net transient maximum segment force on the pipe is obtained by multiplying P_H by the area of cross–section, A_p:

$$F_H = P_H \, A_p \tag{5.6}$$

Figure C–11 gives the segment force as a function of overpressure for various pipe sizes.

5.1.6 Reductions to Calculated Waterhammer Loads

While an upper bound to the resulting loads is easily estimated by the methods described above, actual loads are usually lower by a factor from 2 to 10. These reductions are due to the following phenomena:

a) Cushioning by uncondensed steam or non–condensable gas that remains in the void and is compressed during the final moments of impact.

b) Compliance of the piping, hangers and mounts. If the impact surface "gives" during the impact, some of the momentum of the water is transmitted to the metal and the resulting change in the water momentum is decreased.

c) Oblique impact. If the front of the slug is ragged, wavy or contains entrained vapor, the impact is "sloppy" and spread out over a period of time. Since the water is eventually brought to rest, large loads still occur, but they may be attenuated, especially if the impact time exceeds the time for propagation of pressure waves to and fro in the liquid slug.

d) Friction on the water slug, and other energy dissipating phenomena, that reduce the velocity before impact.

e) Reduction in slug length due to steam breakthrough from the high pressure side during acceleration.

Elaborate analytical methods are necessary to include these effects and estimate a more realistic load. However, it is usually sufficient to ignore these effects for event diagnosis and use the simple approximate analysis to judge the magnitude of a waterhammer event. Precise load calculations are useful mainly to determine the long term effects of a waterhammer event on plant piping.

5.2 EXAMPLES OF CONDENSATION-INDUCED WATERHAMMER

In this section we apply the methods of approximate waterhammer analysis to specific examples of events. The purpose is to demonstrate diagnostic analysis in clearly defined waterhammer scenarios. These scenarios illustrate the variety of ways in which the five stages of waterhammer can occur, while at the same time emphasizing the basic generalities. These examples demonstrate the use of the graphical calculations provided in Appendix C.

Analysis will be performed with the minimum sophistication needed to explain the essentials of the phenomena.

5.2.1 Example 1 – A subcooled water slug event

This simplified example is based on an actual event in the feedwater system of a pressurized water reactor. Case 2 in Volume 2 presents this event in greater detail.

SCENARIO

The key events leading up to the waterhammer are listed chronologically in Table 5.1. Following a loss of power to the feedwater pump, a check valve failed to seat leading to pressurization and failure of part of the east feedwater train. This situation is illustrated in part (a) of Figure 5.1. The steam generators blew down through the failed condensate system and voided the feedwater line. Auxiliary feedwater (AFW) began to flow almost immediately but was swept out of the line until operators closed the MOV isolation valves at 4:55 (part (b) of Figure 5.1). At 5:02 a loud bang was heard. Subsequent examination revealed bulging of the feedwater line and a long crack in the feedwater pipe wall.

Table 5.1 CHRONOLOGICAL SEQUENCE OF EVENTS FOR EXAMPLE 1

TIME	SYSTEM RESPONSE OPERATOR ACTIONS
4:51:11+	East feedwater pump loses power and coasts down. East feedwater pump discharge check valve fails to seat. East flash evaporator is overpressurized, ruptures a tube and allows the steam generators to blow down back through the main feedwater lines.
4:54	Auxiliary feedwater pumps begin pumping approximately 140 gpm AFW at outside ambient temperature to the main feedwater lines downstream of the isolation valves.
4:55	Operators close the feedwater isolation valve.
5:02	A loud "bang" was heard in the control room.

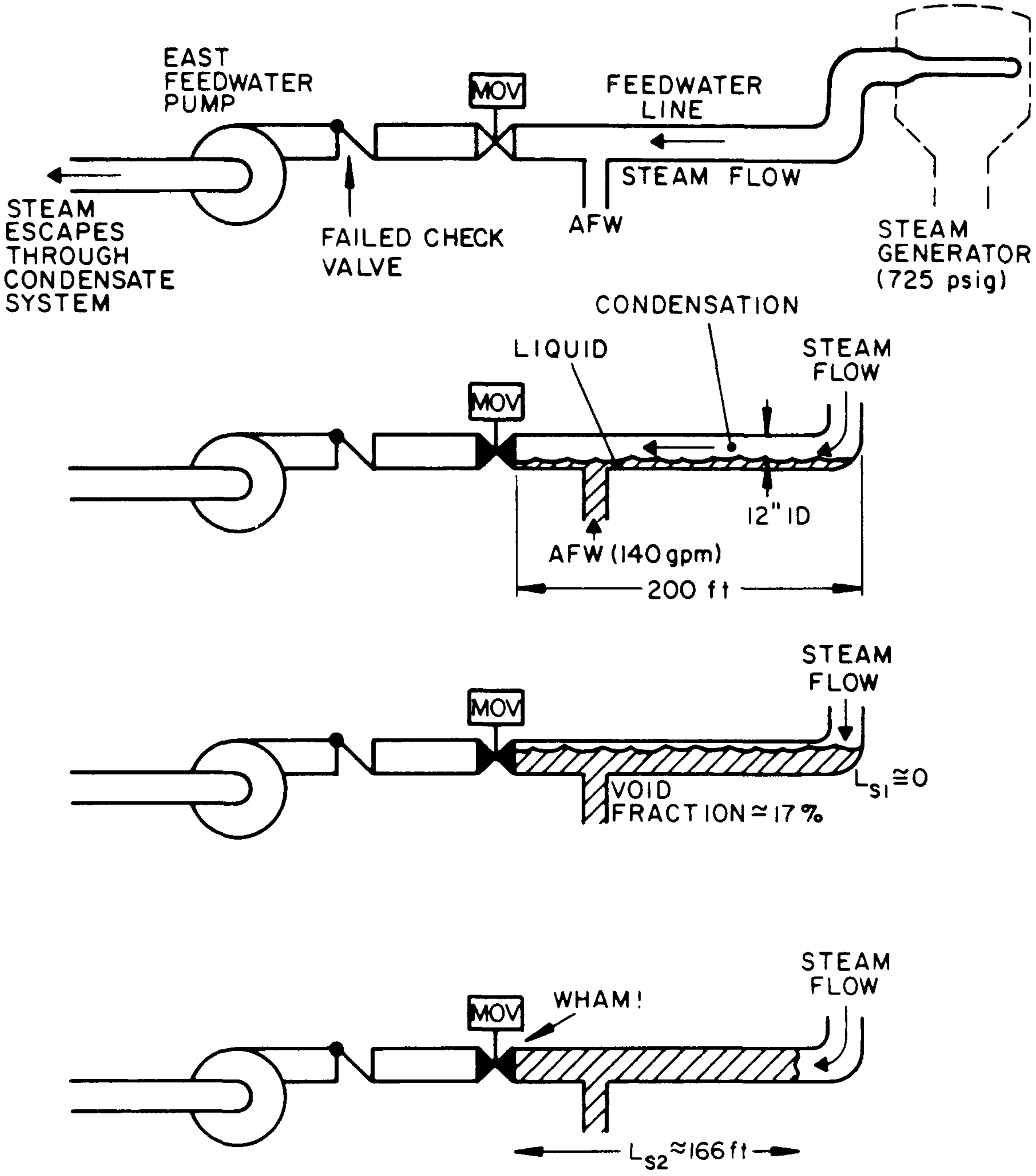


Figure 5.1 SEQUENCE OF EVENTS LEADING TO A SUBCOOLED WATER SLUG EVENT

ANALYSIS

An approximate analysis can be performed following the steps outlined in Section 2.3.

1. Void Formation

The whole horizontal feedwater pipe was essentially voided when steam blew down through it from the steam generator pressure to atmospheric pressure through the burst flash evaporator. The void fraction was then reduced as AFW filled the line following closure of the isolation valve. Waterhammer by acceleration and impact of a subcooled water slug, as shown in segments (c) and (d) of Figure 5.1, is the postulated event scenario.

The effective length of the feedwater line, from the isolation valve to the riser at the steam generator, is about 200 feet. For a waterhammer to have occurred by the mechanism shown in Figure 5.1, a steam void must have remained in the pipe up until the time of the event (5:02). Therefore the flow rate into the feedwater line must be low enough so that the pipe was not completely filled at this time.

Fill rate calculations such as this are common in the analysis of condensation induced waterhammer. Figure C.1 in Appendix C shows the time necessary to fill 100 feet of various diameter pipes as a function of flow rate. The amount of time necessary to fill the 200–foot feedwater line in this example is obtained by simply multiplying the fill–time from Figure C.1 by a factor of two.

Referring to Table 5.1, the AFW flow rate is 140 gpm. The inner diameter of the feedwater line is 12 inches (see Figure 5.1). Reading from Figure C.1, the fill time for 100 feet of pipe is roughly 4 minutes, implying an 8 minute fill time for the actual feedwater line. Using the formula which appears in Figure C.1 for a more precise estimate:

$$\Delta t_{100} = (4.07)\frac{(12 \text{ in})^2}{(140 \text{ gpm})} = 4.2 \text{ minutes}$$

so 8.4 minutes is required to fill 200 feet of the feedwater pipe. Since the AFW pump was only running for seven minutes before the waterhammer, we conclude that a steam void did exist in the pipe at the time of the waterhammer.

The void fraction in the pipe at the time of the waterhammer can also be estimated. Though the pipe would have been full after 8.4 minutes of AFW flow, the waterhammer occurred after only 7 minutes. The fraction of the pipe which was filled with water at this time is therefore 7/8.4. The void fraction at the instant of waterhammer was thus:

$$\text{void fraction} = 1 - \text{liquid fraction} = 1 - \frac{7}{8.4} = 17\%.$$

The void occupies an equivalent length of pipe of $L_V = (0.17)\times(200 \text{ ft}) = 34$ ft.

2. Slug Formation and Collapse

The slug is assumed to be initially formed with zero length by interfacial instability caused by countercurrent steam flow that condenses on the cold AFW water surface and the pipe wall. Therefore $L_{S1} = 0$. At impact, when the void disappears, the slug length is given by conservation of water as $L_{S2} = (1-0.17)(200 \text{ ft}) = 166$ ft.

The pressure in the void (P_2) is essentially zero because the turbulent front of the collapsing slug brings AFW at about 80 F into contact with the trapped steam and rapidly condenses it. The AFW has probably only barely warmed up because it has been essentially quiescent and only a thin surface layer has been heated by condensing steam. The driving pressure for slug acceleration (P_1) is the steam generator pressure of 740 psia.

3. Impact

Substituting the above numbers in (5.3) we get:

$$V_s = 2\sqrt{\frac{(740 \text{ psi})\times(144 \text{ in}^2/\text{ft}^2)\times(32.2 \text{ lb}_m\text{ft/s}^2\text{lb}_f)\times(34 \text{ ft})}{(62 \text{ lb}_m/\text{ft}^3)\times(166 \text{ ft})}} = 212 \text{ ft/s}$$

The impact pressure in psi is estimated to be 60 times the impact velocity in ft/s, i.e. 60×212 = 12,700 psi.

This answer could also be obtained using Figure C.7 and Table C.2. Figure C.7 shows the "base" impact overpressure (P_o) as a function of the differential pressure which accelerates the slug. The overpressures in this Figure are calculated using Eq. (5.4) and do not account for the geometry specific to this example. Geometry is accounted for using Table C.2, in which modification factors are listed for use in conjunction with Figure C.7. If the overpressure from Figure C.7 is multiplied by the appropriate factor from Table C.2, the correct impact overpressure (P_H) will be obtained.

In this case, the overpressure from Figure C.7 is approximately 14,000 psi. The entry in Table C.2 which applies in this case is that for no reservoir, initial slug length $L_{S1} = 0$ and initial void fraction = α = 17%:

$$\text{modification factor} = \sqrt{\alpha/(1-\alpha)} = 2\sqrt{(0.17)/0.83)} = 0.45.$$

The overpressure calculated in this manner is (0.45)×(14,000 psi) = 6,300 psi. This is a case where the simple equation (5.3) overestimates the overpressure by a factor of two.

5.2.2 **<u>Example 2</u> – Another subcooled water slug event: PWR steam generator waterhammer.**

This example is taken from Block (1977), which is a thorough study of a generic problem, originating with the design of feedwater spargers in certain PWRs. Though the scenario contains the previous features of subcooled water injection into a voided line followed by void entrapment and collapse, the mechanism of slug formation is unusual.

SCENARIO

Following a main feedwater pump trip the water level in a PWR steam generator falls below the level of the feedring sparger, as illustrated in Figure 5.2. A short while later, auxiliary feedwater (AFW) comes on and supplies cold (100 F) water to the main feedwater pipe. The flow rate is insufficient to cause the pipe to "run full" in its horizontal portion. Steam condensing on the cold water inside the feedring reduces the pressure, causing steam to be drawn in through some of the feedring holes, and raises the level of the water needed to maintain flow through the remaining holes. This mechanism is progressive and eventually a slug forms in the feedring, accelerating back into the main feedwater pipe as the trapped steam collapses (Figures 5.3 to 5.6). At Indian Point #2, the resulting waterhammer bulged the 18" diameter feedwater pipe near the feedring and the propagating pressure wave caused a 180° circumferential fracture of the same pipe near its penetration of containment about 160 feet away.

ANALYSIS

1. Void Formation

Void formation occurs by draining of the feedring into the steam generator after the level falls below the sparger holes (this was prevented in later designs by discharging from the top of the ring). There is also some draining from an imperfect fit between the feedring and the feedwater pipe. This process takes time, and waterhammer may be avoided if the water level recovers rapidly enough. In the worst case, the feedring is empty when the AFW comes on, and the entire piping is voided back to the vertical bend outside the steam generator.

2. Slug Formation

The mechanism of slug formation in the feedring was already described. It occurs only over a limited range of AFW flow rate. If the flow rate is very low, the water flows in a thin layer along the bottom of the pipe and discharges through a few holes in the sparger. There is little steam–water interaction and no slug formation (Figure 5.7). On the other hand, if the flow rate is sufficiently high, the water fills the pipe behind an advancing "front" and sweeps the steam out without trapping a void. Thus, a possible mitigating procedure is to control the AFW feed rate, if this can be relied upon under all circumstances.

Criteria for slug formation may be established based on detailed thermo–fluid analysis (Block, 1977), albeit with some range of uncertainty.

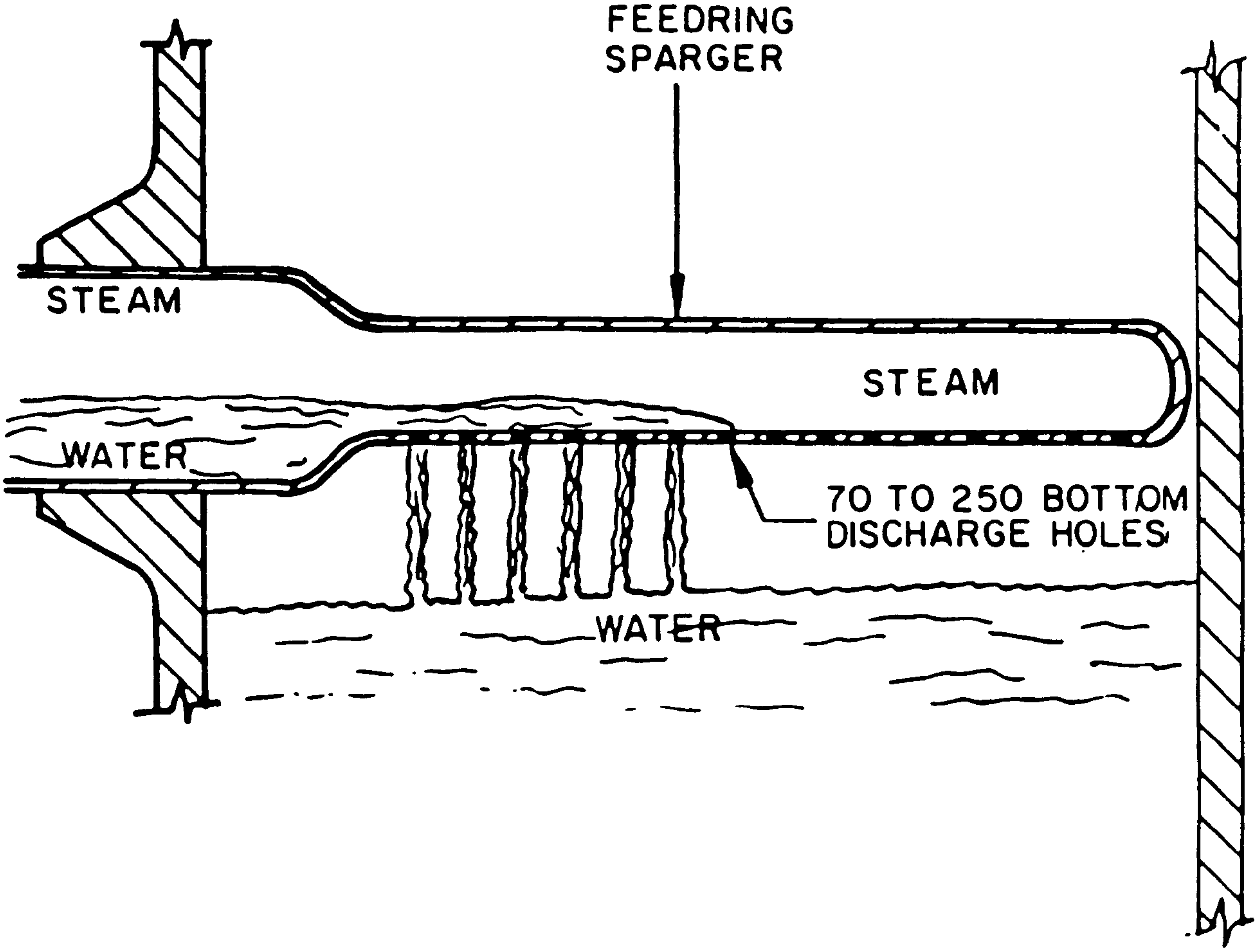


Figure 5.2 POSTULATED STEAM WATER INTERFACE IN THE FEEDRING

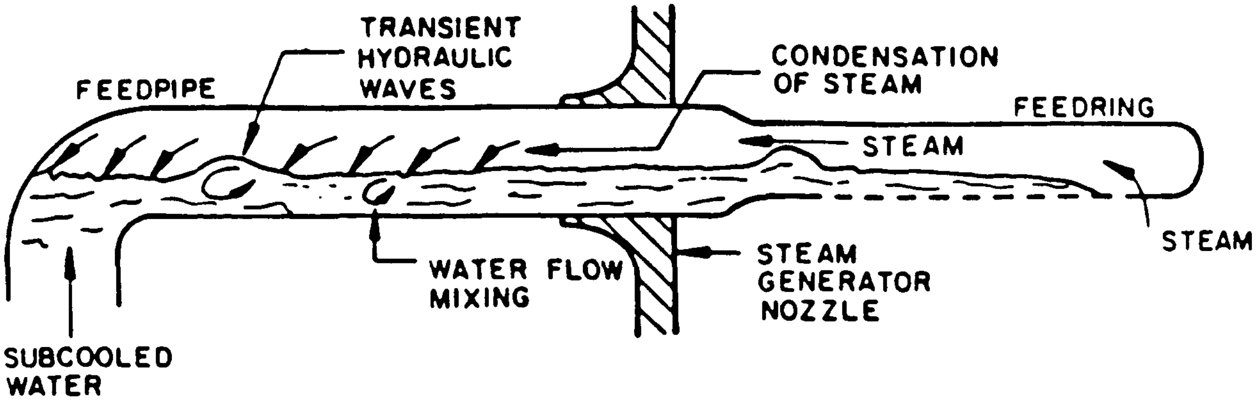


Figure 5.3 POSSIBLE STEAM-WATER MIXING PHENOMENA IN THE FEED SYSTEM

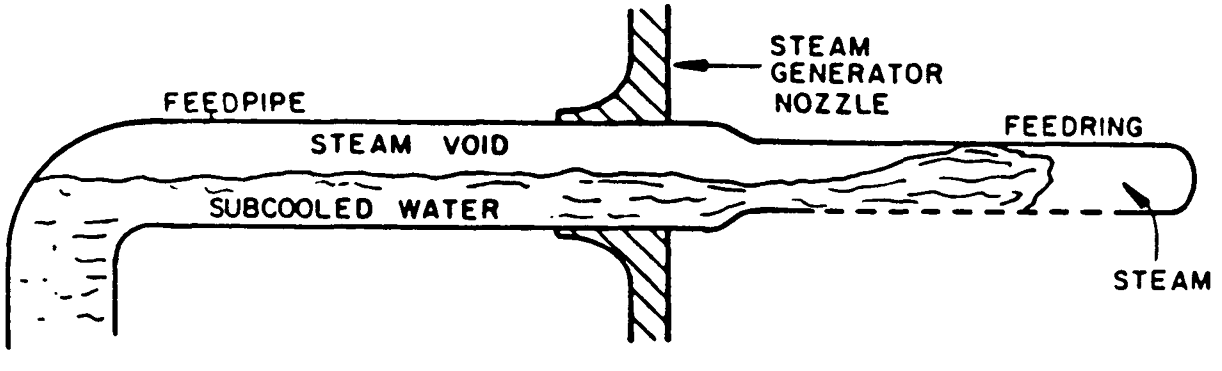


Figure 5.4 POSSIBLE TRAPPING OF A STEAM VOID

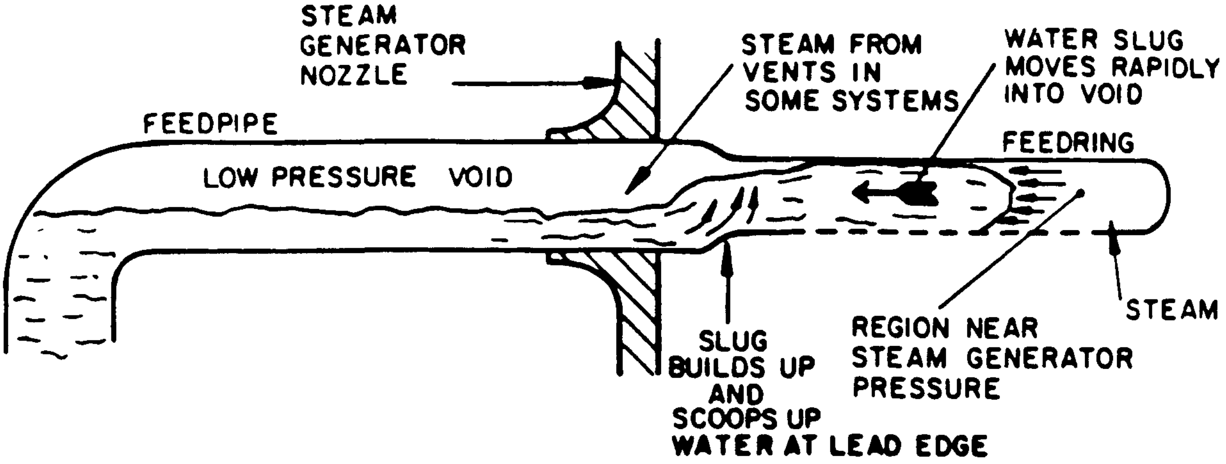


Figure 5.5 POSSIBLE SLUG ACCELERATION INTO VOID

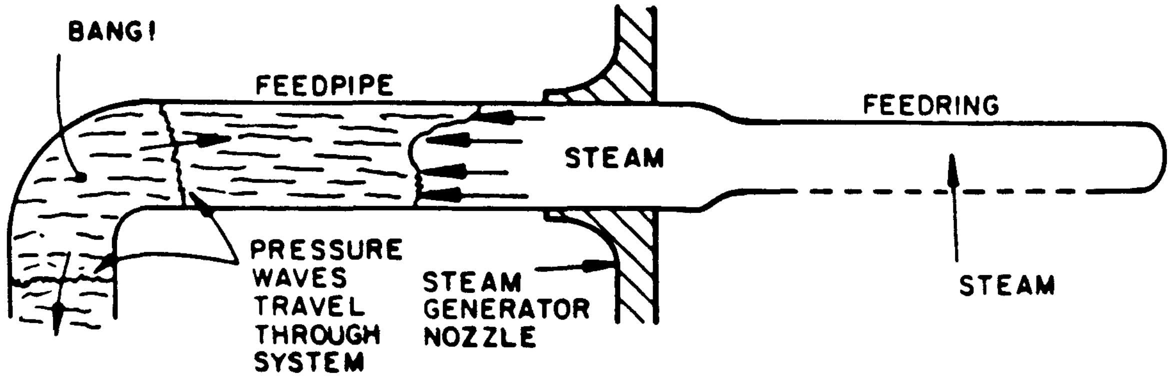


Figure 5.6 POSSIBLE WATER SLUG IMPACT

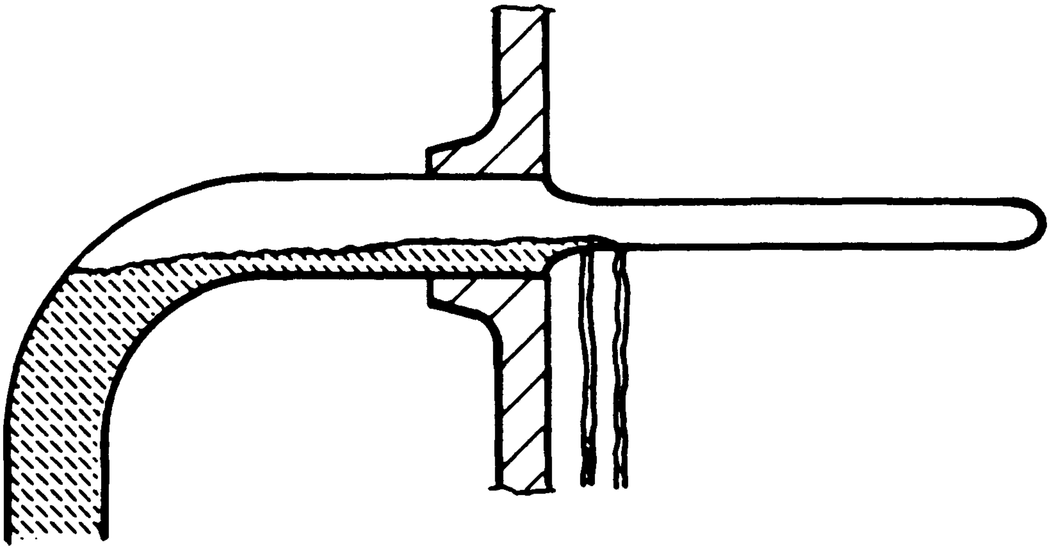


Figure 5.7 STEAM GENERATOR REFILL WITH VERY LOW AFW FLOWRATE

3. Slug Acceleration

Once the slug forms and the cold water lying in the feed pipe and part of the ring becomes agitated, steam condenses rapidly. Until the slug enters the feed pipe, steam will be drawn through the sparger holes to relieve this depressurization, therefore the full steam generator pressure (~1,000 psia) is not applied across the slug. The slug velocity is greatest if the slug has zero length when it enters the feed pipe and the feed pipe contains the least water (then the slug has no mass!). This leads to an absurd limit, therefore we assume the horizontal part of the feedpipe to have length L and be half full. This gives $L_{S1} \cong 0$, $L_{S2} = L/2$, and $L_V = L/2$

4. Impact

The base overpressure P_o is read from Figure C.7. For an applied differential pressure of 1,000 psi acting on a 300°F liquid slug, P_o is roughly 17,000 psi. The appropriate modification factor from Table C.2 is for no reservoir, initial slug length L_{S1} and void fraction α. Then

$$F = \sqrt{\frac{0.5}{0.5}} = 1$$

Thus the impact overpressure is roughly:

$$P_H \cong 17,000 \text{ psi} \qquad !$$

Any assumptions other than those made here probably still lead to unacceptable loads. Clearly, this situation is to be avoided, as indeed is any circumstance in which there is a chance of forming a water slug that is accelerated by the difference between operating steam generator (or reactor) pressure and the essentially zero saturation pressure corresponding to the temperature of cold water.

5.2.3 **Example 3** – **A trapped void collapse.**

This example is based on partly historical and partly hypothetical events following inadvertent draining and refill of a BWR core spray line in a typical installation.

SCENARIO

Figure 5.8 is a sketch of the essential features of a BWR core spray system that takes its suction from the suppression pool and discharges into the reactor drywell at an elevation 60 ft higher.

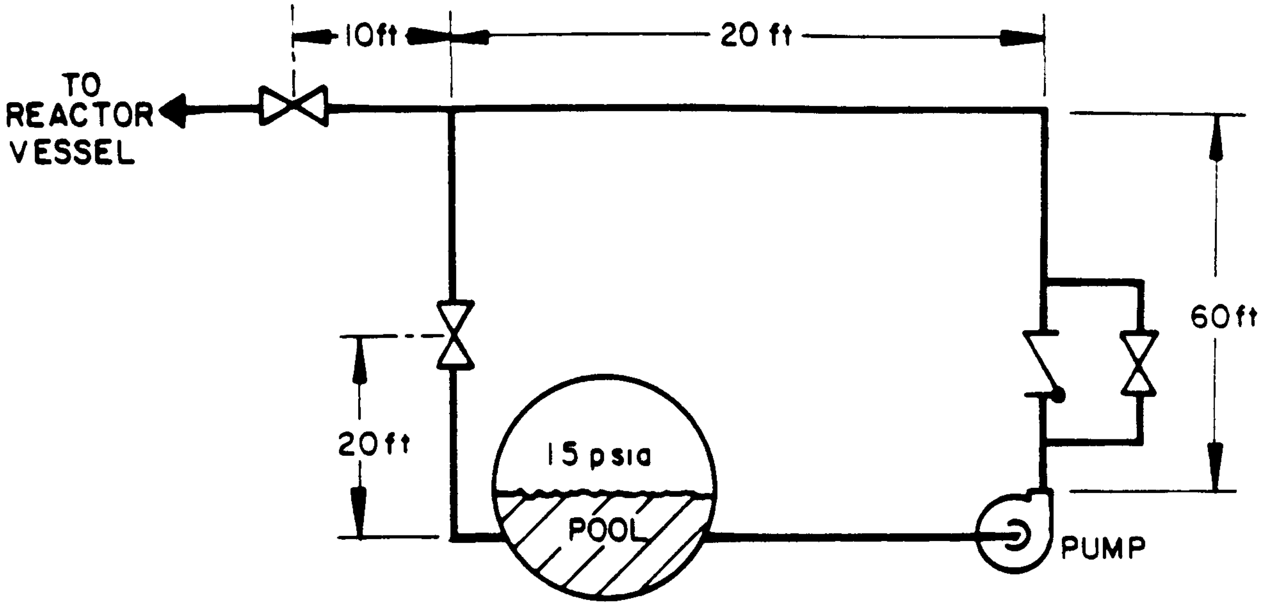


Figure 5.8 SIMPLIFIED SKETCH OF BWR CORE SPRAY SYSTEM

The suppression pool is normally at close to atmospheric pressure of 15 psia. In the postulated scenario the valve in the bypass line shown in the figure has a small leak over a long period of time while all other valves remain closed. This drains the upper part of the system to a level approximately 35 ft above the pool, the maximum height that a pressure of 15 psia can support. When the pump, with a startup time of around 1 second and a capacity of 1,000 gpm, fills the system through the 8" schedule 40 pipeline a waterhammer might occur.

ANALYSIS

1. Void Formation

The initial void occupies the whole of the upper horizontal line and the right-hand vertical line down to a level 35 ft above the pool surface. The pressure in the void is very low (essentially zero), being the vapor pressure of the adjacent cold water.

2. Slug Formation

The initial slug is the water in the lower piping up to a level 35 ft above the pool and downstream of the pump.

3. Slug Acceleration and Impact

The only driving force to accelerate the slug is the pump. After one second the slug is moving at the velocity corresponding to a flow rate of 1,000 gpm in an 8" schedule 40 pipe, that has an area of 50 sq. ins. (Table C.1). Calculations of pumped slug velocities are often necessary for waterhammer diagnoses, and have been graphically summarized in Figure C.8 in Appendix C. This Figure gives P_H directly for pipes of various diameter as a function of the volumetric flow rate. In this case, the overpressure due to the 1,000 gpm flow is roughly 500 psi.

The Froude number (F) is a useful parameter which indicates the flow pattern in a horizontal pipe which is being filled. A Froude number greater than 1.0 implies that the pipe runs full – that is, the slug has a distinct leading edge which fills the entire pipe cross section. For a horizontal pipe of diameter D, the Froude number, F, is:

$$F = V_s / \sqrt{gD}$$

The Froude number for a pipe being filled at a known rate can be evaluated using Figure C.2 in Appendix C. For this example, the Figure indicates a Froude number of 1.4, therefore the slug has a fairly distinct leading edge and does not tend to flow along the bottom of the pipe as it would if F<<1.

Though there will be a "bang" and some transient loads, they are unlikely to be of consequence. This example illustrates that large loads are unlikely unless there is a mechanism for producing sufficiently high water velocities before impact.

5.2.4 Example 4 – A trapped void collapse.

Though the details are different, this example is based on an actual event at a BWR plant. It illustrates a different mechanism for driving the water slug than in the two previous examples.

SCENARIO

Figure 5.9 is a simplified diagram of the relevant parts of the piping in the residual heat removal (RHR) system of a BWR.

In a procedure to test the operation of certain valves, valves A, B and D were simultaneously opened slightly for a short time, allowing reactor water, saturated at 500 psia, 467 F, to fill up the entire line between A and B and part of the line between B and E. The rest of the water in the lines was at around 80 F. Valves A and B were then closed and valve D left open while the pressure in the RHR system was slowly reduced to 20 psig at point F. Valve D was then closed. Sometime later valve B was opened and a waterhammer occurred.

ANALYSIS

1. Void Fraction

After valve B was closed, the sections of piping between B, C and D were slowly depressurized. Any hot water would tend to flash and form steam that would mostly be condensed by the colder water as it tried to flow to D. Since most of the piping contained water at 80 F, the final temperature when D was closed was probably in the range 100 – 150 F with a corresponding saturation pressure between 1 and 4 psia. Since F was then at 20 psig, corresponding to 35 psia or about 81 ft of water, the pressure at C could be below saturation and a void would form. The length of the void depends on the actual temperature of the water in the line, and the accuracy of the pressure gauge at the low end of its range. In the "best case" a void does not form at all. In the "worst" a void about 10 ft long forms below C. Uncertainties of this kind are common when trying to reconstruct a scenario from limited data.

2. Slug Formation

After valve D was closed and the system settled down, the whole of pipes BE and ED, as well as EC up to the steam–water interface were full of water that would be set in motion by any pressure differences (Figure 5.10).

3. Slug Acceleration

The water in the pipe AB was initially at 467 F and had not had much time to cool. When valve B was opened, this hot water was exposed to the pressure in the line BE. The elevation of line BE is 20 feet above the suppression pool surface. The hydrostatic pressure drop due to a 20 foot rise in elevation may be read from Figure C.3 as roughly 9 psia. The pressure in BE was therefore atmospheric pressure (15 psia) less 9 psia, or 6 psia. The hot

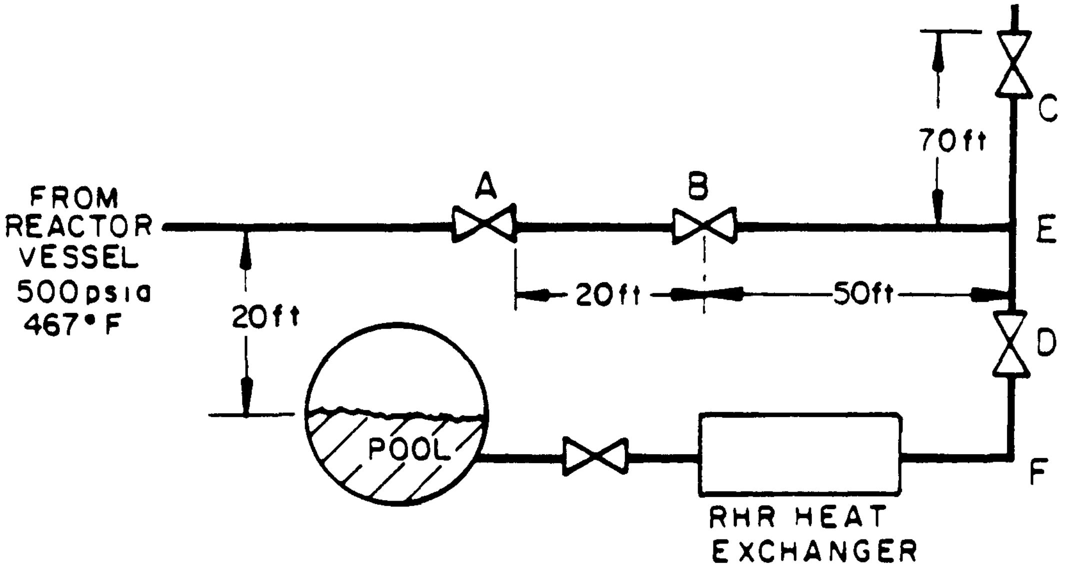


Figure 5.9 SIMPLIFIED SKETCH OF RHR SYSTEM FOR A BWR

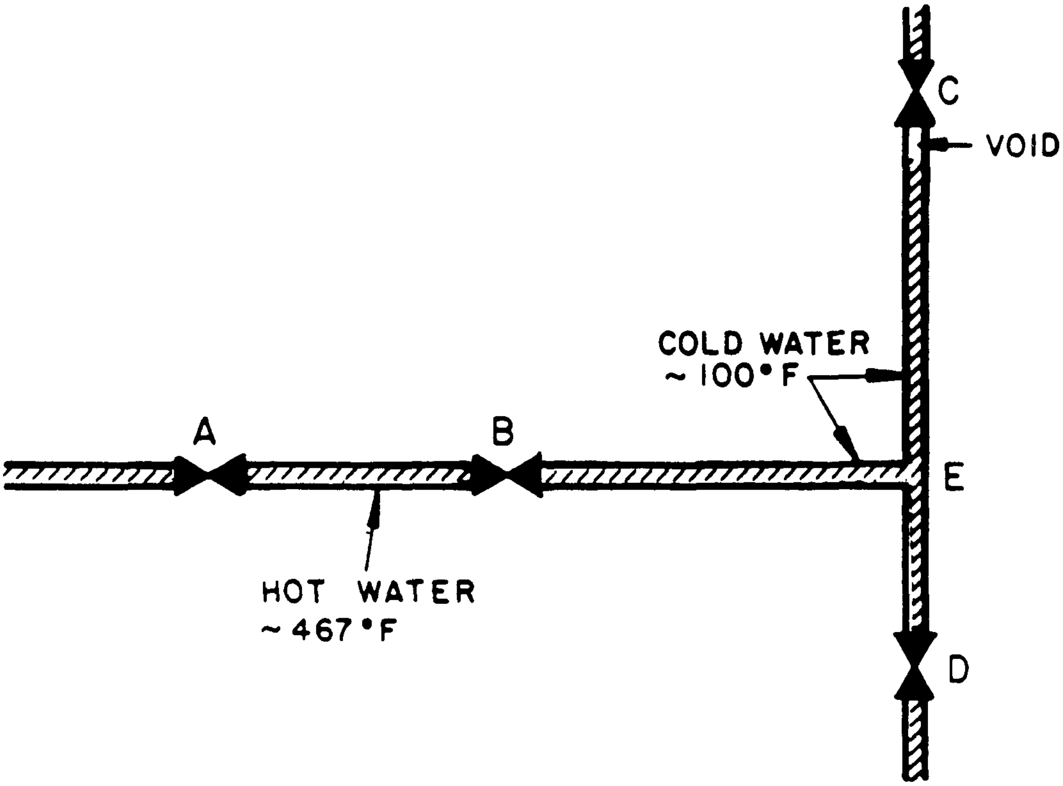


Figure 5.10 THE SITUATION PRIOR TO OPENING OF VALVE B

water therefore flashed rapidly to saturation pressure, forming steam which drove the water slug up to the core spray line to impact at C. In the "worst case", the pressure, P_1, produced by rapid flashing could have been as high as the initial pressure of 500 psia, while the pressure at C was in the range 1–4 psia and negligible. The slug length was 110 feet and L_V/L_{S1} = $10/110 \cong 0.10$.

4. Slug Impact

The base overpressure P_o is found using Figure C.7. With a driving differential pressure of 500 psia, $P_o \cong 12{,}000$. The appropriate modifying factor from Table C.2 is that for no reservoir, void fraction $\alpha=1$:

$$\text{Modifying factor } F = \sqrt{2\left[L_V/L_{S1}\right]} = \sqrt{0.2} = 0.45$$

The waterhammer overpressure P_H is thus:

$$P_H = F \times P_o = (0.45) \times (12{,}000 \text{ psi}) = 5{,}400 \text{ psi}$$

This is a high estimate because of the uncertainties mentioned before. However, this is a case where the analysis may come close to predicting the true value, because the slug of water had been quiescent for a time before acceleration, had a flat top due to the effects of gravity, and would have had to have uniform velocity. Therefore it is not surprising that there was evidence of damage in the actual situation.

5.2.5 Example 5 – A saturated water slug.

This event concerns the effects of a slug of water which is driven through piping by high pressure steam. Loads are generated both when the slug passes through pipe bends and when it is abruptly stopped.

SCENARIO

The system is illustrated in Figure 5.11. The HPCI (High Pressure Coolant Injection) turbine powers the HPCI pump, and is driven by steam extracted from the main steam line. Prior to the waterhammer event, valves A and B were closed in order to perform maintenance on the intermediate piping. During this time the reactor tripped, and in recovering from the trip the reactor vessel was overfilled with water. As a result liquid entered the main steam line and flowed into the HPCI turbine supply line, accumulating upstream of valve A. After the reactor was successfully restarted, maintenance on the steam supply line was completed and valve A was opened. The slug of water was accelerated by 1,000 psig steam through the supply line piping, eventually coming to rest against the closed valve B.

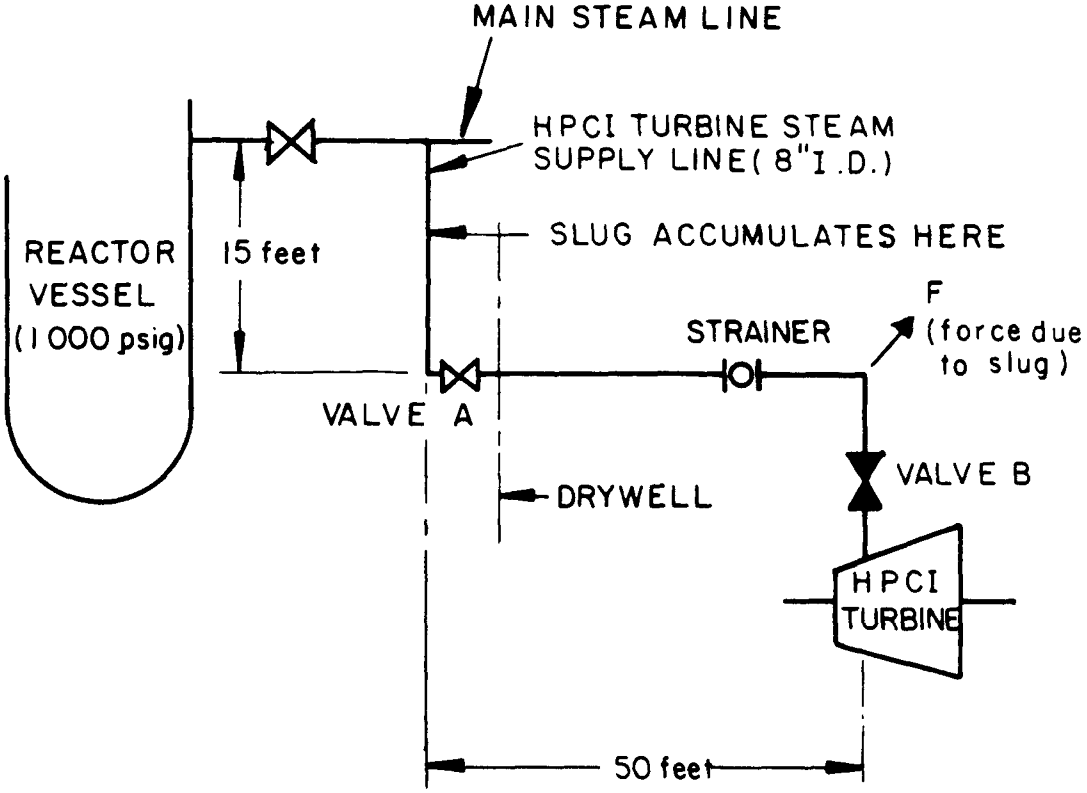


Figure 5.11 HPCI TURBINE STEAM LINE SCHEMATIC

ANALYSIS

A moving slug of water will load the piping in two ways. When the slug changes direction it exerts a reaction force on the pipes. When the slug is stopped, a waterhammer occurs due to impact. If air is present on the low pressure side, it will cushion the final impact and greatly reduce the waterhammer pressure.

The force due to changes in direction can be estimated by a simple expression depending only on the pressure driving the slug, the slug's length and the pipe diameter. The forces exerted on a 90° elbow by a passing water slug are roughly equal to:

$$F = \frac{\Delta p \pi D^3}{8 f L_s} = (10.9)\,\frac{\Delta p D^3}{L_s} \qquad (5.7)$$

where

F = force on the pipe at the elbow (lb_f),
Δp = steam pressure (psi),
D = pipe inner diameter (in),
f = friction factor (assume = 0.03),
L_s = slug length (ft).

The above approximation ignores compressible gas flow effects and will be inaccurate when the distance the slug has travelled is very long compared to the slug length. It will always overestimate the force by some amount. Nevertheless it is adequate for many scoping level calculations.

1. Void Formation

A void is present in the HPCI turbine supply line due to prior maintenance work. It extends from valve A to valve B.

2. Slug Formation and Acceleration

A slug of liquid forms upstream of valve A when the reactor vessel is overfilled. We assume that the slug fills the turbine supply line up to the main steam line. Thus the slug length L_s is 15 feet. When valve A is opened, the slug is accelerated by full reactor pressure of 1,000 psi.

3. Impact

The 90° elbow is 50 feet from the slug's initial location and the turbine supply line has an inner diameter of 8 inches. The maximum force possible at the elbow is then:

$$\begin{aligned} F &= (10.9)(1{,}000\ lb_f/in^2)(8in)^3/(15\ ft) \\ &= 372{,}000\ lb_f \end{aligned}$$

Thus, passing water slugs are capable of generating very high loads.

5.2.6 Example 6 – A Watercannon

This example illustrates simple methods for approximating the loads due to a watercannon event.

SCENARIO

Another schematic of the HPCI turbine system in a BWR is presented in Figure 5.12. The turbine exhaust flows through an 8 inch exhaust line, through two check valves and condenses in the pressure suppression pool. Plant technical specifications require that operability of the HPCI turbine system be demonstrated by regular tests. In one test the HPCI turbine tripped on a high flow signal, then quickly restarted (this system transient was caused by faulty turbine instrumentation). Waterhammer damage was discovered following the turbine trip. The damage consisted of a broken exhaust line upper snubber rated at 20,000 lb_f, displaced concrete expansion anchors and a bent piston rod on an exhaust line lower snubber.

ANALYSIS

1. Void Formation

The void consists of turbine exhaust steam. When the turbine trips, a pocket of steam is trapped between the lower check valve (A) and the suppression pool surface.

2. Slug Formation and Acceleration

The slug consists of liquid from the suppression pool which is drawn up into the exhaust line. The initial slug length L_{S1} is zero. It is accelerated by atmospheric pressure which acts on the surface of the suppression pool. As the steam bubble trapped in the exhaust line condenses, liquid is forced into the exhaust line.

3. Impact

The overpressures and loads due to impact of the slug on check valve (A) can be estimated using the Figures in Appendix C. We will ignore friction and gravity in this scoping analysis and therefore calculate a load which is conservatively high.

The procedure is first to find P_0 using Figure C.7., then use the appropriate modifying factor from Table C.2 to account for the geometry which applies in this case. Referring to Figure C.7., the value of P_0 for an applied pressure of 15 psi (one atmosphere) is about 2,000 psi. The modifying factor from Table C.2 is that for zero initial slug length and initial void fraction of 1.0. The modifying factor in this case is simply 1.0, so the overpressure is:

$$P_H \approx 2{,}000 \text{ psi}$$

Referring to Figure C.11, the axial force on the vertical segment of the turbine exhaust line due to this overpressure is:

$$F_H \approx 100{,}000 \ lb_f$$

This load appears sufficient to damage the snubber rated at 20,000 lb_f.

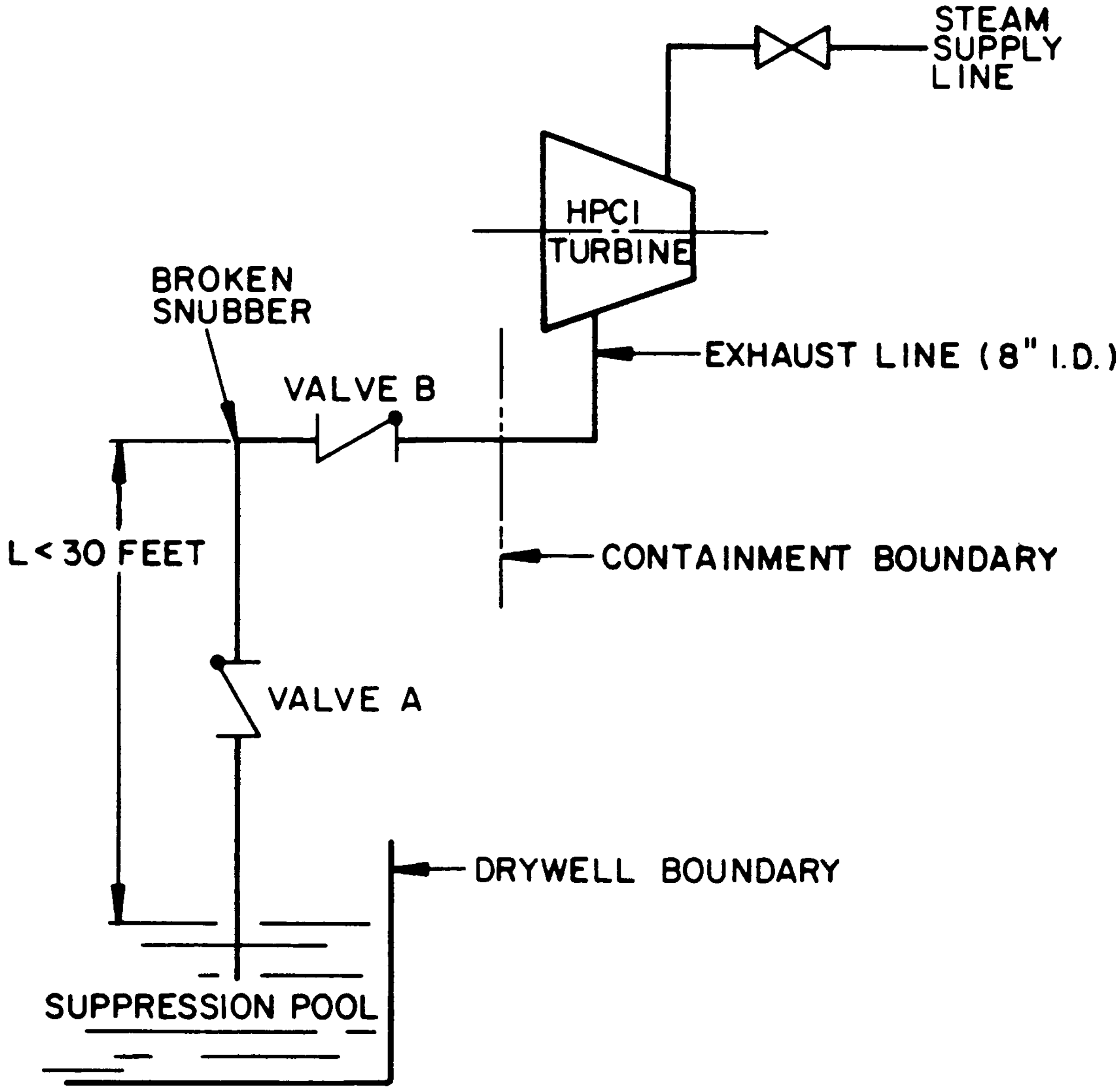


Figure 5.12 HPCI TURBINE EXHAUST LINE SCHEMATIC

5.2.7 Example 7 – Thermal Inversion.

In a thermal inversion event, a slug is driven by gravity into a void formed by flashing. This example is based on an event documented by Wilkinson and Dartnell (1980), which occurred at a fossil station in England.

SCENARIO

The event in question occurred in the boiler feed pump suction system, illustrated in Figure 5.13. The system includes a high level heater–de–aerator–storage tank (a) which supplies liquid at 250 F to the boiler feed pump (b). An emergency supply of cold feedwater (at 70 F) is contained in tank (c), at an elevation higher than tank (a). The difference in elevation corresponds to the difference between saturation pressure in (a) and atmospheric pressure in (c). An emergency valve (d) opens automatically when the liquid level in (a) falls to a low level, admitting cold emergency feedwater from (a) to the pump.

After many years of successful operation, a situation arose in which the liquid level in (a) was decreasing while the pressure was increasing due to a steam turbine overload condition. When the level in (a) reached a low level the emergency valve (d) opened. However, the water pressure in tank (c) did not exceed that from (a), so that hot water from (a) flowed back through the valve (d) and upward towards the emergency FW tank.

As the hot water rose the pressure fell and flashing occurred. The subsequent waterhammer due to thermal inversion fractured the cast iron emergency valve (d).

ANALYSIS

1. Void Formation

A void is formed in the vertical line leading to the cold tank (a) when the static pressure of the hot water flowing upwards falls below its saturation pressure. Figure C.9 gives the distance below a cold water surface that a hot water column will begin to flash, which in this case (250 F) is 65 feet. Since the presence of voids above the hot water front further reduces the pressure, causing more liquid to flash, it is reasonable to assume that the void quickly expands to occupy the entire length of pipe above the hot water front.

2. Slug Formation

The slug consists of cold water from tank (c) accelerated by gravity down the vertical pipe. Its initial length is zero.

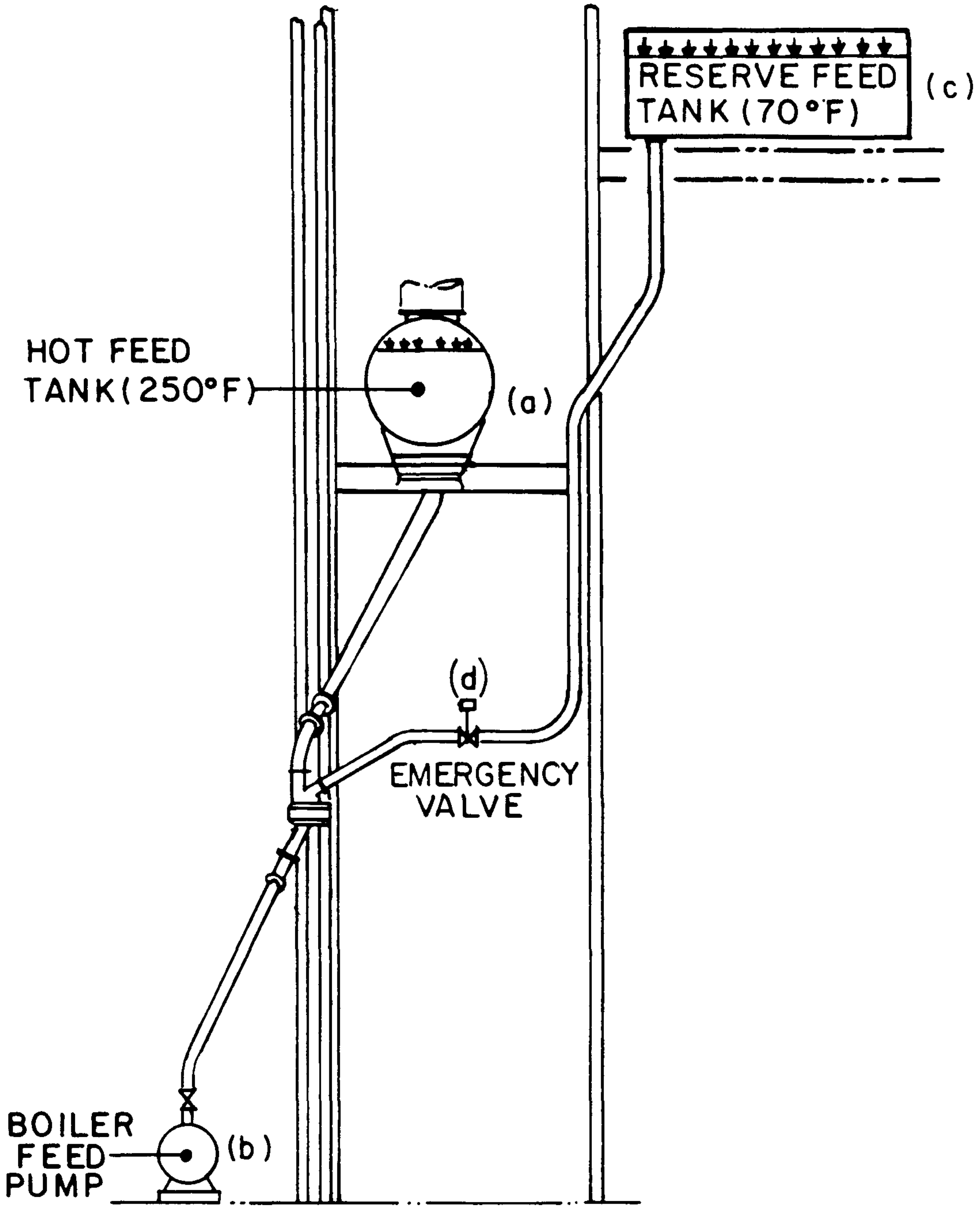


Figure 5.13 FEED PUMP SUCTION SYSTEM AT NOTTINGHAM POWER STATION

3. Slug Acceleration

The slug is accelerated downward by gravity and by atmospheric pressure (there is a vacuum inside the riser) until it strikes the hot water column. As it moves down the pipe its mass increases as well. The slug velocity after falling a height h is conservatively estimated by:

$$V_s = \sqrt{gh} = (5.7)\ \sqrt{h(ft)} = 46 \text{ ft/sec} \qquad (5.8)$$

in which frictional effects have been ignored.

4. Impact

The overpressure due to slug impact may be easily estimated using Figure C.10, which shows the waterhammer pressure as a function of void height. For this example, the pressure pulse magnitude may be read from the Figure or calculated simply as:

$$P_H = 60\ \frac{psi}{ft/s} \times 46 \text{ ft/s} = 2{,}800 \text{ psia}$$

This pressure is significantly greater than those found necessary to fracture large cast iron valves by Wilkinson and Dartnell. The above value is probably high because the leading edge of the falling slug is not flat. However, the example illustrates that significant pressure pulses can arise from thermal inversion events.

5.2.8 Example 8 – Waterhammer wave reflection, transmission and attenuation.

When a waterhammer pressure wave travelling along a pipe reaches a junction, it will be partially reflected back down the original pipe and partially transmitted along the other pipes which meet at the junction. This situation is illustrated in Figure 5.14. Since the junction pressure is the same for all pipes, the transmitted waves are all equal in magnitude. The magnitudes of the transmitted and reflected waves are related to the incident wave magnitude by pipe size and wave speed. Referring to Figure 5.14, let:

A_i = area of pipe with incident wave,

a_i = wave velocity in incident pipe,

and A_j and a_j = corresponding parameters for transmitting pipes,

$p' - p_o$ = magnitude of incident wave

$p'' - p'$ = magnitude of reflected wave

$p'' - p_o$ = magnitude of transmitted waves (all are identical)

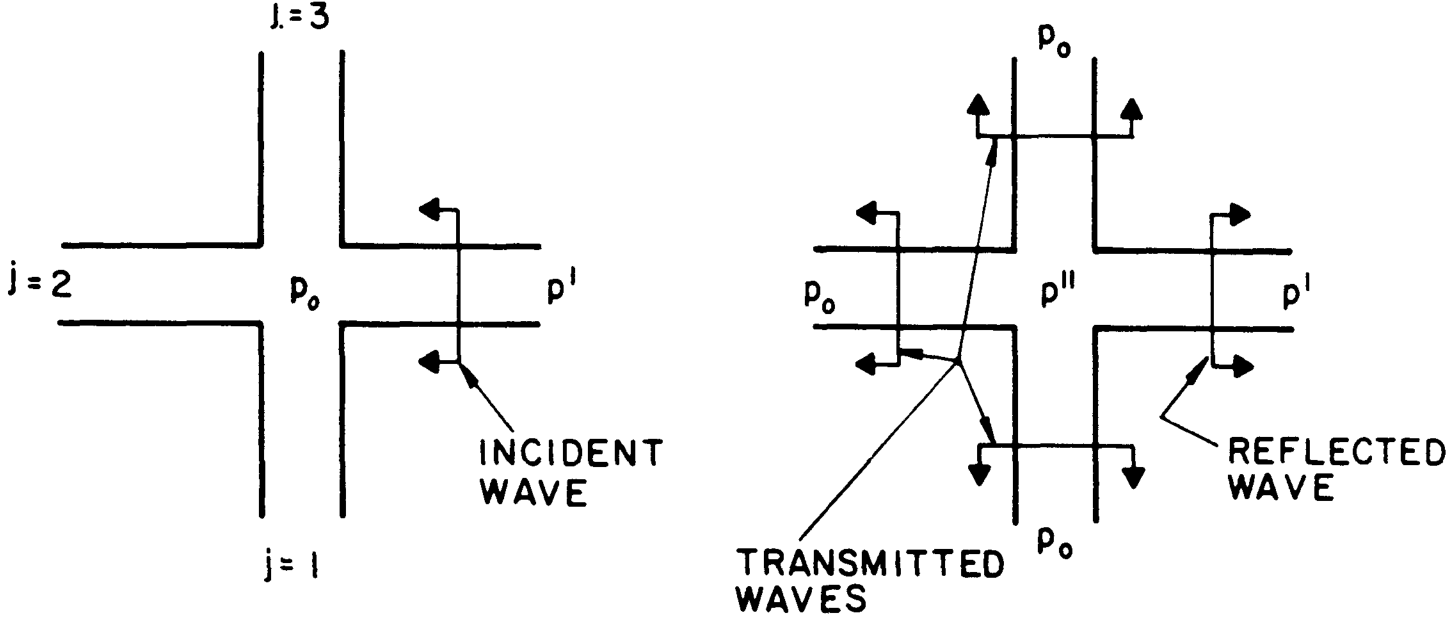


Figure 5.14 REFLECTION AND TRANSMISSION OF WATERHAMMER PRESSURE WAVES

Transmission Coefficient: $s \equiv \frac{p'' - p_o}{p' - p_o} = \frac{2(A_i/a_i)^2}{(A_i/a_i)^2 + \sum_{j=i+1}^{n} (A_i/a_i)^2}$

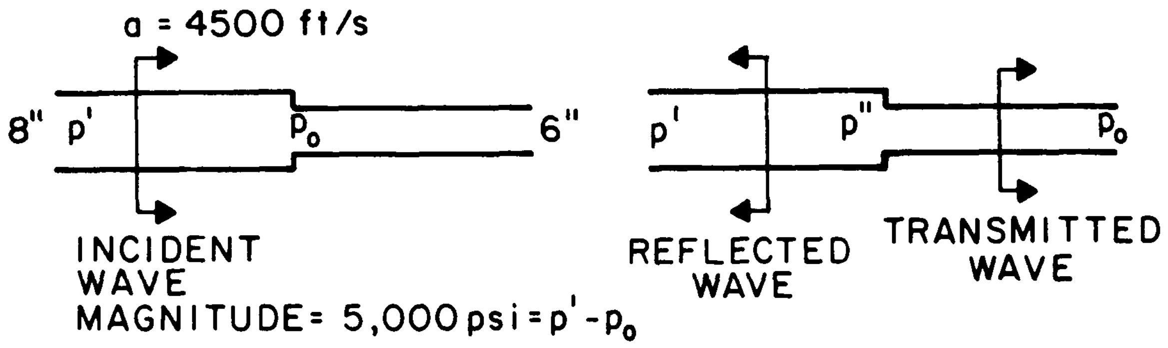
Reflection Coefficient: $r \equiv 1 - s = \frac{p'' - p'}{p' - p_o}$

Note: If wave speeds are identical and D_j is the inner diameter of pipe j:

$$s = \frac{2D_i^2}{D_i^2 + \sum_{j=i+1}^{n} D_j^2}$$

The following two examples illustrate these principles.

1. AREA REDUCTION INCREASES THE WATERHAMMER PRESSURE.



Assume the wave speed a = 4500 ft/s in both the 8" and 6" pipes

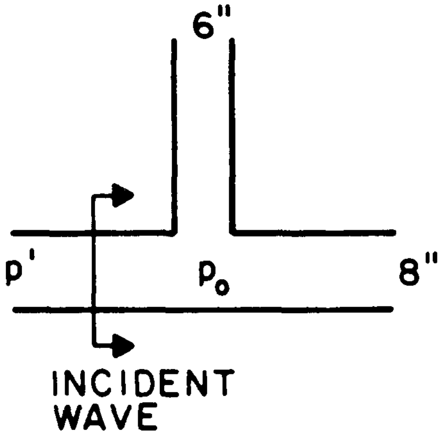
Transmission coefficient $s = \frac{2(8)^2}{(8)^2 + (6)^2} = 1.28$

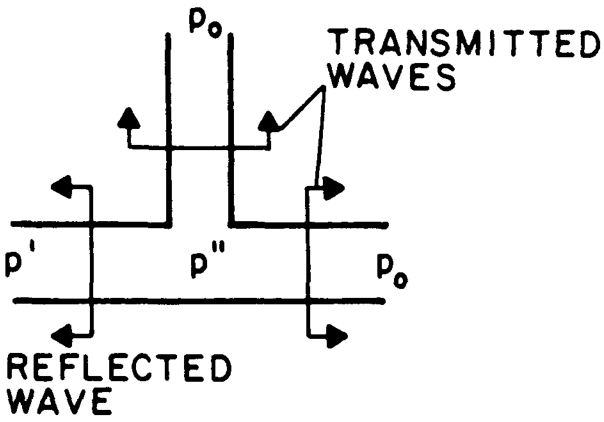
Reflection coefficient $r = s - 1 = 0.28$

Thus the transmitted wave magnitude $(p'' - p_o)$ is equal to (1.28)(5,000) = 6,400 psi. The transmitted wave is of greater magnitude than the incident wave because the fluid velocity must increase in the 6" pipe.

The reflected wave magnitude $(p'' - p_o)$ is (.28)(5,000) = 1,400 psi.

2. T–JUNCTIONS ATTENUATE WATERHAMMER PRESSURES





Incident wave magnitude $(p' - p_o) = 5{,}000$ psi
Assume wave velocity "a" is identical in both pipes.

Transmission coefficient $$s = \frac{2(8)^2}{(8)^2 + (8)^2 + (6)^2} = 0.39$$

Reflection coefficient $$r = s - 1 = -0.61$$

The transmitted wave magnitude is $(p'' - p_o) = (0.39)(5{,}000) = 1{,}950$ psi
Reflected wave magnitude $(p'' - p') = (-0.61)(5{,}000) = -3{,}050$ psi

(Note: In this case p" is less than the pressure p' in the incident pipe, so that the reflected wave has a negative magnitude)

5.3 REFERENCES

1 Wilkinson, D.H., and Dartnell, L.M., "Water Hammer Phenomena in Thermal Power Station Feed Water Systems," Proceedings of the Inst. of Mech. Engineers, Vol. 194, March 1980.

APPENDIX A

WATERHAMMER MITIGATION AND PREVENTION TECHNIQUES

This appendix briefly lists techniques for preventing and mitigating waterhammer events. NRC has published thorough reports detailing waterhammer mitigation and prevention techniques. For convenience, this Appendix simply summarizes the main results of these reports which are relevant to condensation–induced waterhammer. The reader is referred to References A–1 (NUREG–0927) and A–2 (NUREG/CR–2781) for a more complete discussion of this topic.

Tables A–1 and A–2 (adapted from NUREG–0927) present a system by system review of the primary causes of condensation–induced waterhammer in BWRs and PWRs. The Table also suggests preventive measures, often from both a design and an operational standpoint. Eight generic preventive techniques are included in the recommendations which are applicable to condensation–induced waterhammer problems. These techniques are discussed below.

1. VOID DETECTION SYSTEMS. Void detection systems can be provided at the high points in liquid filled piping which is normally idle, where voids or steam bubbles may form as a result of maintenance, operation, draining, out–leakage, gas evolvement, or in–leakage of steam or flashing fluid.

2. VENTING. Vent lines should be provided to vent components or piping at the high points in liquid–filled systems which are normally idle, where voids or steam bubbles may form.

3. HPCI TURBINE INLET VALVE. The HPCI turbine inlet line inboard or outboard isolation valves should not contain a "seal in" feature on opening when the valves are in manual mode. The valve design should permit gradual opening to enable acceptable line warmup. Operating procedures should prohibit closing the outboard isolation valve unless the inboard valve is fully closed and opening the inboard isolation valve unless the outboard valve is fully open, when the valves are in manual mode (for systems in which the outboard valve is normally open).

4. HPCI AND RCIC TURBINE EXHAUST LINE VACUUM BREAKERS. The HPCI and RCIC turbine exhaust lines should be provided with vacuum breakers to prevent vacuum formation in any portion of the exhaust line due to steam condensation. The design should preclude introduction of water slugs from the suppression pool and rapid check valve closure, and should account for the effects of condensation caused by a cold exhaust line and water backflow.

5. HPCI TURBINE LINE DRAIN POT LEVEL DETECTION. Drain systems should be provided for the HPCI turbine lines to remove all condensate from low levels. The HPCI system piping configuration should be reviewed to verify that all low spots drain to the drain system and that sufficient slope is provided to ensure complete drainage. Drain pots must be of adequate size to handle all expected condensate.

Table A-1. BWR SYSTEM CONDENSATION-INDUCED WATERHAMMER CAUSES AND PREVENTIVE MEASURES

SYSTEM	PRIMARY CAUSES OF WATERHAMMER	PREVENTIVE MEASURES	
		DESIGN	PLANT OPERATION
RHR	Voiding, Steam-Bubble Collapse	Void Detection, Venting	Void Detection and Correction, Venting, Operating Procedures, Operator Training
HPCI	Steam Water Entrainment, Turbine Inlet Valve Operation	No Opening Seal-in in Manual Mode, Gradual Opening	Valve Opening Sequence Operator Training, Operating Procedures
	Steam Water Entrainment due to Drain Pot Malfunction	Proper Drain System Including Drain Pot Sizing and Level Verification	Verification of Drain Pot Level, Operating Procedures
	Turbine Exhaust Line Bubble Collapse	Exhaust Line, Vacuum Breakers	
	Pump Discharge Line Voiding	Void Detection, Venting	Void Detection and Correction, Venting, Operating Procedures, Operator Training
Core Spray	Voiding, Steam-Bubble Collapse	Void Detection, Venting	Void Detection and Correction, Venting, Operating Procedures Operator Training
Essential Service Water	Voiding, Column Separation	Void Detection, Venting	Void Detection and Correction, Venting, Operating Procedures, Operator Training
Main Steam	Steam Water Entrainment		Operating Procedures, Operator Training
RCIC	Exhaust Line Steam Bubble Collapse	Exhaust Line Vacuum Breakers	
Isolation Condenser	High Reactor Water Level		Operating Procedures, Operator Training

Table A–2. PWR SYSTEM WATERHAMMER CAUSES AND PREVENTIVE MEASURES

SYSTEM	PRIMARY CAUSES	PREVENTIVE MEASURES	
		DESIGN	PLANT OPERATION
Feed–water	Unknown and Operator Error Induced Steam Bubble Collapse		Operating Procedures, Operator Training
Main Steam	Steam Water Entrainment, Unknown		Operating Procedures, Operator Training
RHR	Voiding	Venting	Operating Procedures, Operator Training
ECCS	Voiding	Venting, Void Detection	Operating Procedures, Operator Training
CVCS	Steam Bubble Collapse or Vibration		Operating Procedures, Operator Training
Essential Cooling Water	Voiding	Venting	Operating Procedures, Operator Training
Steam Generator	Line Voiding Followed by Steam Bubble Collapse	BTP ASB 10–2 Provisions: Top Discharge, Short Line Lengths	BTP ASB 10–2 Provisions: Testing, Keeping Line Full. Automatic AFW Initiation

6. PLANT PERSONNEL TRAINING. All operating personnel and maintenance personnel who service plant fluid systems in which waterhammer can occur should receive training in the causes, effects and prevention of waterhammer. New operating information relevant to waterhammer should be continuously incorporated into this training.

7. OPERATING AND MAINTENANCE PROCEDURES. Operating and maintenance procedures for systems in which waterhammer can occur should take into consideration the potential for waterhammer. These procedures should address the following issues:

- rapid valve motion,
- introduction of steam bubbles into water–filled lines and components,
- proper filling and venting of water–filled lines and components,
- introduction of steam or heated water (which can potentially flash) into water–filled lines and components

- introduction of water into steam–filled lines or components,
- proper warmup of steam–filled lines,
- proper drainage of steam–filled lines,
- the effects of valve alignment on line conditions.

8. PREVENTION OF STEAM GENERATOR WATERHAMMER. The following techniques from Reference A–3 (NRC Branch Technical Position ASB 10–2) are recommended:

- For top–feed steam generators, J–tube feedrings are advised, as well as minimizing the length of horizontal piping to the feedring.

- For preheater steam generators, the horizontal length of pipe leading into the steam generator should be minimized, a check valve can be provided upstream of the auxiliary feedwater connection to the top feedwater line, and the top feedwater line should be maintained full of water at all times.

- For once–through designs, the auxiliary feedwater should be provided to the steam generator through an external header.

In all cases, automatic auxiliary feedwater system initiation is required as per NUREG–0737 (Reference A–4). Testing procedures are recommended in NUREG–0927.

APPENDIX A REFERENCES:

1. Evaluation of Water Hammer Occurrence in Nuclear Power Plants; U.S. Nuclear Regulatory Commission; Office of Nuclear Reactor Regulation; NUREG–0927.

2. Evaluation of Water Hammer Events in Light Water Reactor Plants; U.S. Nuclear Regulatory Commission; Office of Nuclear Reactor Regulation; NUREG/CR–2781.

3. U.S. Nuclear Regulatory Commission, "*Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants - LWR Edition*," USNRC Report NUREG–0800, July 1981, Branch Technical Position ASB 10–2, attached to section 10.4.7. Available for purchase from National Technical Information Service, Springfield, Virginia 22161.

4. U.S. Nuclear Regulatory Commission, "*Clarification of TMI Action Plan Requirements*," NUREG–0737, November 1980, paragraphs II.D.1 and II.E.1.2. Available for purchase from National Technical Information Service, Springfield, Virginia 22161

APPENDIX B

SYSTEMS REVIEW

This appendix summarizes historical waterhammer events in terms of the resulting damage, class of event, and system. These tables can be used to determine the historical frequency of similar event occurrence in similar systems. Table B.1 lists the number of reported waterhammer events indexed by event class and damage level. Table B.2 gives the number of reported waterhammer events as a function of event class and BWR system; Table B.3 does the same for PWRs.

For a more up–to–date exposition of waterhammer statistics, refer to:

> Serkiz, A.W.; *Waterhammer in U.S. Nuclear Power Plants*; Presented at the ASME Pressure Vessel and Piping Conference, San Diego, CA, June 28–July 2, 1987.
>
> or
>
> Van Duyne, D.A. and Yow, W.; *Plant Waterhammer Experience*; Prepared for the Electric Power Research Institute by Stone & Webster Eng. Corp., January 1988.

Table B-1. WATERHAMMER DAMAGE STATISTICS FOR WATERHAMMER EVENTS REPORTED TO THE NUCLEAR REGULATORY COMMISSION (SOURCE: NUREG/CR-2781)

EVENT TYPE	DAMAGE LEVEL				
	SEVERE	MODERATE	MINOR	NO DAMAGE	DAMAGE LEVEL UNKNOWN
1 SUBCOOLED WATER SLUG	3(SG)	5(SG)	3(SG)	12(SG) 1(PWR)	5(SG)
2 WATER CANNON	0	0	3(BWR)	3(BWR)	
3 TRAPPED VOID COLLAPSE	0	1(BWR)	9(BWR)	1(BWR)	2(BWR)
4 SATURATED WATER SLUG	0	0	10(BWR) 1(PWR)	4(BWR)	2(BWR)
TYPE UNKNOWN	0	4(BWR) 3(PWR)	7(BWR) 6(PWR)	0	8(BWR)

NOTES: 1) "SG" implies a steam-generator waterhammer event;
"BWR" implies an event which occurred in a BWR;
"PWR" implies an event which occurred in a PWR which was not a steam-generator waterhammer.

2) This table covers the years 1969 through 1981.

3) This table only includes events which are known to involve waterhammer.

Table B-2. KNOWN WATERHAMMER EVENTS IN BWRS BY SYSTEM AND EVENT CLASS					
BWR SYSTEM	EVENT CLASS				
	1 SUBCOOLED WATER SLUG	2 WATER CANNON	3 TRAPPED VOID COLLAPSE	4 SATURATED WATER SLUG	5 UNKNOWN OR OTHER EVENT CLASS
CONDENSER			1	1	1
CORE SPRAY			1		7
FEEDWATER					3
HPCI		6		10	4
MAIN STEAM				2	4
PROCESS STEAM			1		
RCIC				1	1
RHR:					
Containment Spray					3
Fuel Pool Cooling					3
Head Spray					1
LPCI					3
Steam Supply/ Exhaust			5	4	2
Shutdown Cooling			1		4
Unidentified			1		1
RWCU					1
SCW			3		6

NOTES: 1) The current table is drawn from NUREG/CR-2781, and covers the time period 1969 through 1981.

2) The current table includes only events designated in NUREG/CR-2781 as known waterhammers.

Table B-3. KNOWN WATERHAMMER EVENTS IN PWRS BY SYSTEM AND EVENT CLASS

PWR SYSTEM	EVENT CLASS				
	1 SUBCOOLED WATER SLUG	2 WATER CANNON	3 COMPONENT TRAPPED VOID	4 SATURATED WATER SLUG	5 UNKNOWN OR OTHER EVENT CLASS
CONDENSER					4
CVCS					2
ECCS			1		3
FEEDWATER			1	1	12
RHR					1
RCS					5
SCW					3
STEAM (MAIN)					7
STEAM GENERATOR	27				

NOTES:
1) The current table is drawn fron NUREG/CR-2781, and covers the time period 1969 through 1981.
2) The current table includes only events designatd in NUREG/CR-2781 as known waterhammers.

APPENDIX C

METHODS AND REFERENCE MATERIALS

This appendix contains Figures and Tables to aid in the field diagnosis of waterhammer. Each Figure or Table is briefly explained in the following text. In addition, the use of almost all Figures or Tables is illustrated either by one of the examples in Chapter 5 or by a case study in Volume 2. The Figures and Tables are cross–referenced to indicate previous sections which demonstrate their use.

TABLE C.1: PIPE PROPERTIES

The geometric properties of pipes of various schedules are listed in Table C.1*. For each nominal outside diameter and schedule number the table lists wall thickness, inner diameter, inner area for fluid flow, metal cross sectional area, and longitudinal area per unit length on both the inner and outer pipe surfaces.

Example applications: See Sections 5.2.1 (Vol. 1) and 5.2.3 (Vol. 1).

FIGURE C.1: FILL TIMES FOR 100 FEET OF PIPE

It is often necessary to calculate the time required to fill a pipe with water at a known flow rate. The fill times for 100 feet of pipe of various inner diameters are given in Figure C.1. The fill time for a different length of pipe is obtained by multiplying the fill time from Figure C.1 by the ratio of actual pipe length to 100 feet.

Example applications: See Sections 5.2.1 (Vol. 1), 2.5 (Vol. 2) and 3.5 (Vol. 2).

FIGURE C.2: FROUDE NUMBER AS FUNCTION OF PIPE SIZE AND FLOW RATE

The Froude number (F) roughly indicates the flow pattern when water flows into an empty horizontal pipe. Froude numbers greater than 1.0 imply that the pipe "runs full," i.e. the flow rate is high enough so that all steam is pushed out of the pipe ahead of an advancing slug of water. Froude numbers less than 1.0 generally imply that the flow rate is too low to run full. Incoming water first coats the bottom of the pipe, which is gradually filled as water continues to flow in. Figure C.2 shows the value of F as a function of flowrate for pipes of various inner diameters.

Example applications: See Sections 5.2.3 (Vol. 1), 1.5 (Vol. 2) and 2.5 (Vol. 2).

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* This table is reproduced from: PIPING DESIGN AND ENGINEERING, FIFTH EDITION; ITT Grinnell Industrial Piping, Inc.; 1976.

FIGURE C.3: HYDROSTATIC PRESSURE DIFFERENCE IN A VERTICAL COLUMN OF WATER

The pressure within piping systems is partially determined by elevation. Pressure differences caused by elevation differences in water of various temperatures may be read from Figure C.3. This Figure is useful for estimating the pressure in a pipe based on a known pressure at a different elevation.

Example applications: See Sections 4.5 (Vol. 2) and 5.5 (Vol. 2).

FIGURE C.4: WATERHAMMER OVERPRESSURE DEPENDS ON THE FLUID VELOCITY AND TEMPERATURE

When a slug of liquid is suddenly decelerated, the resulting waterhammer overpressure P_H depends on the slug's initial velocity and its temperature. The overpressure as a function of velocity and temperature is presented in Figure C.4. The dashed line in the Figure corresponds to the simple approximation that the overpressure in psi is equal to 60 times the slug velocity in ft/s.

FIGURE C.5: WATERHAMMER OVERPRESSURE DECREASES WITH RISING WATER TEMPERATURE

This Figure presents a modification factor for waterhammer overpressures to account for fluid temperatures. In Figures C.8 and C.10, overpressures are calculated at an assumed temperature of 300 F. If the actual slug temperature is not 300 F and a more precise estimate of P_H is desired, Figure C.5 should be used. The overpressure at a fluid temperature not equal to 300 F is obtained by this procedure:

1. determine the overpressure for a slug temperature of 300 F,
2. use Figure C.5 to obtain a modification factor which corresponds to the actual slug temperature,
3. multiply the 300 F overpressure by the modification factor.

The modified overpressure will account more precisely for the actual slug temperature.

FIGURE C.6: GEOMETRY FOR SLUG ACCELERATION INTO A VOID

This Figure defines geometrical parameters (initial and final slug lengths, initial void length, and void fraction) which are used in succeeding Figures to calculate waterhammer overpressures.

Example applications: See Sections 5.2.1 (Vol. 1), 5.2.2 (Vol. 1), 5.2.4 (Vol. 1), 5.2.6 (Vol. 1), 1.5 (Vol. 2) and 2.5 (Vol. 2).

FIGURE C.7: BASE OVERPRESSURE P_0

This Figure presents values for the base overpressure P_0 as a function of slug temperature and the differential pressure acting on the slug. This Figure can be used to calculate the waterhammer overpressure in a given situation (in conjunction with Table C.2) as described above. The value of P_0 is useful by itself because it depends only on the slug differential pressure (the effects of slug temperature on P_0 are relatively small). In situations where there is not enough data or evidence to calculate a modifying factor F, the value of P_0 provides a reasonable, first–order approximation to the waterhammer overpressure.

Example applications: See Sections 5.2.1 (Vol. 1), 5.2.2 (Vol. 1), 5.2.4 (Vol. 1), 5.2.6 (Vol. 1), 1.5 (Vol. 2) and 2.5 (Vol. 2).

TABLE C.2: FACTORS TO MODIFY OVERPRESSURES TO ACCOUNT FOR SPECIFIC GEOMETRY

This table contains modification factors (F) which are used to modify the base overpressures (P_0) from Figure C.7. P_0 depends only on the differential pressure acting on a liquid slug. The modification factors presented in this table are used to account for specific geometries. The geometrical parameters used in this Table are defined in Figure C.6. The procedure for estimating P_H, the waterhammer overpressure, is as follows:

1. From Figure C.7 determine P_0,
2. From Table C.2 and Figure C.6, calculate the value of F which corresponds to the particular geometry, and
3. Calculate $P_H = F \times P_0$.

Example applications: See Sections 5.2.1 (Vol. 1), 5.2.2 (Vol. 1), 5.2.4 (Vol. 1), 5.2.6 (Vol. 1), 1.5 (Vol. 2) and 2.5 (Vol. 2).

FIGURE C.8: WATERHAMMER OVERPRESSURE FROM SUDDEN DECELERATION OF A FLUID COLUMN

A common waterhammer scenario involves a pumped fluid column which collapses a steam void and is suddenly stopped by a stationary column or other non–compliant surface, such as a closed valve. The slug or column dynamics are often governed by the pump in these cases. When the pump flow rate is known, the column velocities and waterhammer overpressures can be calculated. Figure C.8 presents the results of such a calculation. Waterhammer overpressures are shown as a function of pump flow rate and pipe inner diameter.

Example applications: See Sections 5.2.3 (Vol. 1), 3.5 (Vol. 2), 4.5 (Vol. 2) and 5.5 (Vol. 2).

FIGURE C.9: THE HEIGHT BELOW A COLD WATER SURFACE AT WHICH A HOT WATER COLUMN WILL FLASH TO STEAM

This Figure applies to a situation in which hot water flows upwards towards a free liquid surface which is at atmospheric pressure. As the hot column rises, its pressure falls. At some distance below the free surface, the hot column will reach its saturation pressure and flash to steam. (This is the first step in a thermal inversion waterhammer.) The distance is primarily a function of the hot water temperature, and is presented in Figure C.9.

Example application: See Section 5.2.7 (Vol. 1).

FIGURE C.10: WATERHAMMER OVERPRESSURES FROM IMPACT OF A FALLING COLUMN OF WATER

The impact of a falling column of water on a stationary column or metal surface can generate significant overpressures. This Figure presents the overpressure as a function of the initial height from which the fluid column falls. In conjunction with Figure C.9, the overpressure resulting from a thermal inversion waterhammer may be estimated. The procedure is:

1. Use Figure C.9 to estimate the length of vertical pipe which is voided by flashing, and
2. Use Figure C.10 to estimate the waterhammer overpressure resulting from impact of a cold water column after falling the voided length.

Example application: See Section 5.2.7 (Vol. 1).

FIGURE C.11: SEGMENT FORCES DEPEND ON THE WATERHAMMER OVERPRESSURE AND PIPE DIAMETER

The axial forces on a segment of pipe through which a waterhammer pressure wave travels is simply the magnitude of the pressure wave multiplied by the pipe's cross sectional area. This calculation is presented in Figure C.11, which shows the segment force as a function of overpressure for pipes of various inner diameters.

Example applications: See Sections 3.5 (Vol. 2), 4.5 (Vol. 2) and 5.5 (Vol. 2).

TABLE C-1. PIPE PROPERTIES

nominal pipe size *outside diameter* in.	schedule number*			wall thick ness, in.	inside diam- eter in.	inside area, sq. in.	metal area, sq. in.	sq ft outside surface, per ft	sq ft inside surface, per ft	weight per ft, lb†	weight of water per ft, lb	moment of inertia, in.⁴	section modu- lus, in.³	radius gyra- tion, in.
	a	b	c											
6 *6 625*			5S	0 109	6 407	32 2	2 231	1 734	1 677	5 37	13 98	11 85	3 58	2 304
			10S	0 134	6 357	31 7	2 733	1 734	1 664	9 29	13 74	14 40	4 35	2 295
				0 219	6 187	30 100	4 410	1 734	1 620	15 020	13 100	22 6600	6 8400	2 2700
	40	Std	40S	0 280	6 065	28 89	5 58	1 734	1 588	18 97	12 51	28 14	8 50	2 245
	80	XS	80S	0 432	5 761	26 07	8 40	1 734	1 508	28 57	11 29	40 5	12 23	2 195
	120			0 562	5 501	23 77	10 70	1 734	1 440	36 39	10 30	49 6	14 98	2 153
	160			0 718	5 189	21 15	13 33	1 734	1 358	45 30	9 16	59 0	17 81	2 104
		XXS		0 864	4 897	18 83	15 64	1 734	1 282	53 16	8 17	66 3	20 03	2 060
				1 000	4 625	16 792	17 662	1 734	1 211	60 076	7 284	72 1190	21 7720	2 0200
				1 125	4 375	15 025	19 429	1 734	1 145	66 084	6 517	76 5970	23 1240	1 9850
8 *8 625*			5S	0 109	8 407	55 5	2 916	2 258	2 201	9 91	24 07	26 45	6 13	3 01
			10S	0 148	8 329	54 5	3 94	2 258	2 180	13 40	23 59	35 4	8 21	3 00
				0 219	8 187	52 630	5 800	2 258	2 150	19 640	22 900	51 3200	11 9000	2 9700
	20			0 250	8 125	51 8	6 58	2 258	2 127	22 36	22 48	57 7	13 39	2 962
	30			0 277	8 071	51 2	7 26	2 258	2 113	24 70	22 18	63 4	14 69	2 953
	40	Std	40S	0 322	7 981	50 0	8 40	2 258	2 089	28 55	21 69	72 5	16 81	2 938
	60			0 406	7 813	47 9	10 48	2 258	2 045	35 64	20 79	88 8	20 58	2 909
	80	XS	80S	0 500	7 625	45 7	12 76	2 258	1 996	43 39	19 80	105 7	24 52	2 878
8 *8 625*	100			0 593	7 439	43 5	14 96	2 258	1 948	50 87	18 84	121 4	28 14	2 847
	120			0 718	7 189	40 6	17 84	2 258	1 882	60 63	17 60	140 6	32 6	2 807
	140			0 812	7 001	38 5	19 93	2 258	1 833	67 76	16 69	153 8	35 7	2 777
	160			0 906	6 813	36 5	21 97	2 258	1 784	74 69	15 80	165 9	38 5	2 748
				1 000	6 625	34 454	23 942	2 258	1 734	81 437	14 945	177 1320	41 0740	2 7190
				1 125	6 375	31 903	26 494	2 258	1 669	90 114	13 838	190 6210	44 2020	2 6810
10 *10 750*			5S	0 134	10 482	86 3	4 52	2 815	2 744	15 15	37 4	63 7	11 85	3 75
			10S	0 165	10 420	85 3	5 49	2 815	2 728	18 70	36 9	76 9	14 30	3 74
				0 219	10 312	83 52	7 24	2 815	2 70	24 63	36 2	100 46	18 69	3 72
	20			0 250	10 250	82 5	8 26	2 815	2 683	28 04	35 8	113 7	21 16	3 71
	30			0 307	10 136	80 7	10 07	2 815	2 654	34 24	35 0	137 5	25 57	3 69
	40	Std	40S	0 365	10 020	78 9	11 91	2 815	2 623	40 48	34 1	160 8	25 90	3 67
	60	XS	80S	0 500	9 750	74 7	16 10	2 815	2 553	54 74	32 3	212 0	39 4	3 63
	80			0 593	9 564	71 8	18 92	2 815	2 504	64 33	31 1	244 9	45 6	3 60
	100			0 718	9 314	68 1	22 63	2 815	2 438	76 93	29 5	286 2	53 2	3 56
	120			0 843	9 064	64 5	26 24	2 815	2 373	89 20	28 0	324	60 3	3 52
				0 875	9 000	63 62	27 14	2 815	2 36	92 28	27 6	333 46	62 04	3 50
	140			1 000	8 750	60 1	30 6	2 815	2 291	104 13	26 1	368	68 4	3 47
	160			1 125	8 500	56 7	34 0	2 815	2 225	115 65	24 6	399	74 3	3 43
				1 250	8 250	53 45	37 31	2 815	2 16	126 82	23 2	428 17	79 66	3 39
				1 500	7 750	47 15	43 57	2 815	2 03	148 19	20 5	478 59	89 04	3 31
12 *12 750*			5S	0 156	12 438	121 4	6 17	3 34	3 26	20 99	52 7	122 2	19 20	4 45
			10S	0 180	12 390	120 6	7 11	3 34	3 24	24 20	52 2	140 5	22 03	4 44
	20			0 250	12 250	117 9	9 84	3 34	3 21	33 38	51 1	191 9	30 1	4 42
	30			0 330	12 090	114 8	12 88	3 34	3 17	43 77	49 7	248 5	39 0	4 39
		Std	40S	0 375	12 000	113 1	14 58	3 34	3 14	49 56	49 0	279 3	43 8	4 38
	40			0 406	11 938	111 9	15 74	3 34	3 13	53 53	48 5	300	47 1	4 37
		XS	80S	0 500	11 750	108 4	19 24	3 34	3 08	65 42	47 0	362	56 7	4 33
	60			0 562	11 626	106 2	21 52	3 34	3 04	73 16	46 0	401	62 8	4 31
	80			0 687	11 376	101 6	26 04	3 34	2 978	88 51	44 0	475	74 5	4 27
				0 750	11 250	99 40	28 27	3 34	2 94	96 2	43 1	510 7	80 1	4 25
	100			0 843	11 064	96 1	31 5	3 34	2 897	107 20	41 6	562	88 1	4 22
				0 875	11 000	95 00	32 64	3 34	2 88	110 9	41 1	578 5	90 7	4 21
	120			1 000	10 750	90 8	36 9	3 34	2 814	125 49	39 3	642	100 7	4 17
	140			1 125	10 500	86 6	41 1	3 34	2 749	139 68	37 5	701	109 9	4 13
				1 250	10 250	82 50	45 16	3 34	2 68	153 6	35 8	755 5	118 5	4 09
	160			1 312	10 126	80 5	47 1	3 34	2 651	160 27	34 9	781	122 6	4 07

TABLE C-1. PIPE PROPERTIES (Continued)

nominal pipe size outside diameter in.	schedule number*			wall thick-ness, in.	inside diam-eter, in.	inside area, sq. in.	metal area, sq. in.	sq ft outside surface, per ft	sq ft inside surface, per ft	weight per ft, lb†	weight of water per ft, lb	moment of inertia in.^{4}	section modulus in.^{3}	radius gyration in.
	a	b	c											
			5S	0 156	13 688	147 20	6 78	3 67	3 58	23 0	63 7	162 6	23 2	4 90
			10S	0 188	13 624	145 80	8 16	3 67	3 57	27 7	63 1	194 6	27 8	4 88
				0 210	13 580	144 80	9 10	3 67	3 55	30 9	62 8	216 2	30 9	4 87
				0 219	13 562	144 50	9 48	3 67	3 55	32 2	62 6	225 1	32 2	4 87
	10			0 250	13 500	143 1	10 80	3 67	3 53	36 71	62 1	255 4	36 5	4 86
				0 281	13 438	141 80	12 11	3 67	3 52	41 2	61 5	285 2	40 7	4 85
	20			0 312	13 376	140 5	13 42	3 67	3 50	45 68	60 9	314	44 9	4 84
				0 344	13 312	139 20	14 76	3 67	3 48	50 2	60 3	344 3	49 2	4 83
14	30	Std		0 375	13 250	137 9	16 05	3 67	3 47	54 57	59 7	373	53 3	4 82
14 000	40			0 437	13 126	135 3	18 62	3 67	3 44	63 37	58 7	429	61 2	4 80
				0 469	13 062	134 00	19 94	3 67	3 42	67 8	58 0	456 8	65 3	4 79
		XS		0 500	13 000	132 7	21 21	3 67	3 40	72 09	57 5	484	69 1	4 78
	60			0 593	12 814	129 0	24 98	3 67	3 35	84 91	55 9	562	80 3	4 74
				0 625	12 750	127 7	26 26	3 67	3 34	89 28	55 3	589	84 1	4 73
	80			0 750	12 500	122 7	31 2	3 67	3 27	106 13	53 2	687	98 2	4 69
	100			0 937	12 126	115 5	38 5	3 67	3 17	130 73	50 0	825	117 8	4 63
	120			1 093	11 814	109 6	44 3	3 67	3 09	150 67	47 5	930	132 8	4 58
	140			1 250	11 500	103 9	50 1	3 67	3 01	170 22	45 0	1127	146 8	4 53
	160			1 406	11 188	98 3	55 6	3 67	2 929	189 12	42 6	1017	159 6	4 48
			5S	0 165	15 670	192 90	8 21	4 19	4 10	28	83 5	257	32 2	5 60
			10S	0 188	15 624	191 70	9 34	4 19	4 09	32	83 0	292	36 5	5 59
	10			0 250	15 500	188 7	12 37	4 19	4 06	42 05	81 8	384	48 0	5 57
	20			0 312	15 376	185 7	15 38	4 19	4 03	52 36	80 5	473	59 2	5 55
	30	Std		0 375	15 250	182 6	18 41	4 19	3 99	62 58	79 1	562	70 3	5 53
16	40	XS		0 500	15 000	176 7	24 35	4 19	3 93	82 77	76 5	732	91 5	5 48
16 000	60			0 656	14 688	169 4	31 6	4 19	3 85	107 50	73 4	933	116 6	5 43
	80			0 843	14 314	160 9	40 1	4 19	3 75	136 46	69 7	1157	144 6	5 37
	100			1 031	13 938	152 6	48 5	4 19	3 65	164 83	66 1	1365	170 6	5 30
	120			1 218	13 564	144 5	56 6	4 19	3 55	192 29	62 6	1556	194 5	5 24
	140			1 437	13 126	135 3	65 7	4 19	3 44	223 64	58 6	1760	220 0	5 17
	160			1 593	12 814	129 0	72 1	4 19	3 35	245 11	55 9	1894	236 7	5 12
			5S	0 165	17 670	245 20	9 24	4 71	4 63	31	106 2	368	40 8	6 31
			10S	0 188	17 624	243 90	10 52	4 71	4 61	36	105 7	417	46 4	6 30
	10			0 250	17 500	240 5	13 94	4 71	4 58	47 39	104 3	549	61 0	6 28
	20			0 312	17 376	237 1	17 34	4 71	4 55	59 03	102 8	678	75 5	6 25
		Std		0 375	17 250	233 7	20 76	4 71	4 52	70 59	101 2	807	89 6	6 23
18	30			0 437	17 126	230 4	24 11	4 71	4 48	82 06	99 9	931	103 4	6 21
		XS		0 500	17.00	227 0	27 49	4 71	4 45	93 45	98 4	1053	117 0	6 19
18 000	40			0 562	16 876	223 7	30 8	4 71	4 42	104 75	97 0	1172	130 2	6 17
	60			0 750	16 500	213 8	40 6	4 71	4 32	138 17	92 7	1515	168 3	6 10
	80			0 937	16 126	204 2	50 2	4 71	4 22	170 75	88 5	1834	203 8	6 04
	100			1 156	15 688	193 3	61 2	4 71	4 11	207 96	83 7	2180	242 2	5 97
	120			1 375	15 250	182 6	71 8	4 71	3 99	244 14	79 2	2499	277 6	5 90
	140			1 562	14 876	173 8	80 7	4 71	3 89	274 23	75 3	2750	306	5 84
	160			1 781	14 438	163 7	90 7	4 71	3 78	308 51	71 0	3020	336	5 77
			5S	0 188	19 634	302 40	11 70	5 24	5 14	40	131 0	574	57 4	7 00
			10S	0 218	19 564	300 60	13 55	5 24	5 12	46	130 2	663	66 3	6 99
	10			0 250	19 500	298 6	15 51	5 24	5 11	52 73	129 5	757	75 7	6 98
	20	Std		0 375	19 250	291 0	23 12	5 24	5 04	78 60	126 0	1114	111 4	6 94
20	30	XS		0 500	19 000	283 5	30 6	5 24	4 97	104 13	122 8	1457	145 7	6 90
20 000	40			0 593	18 814	278 0	36 2	5 24	4 93	122 91	120 4	1704	170 4	6 86
	60			0 812	18 376	265 2	48 9	5 24	4 81	166 40	115 0	2257	225 7	6 79
				0 875	18 250	261 6	52 6	5 24	4 78	178 73	113 4	2409	240 9	6 77
	80			1 031	17 938	252 7	61 4	5 24	4 70	208 87	109 4	2772	277 2	6 72
	100			1 281	17 438	238 8	75 3	5 24	4 57	256 10	103 4	3320	332	6 63

TABLE C–1. PIPE PROPERTIES (Continued)

nominal pipe size *outside diameter* in	schedule number*			wall thickness in	inside diameter in.	inside area sq in.	metal area, sq in.	sq ft outside surface per ft	sq ft inside surface per ft	weight per ft, lb†	weight of water per ft, lb	moment of inertia, in.^{4}	section modulus, in.^{3}	radius gyration, in.
	a	b	c											
20 *20 000*	120			1 500	17 000	227 0	87 2	5 24	4 45	296 37	98 3	3760	376	6 56
	140			1 750	16 500	213 8	100 3	5 24	4 32	341 10	92 6	4220	422	6 48
	160			1 968	16 064	202 7	111 5	5 24	4 21	379 01	87 9	4590	459	6 41
22 *22 000*			5S	0 188	21 624	367 3	12 88	5 76	5 66	44	159 1	766	69 7	7 71
			10S	0 218	21 564	365 2	14 92	5 76	5 65	51	158 2	885	80 4	7 70
	10			0 250	21 500	363 1	17 18	5 76	5 63	58	157 4	1010	91 8	7 69
	20	Std		0 375	21 250	354 7	25 48	5 76	5 56	87	153 7	1490	135 4	7 65
	30	XS		0 500	21 000	346 4	33 77	5 76	5 50	115	150 2	1953	177 5	7 61
				0 625	20 750	338 2	41 97	5 76	5 43	143	146 6	2400	218 2	7 56
				0 750	20 500	330 1	50 07	5 76	5 37	170	143 1	2829	257 2	7 52
	60			0 875	20 250	322 1	58 07	5 76	5 30	197	139 6	3245	295 0	7 47
	80			1 125	19 750	306 4	73 78	5 76	5 17	251	132 8	4029	366 3	7 39
	100			1 375	19 250	291 0	89 09	5 76	5 04	303	126 2	4758	432 6	7 31
	120			1 625	18 750	276 1	104 02	5 76	4 91	354	119 6	5432	493 8	7 23
	140			1 875	18 250	261 6	118 55	5 76	4 78	403	113 3	6054	550 3	7 15
	160			2 125	17 750	247 4	132 68	5 76	4 65	451	107 2	6626	602 4	7 07
24 *24 000*	10			0 250	23 500	434	18 65	6 28	6 15	63 41	188 0	1316	109 6	8 40
	20	Std		0 375	23 250	425	27 83	6 28	6 09	94 62	183 8	1943	161 9	8 35
		XS		0 500	23 000	415	36 9	6 28	6 02	125 49	180 1	2550	212 5	8 31
	30			0 562	22 876	411	41 4	6 28	5 99	140 80	178 1	2840	237 0	8 29
				0 625	22 750	406	45 9	6 28	5 96	156 03	176 2	3140	261 4	8 27
	40			0 687	22 626	402	50 3	6 28	5 92	171 17	174 3	3420	285 2	8 25
				0 750	22 500	398	54 8	6 28	5 89	186 24	172 4	3710	309	8 22
			5S	0 218	23 564	436 1	16 29	6 28	6 17	55	188 9	1152	96 0	8 41
				0 875	22 250	388 6	63 54	6 28	5 83	216	168 6	4256	354 7	8 18
	60			0 968	22 064	382	70 0	6 28	5 78	238 11	165 8	4650	388	8 15
	80			1 218	21 564	365	87 2	6 28	5 65	296 36	158 3	5670	473	8 07
	100			1 531	20 938	344	108 1	6 28	5 48	367 40	149 3	6850	571	7 96
	120			1 812	20 376	326	126 3	6 28	5 33	429 39	141 4	7830	652	7 87
	140			2 062	19 876	310	142 1	6 28	5 20	483 13	134 5	8630	719	7 79
	160			2 343	19 314	293	159 4	6 28	5 06	541 94	127 0	9460	788	7 70
26 *26 000*				0 250	25 500	510 7	19 85	6 81	6 68	67	221 4	1646	126 6	9 10
	10			0 312	25 376	505 8	25 18	6 81	6 64	86	219 2	2076	159 7	9 08
		Std		0 375	25 250	500 7	30 19	6 81	6 61	103	217 1	2478	190 6	9 06
	20	XS		0 500	25 000	490 9	40 06	6 81	6 54	136	212 8	3259	250 7	9 02
				0 625	24 750	481 1	49 82	6 81	6 48	169	208 6	4013	308 7	8 98
				0 750	24 500	471 4	59 49	6 81	6 41	202	204 4	4744	364 9	8 93
				0 875	24 250	461 9	69 07	6 81	6 35	235	200 2	5458	419 9	8 89
				1 000	24 000	452 4	78 54	6 81	6 28	267	196 1	6149	473 0	8 85
				1 125	23 750	443 0	87 91	6 81	6 22	299	192 1	6813	524 1	8 80
28 *28 000*				0 250	27 500	594 0	21 80	7 33	7 20	74	257 3	2098	149 8	9 81
	10			0 312	27 376	588 6	27 14	7 33	7 17	92	255 0	2601	185 8	9 79
		Std		0 375	27 250	583 2	32 54	7 33	7 13	111	252 6	3105	221 8	9 77
	20	XS		0 500	27 000	572 6	43 20	7 33	7 07	147	248 0	4085	291 8	9 72
	30			0 625	26 750	562 0	53 75	7 33	7 00	183	243 4	5038	359 8	9 68
				0 750	26 500	551 6	64 21	7 33	6 94	218	238 9	5964	426 0	9 64
				0 875	26 250	541 2	74 56	7 33	6 87	253	234 4	6865	490 3	9 60
				1 000	26 000	530 9	84 82	7 33	6 81	288	230 0	7740	552 8	9 55
				1 125	25 750	520 8	94 98	7 33	6 74	323	225 6	8590	613 6	9 51
30 *30 000*			5S	0 250	29 500	683 4	23 37	7 85	7 72	79	296 3	2585	172 3	10 52
	10		10S	0 312	29 376	677 8	29 19	7 85	7 69	99	293 7	3201	213 4	10 50
		Std		0 375	29 250	672 0	34 90	7 85	7 66	119	291 2	3823	254 8	10 48
	20	XS		0 500	29 000	660 5	46 34	7 85	7 59	158	286 2	5033	335 5	10 43
	30			0 625	28 750	649 2	57 68	7 85	7 53	196	281 3	6213	414 2	10 39

TABLE C-1. PIPE PROPERTIES (Concluded)

nominal pipe size *outside diameter*, in.	**schedule number***			**wall thickness, in.**	**inside diameter, in.**	**inside area, sq. in.**	**metal area, sq. in.**	**sq ft outside surface, per ft**	**sq ft inside surface, per ft**	**weight per ft, lb†**	**weight of water per ft lb**	**moment of inertia, in ^{4}**	**section modulus, in ^{3}**	**radius gyration in**
	a	**b**	**c**											
30 *30 000*	40			0 750	28 500	637 9	68 92	7 85	7 46	234	276 6	7371	491 4	.0 34
				0 875	28 250	620 7	80 06	7 85	7 39	272	271 8	8494	566 2	.0 30
				1 000	28 000	615 7	91 11	7 85	7 33	310	267 0	9591	639 4	10 26
				1 125	27 750	604 7	102 05	7 85	7 26	347	262 2	10653	710 2	10 22
32 *32 000*				0 250	31 500	779 2	24 93	8 38	8 25	85	337 8	3141	196 3	11 22
	10			0 312	31 376	773 2	31 02	8 38	8 21	106	335 2	3891	243 2	11 20
		Std		0 375	31 250	766 9	37 25	8 38	8 18	127	332 5	4656	291 0	11 18
	20	XS		0 500	31 000	754 7	49 48	8 38	8 11	168	327 2	6140	383 8	11 14
	30			0 625	30 750	742 5	61 59	8 38	8 05	209	321 9	7578	473 6	11 09
	40			0 688	30 624	736 6	67 68	8 38	8 02	230	319 0	8298	518 6	11 07
				0 750	30 500	730 5	73 63	8 38	7 98	250	316 7	8990	561 9	11 05
				0 875	30 250	718 3	85 52	8 38	7 92	291	311 6	10372	648 2	11 01
				1 000	30 000	706 8	97 38	8 38	7 85	331	306 4	11680	730 0	10 95
				1 125	29 750	694 7	109 0	8 38	7 79	371	301 3	13023	814 0	10 92
34 *34 000*				0 250	33 500	881 2	26 50	8 90	8 77	90	382 0	3773	221 9	11 93
	10			0 312	33 376	874 9	32 99	8 90	8 74	112	379 3	4680	275 3	11 91
		Std		0 375	33 250	867 8	39 61	8 90	8 70	135	376 2	5597	329 2	11 89
	20	XS		0 500	33 000	855 3	52 62	8 90	8 64	179	370 8	7385	434 4	11 85
	30			0 625	32 750	841 9	65 53	8 90	8 57	223	365 0	9124	536 7	11 80
	40			0 688	32 624	835 9	72 00	8 90	8 54	245	362 1	9992	587 8	11 78
				0 750	32 500	829 3	78 34	8 90	8 51	266	359 5	10829	637 0	11 76
				0 875	32 250	816 4	91 01	8 90	8 44	310	354 1	12501	735 4	11 72
				1 000	32 000	804 2	103 67	8 90	8 38	353	348 6	14114	830 2	11 67
				1 125	31 750	791 3	116 13	8 90	8 31	395	343 2	15719	924 7	11 63
36 *36 000*				0 250	35 500	989 7	28 11	9 42	9 29	96	429 1	4491	249 5	12 64
	10			0 312	35 376	982 9	34 95	9 42	9 26	119	426 1	5565	309 1	12 62
		Std		0 375	35 250	975 8	42 01	9 42	9 23	143	423 1	6664	370 2	12 59
	20	XS		0 500	35 000	962 1	55 76	9 42	9 16	190	417 1	8785	488 1	12 55
	30			0 625	34 750	948 3	69 50	9 42	9 10	236	411 1	10872	604 0	12 51
	40			0 750	34 500	934 7	83 01	9 42	9 03	282	405 3	12898	716 5	12 46
				0 875	34 250	920 6	96 50	9 42	8 97	328	399 4	14903	827 9	12 42
				1 000	34 000	907 9	109 96	9 42	8 90	374	393 6	16851	936 2	12 38
				1 125	33 750	894 2	123 19	9 42	8 89	419	387 9	18763	1042 4	12 34
42 *42 000*				0 250	41 500	1352 6	32 82	10 99	10 86	112	586 4	7126	339 3	14 73
		Std		0 375	41 250	1336 3	49 08	10 99	10 80	167	579 3	10627	506 1	14 71
	20	XS		0 500	41 000	1320 2	65 18	10 99	10 73	222	572 3	14037	668 4	.14 67
	30			0 625	40 750	1304 1	81 28	10 99	10 67	276	565 4	17373	827 3	14 62
	40			0 750	40 500	1288 2	97 23	10 99	10 60	330	558 4	20689	985 2	14 59
				1 000	40 000	1256 6	128 81	10 99	10 47	438	544 8	27080	1289 5	14 50
				1 250	39 500	1225 3	160 03	10 99	10 34	544	531 2	33233	1582 5	14 41
				1 500	39 000	1194 5	190 85	10 99	10 21	649	517 9	39181	1865 7	14 33

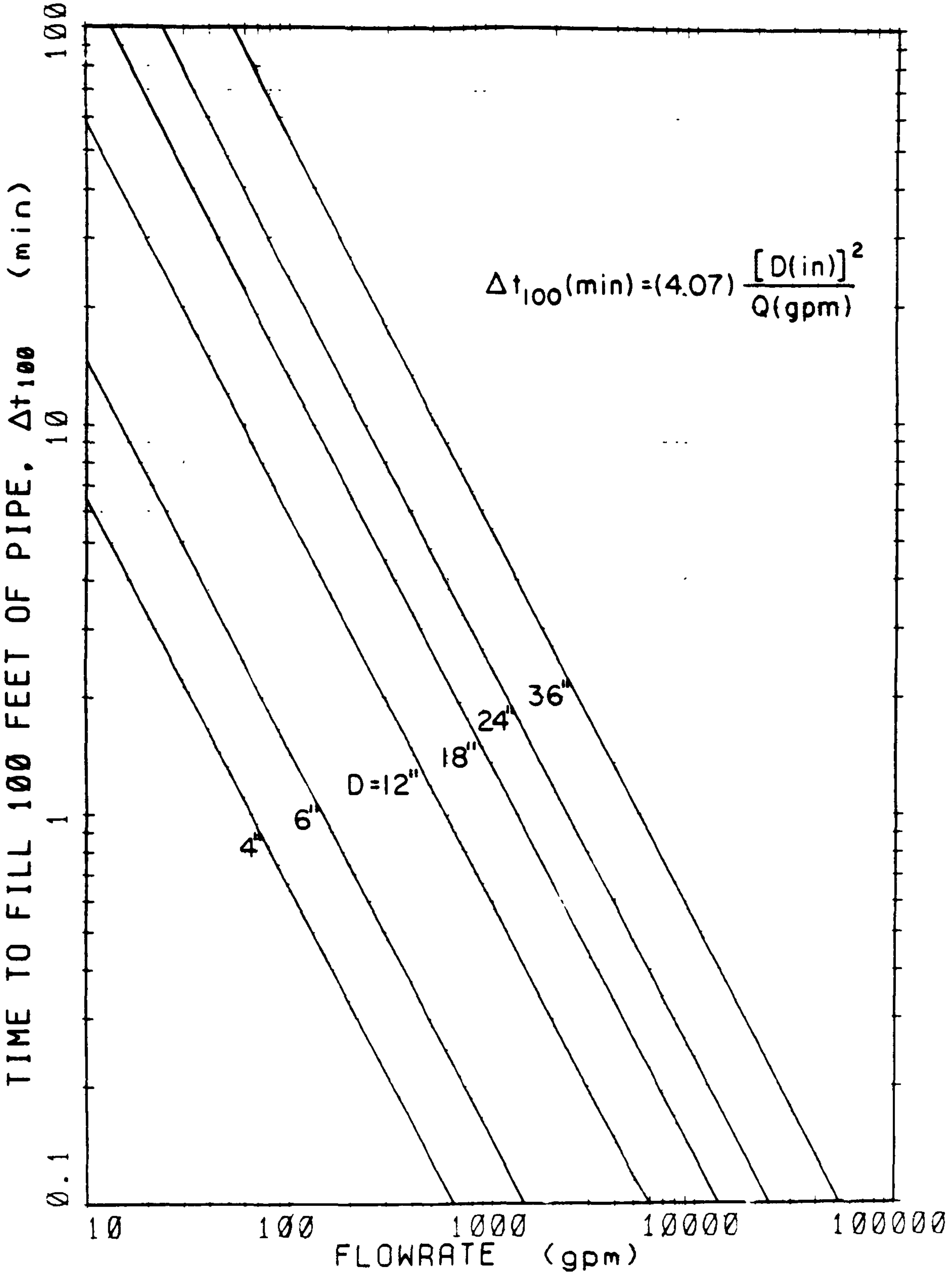

Figure C.1 FILL TIMES FOR 100 FEET OF PIPE

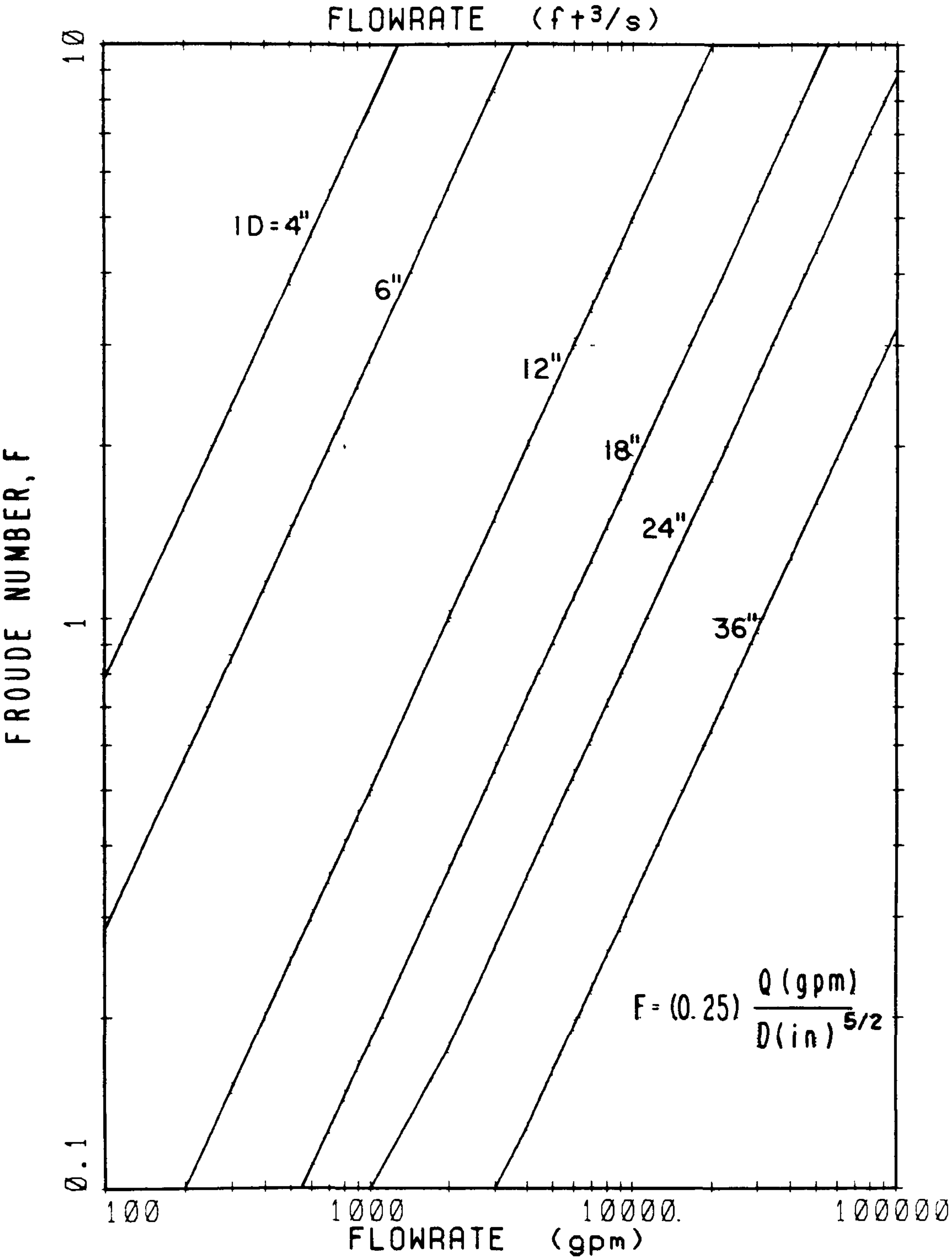

Figure C.2 FROUDE NUMBER IS A FUNCTION OF PIPE SIZE AND FLOW RATE

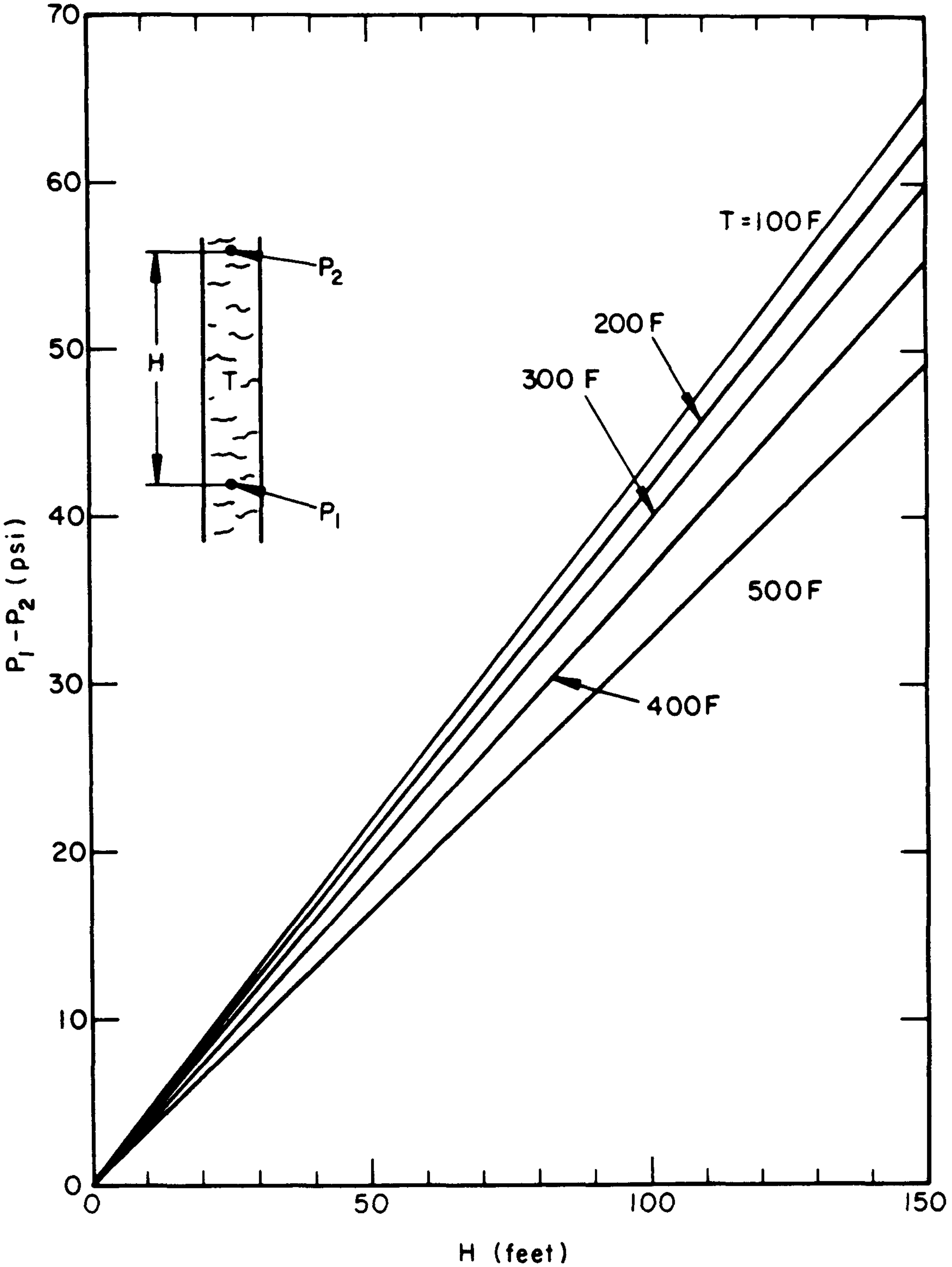

Figure C.3 HYDROSTATIC PRESSURE DIFFERENCE IN A VERTICAL COLUMN OF WATER

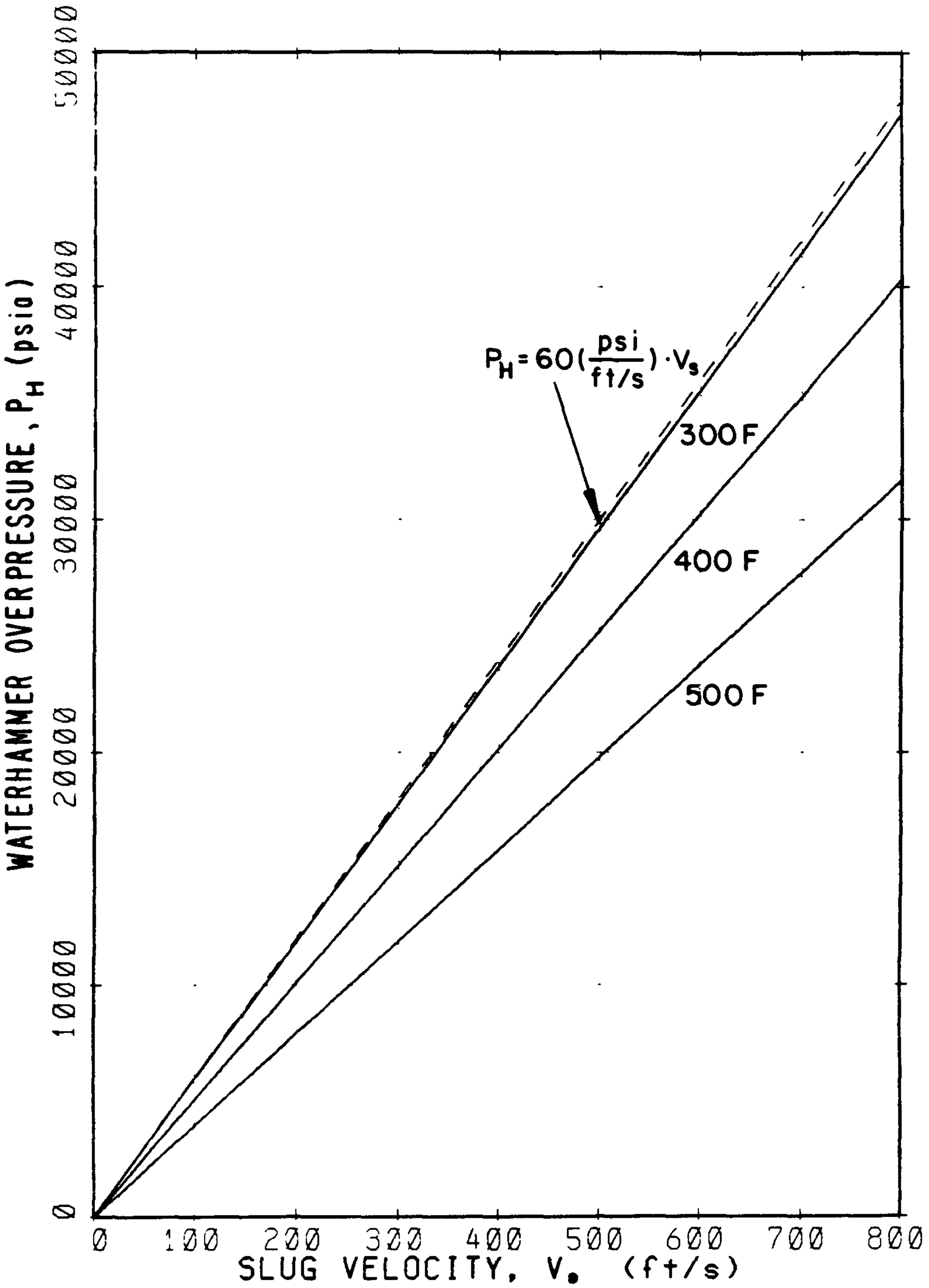

Figure C.4 WATERHAMMER OVERPRESSURE DEPENDS ON THE FLUID VELOCITY AND TEMPERATURE

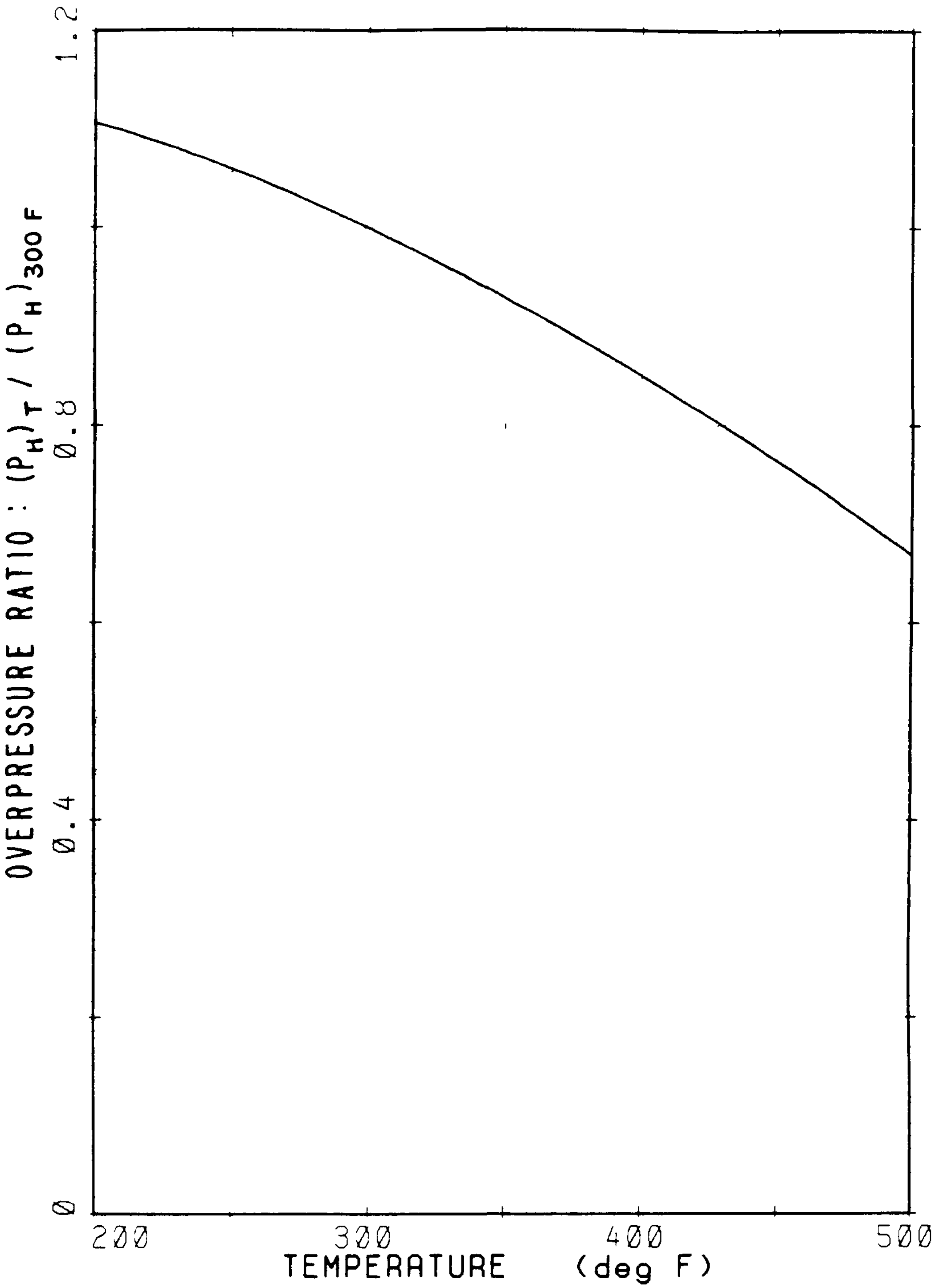

Figure C.5 WATERHAMMER OVERPRESSURE DECREASES WITH RISING WATER TEMPERATURE

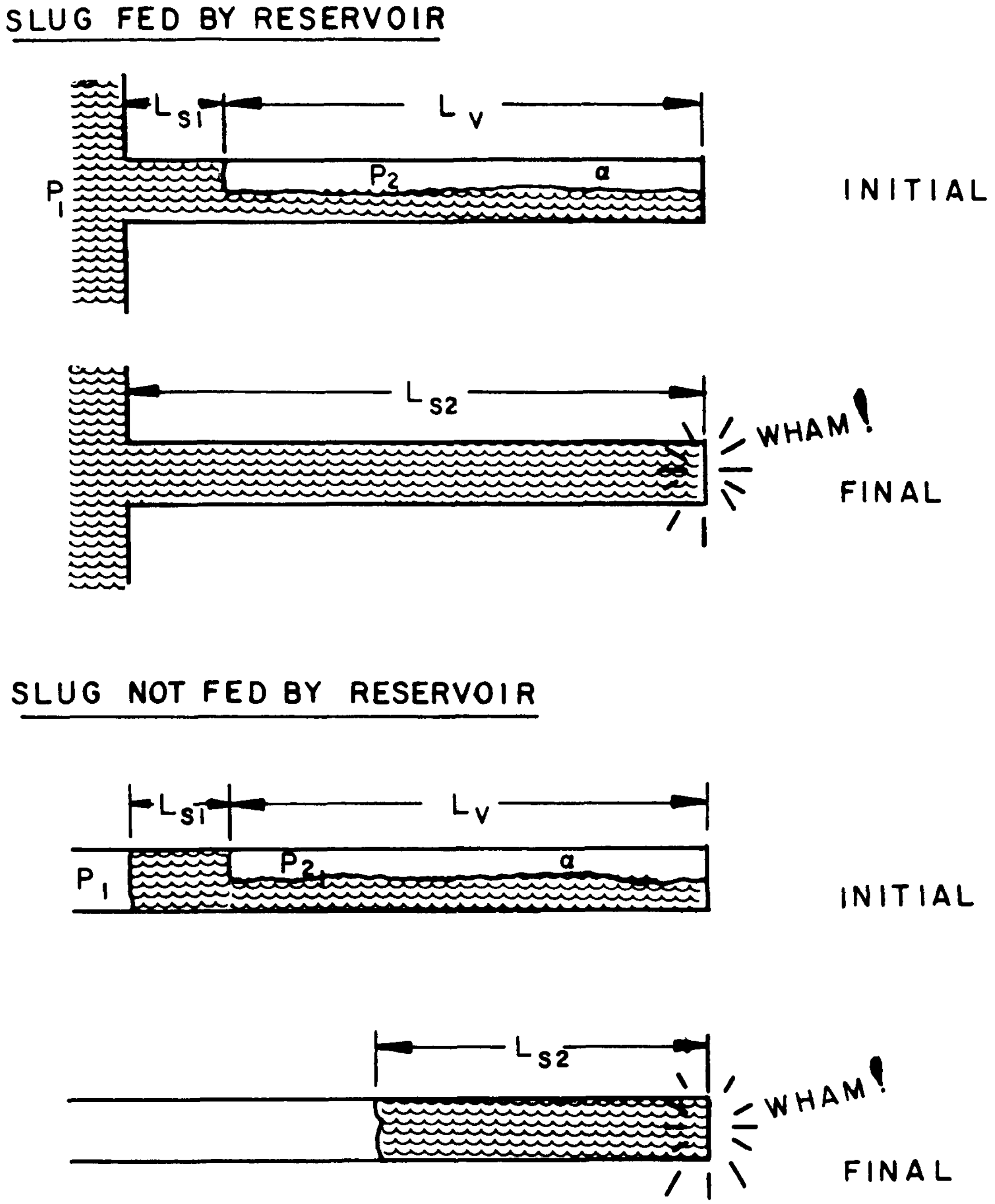

Figure C.6 GEOMETRY FOR SLUG ACCELERATION INTO A VOID (USE WITH TABLE C.2)

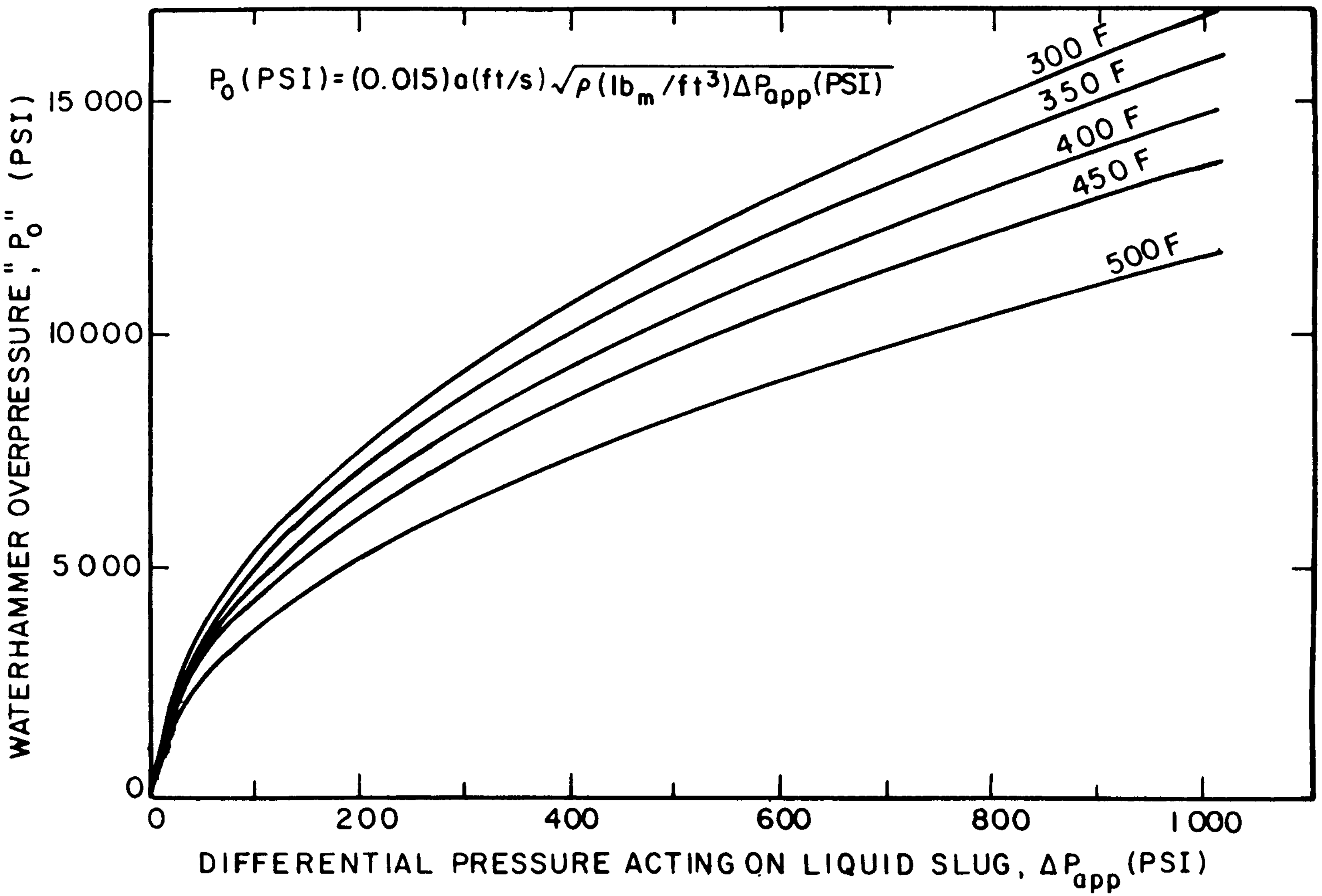

Figure C.7 BASE OVERPRESSURE ΔP_o

Table C.2 FACTORS TO MODIFY OVERPRESSURES TO ACCOUNT FOR SPECIFIC GEOMETRY

SLUG FED BY RESERVOIR?	INITIAL SLUG LENGTH	VOID FRACTION	MODIFY P_o FROM FIGURE C.7 BY THIS FACTOR F: $P_H = FP_o$*
Yes	0	1	$F = 1$
No	L_{S1}	1	$\sqrt{2 \frac{L_v}{L_{S1}}}$
Yes	0	α	$F = \sqrt{\alpha}$
Yes	L_{S1}	α	$F = \sqrt{\alpha} \sqrt{1 - \left[\frac{L_{S1}}{L_{S2}}\right]^2}$
No	L_{S1}	α	$F = \sqrt{\frac{\alpha}{1-\alpha}} \sqrt{1 - \left[\frac{L_{S1}}{\alpha L_{S1} + (1-\alpha) L_v}\right]^2}$

* Geometric parameters are defined in Figure C.6.

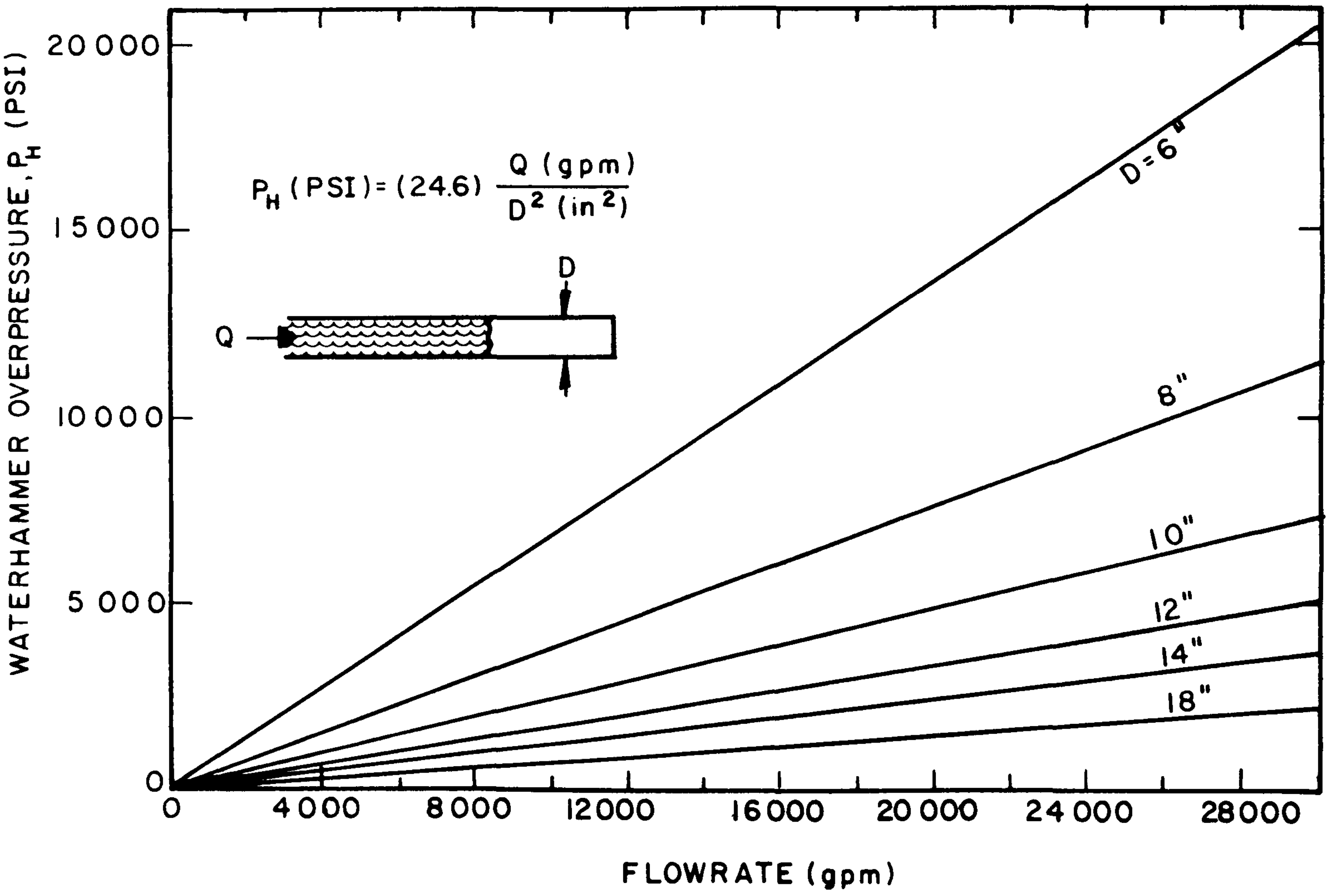

Figure C.8 **WATERHAMMER OVERPRESSURE FROM SUDDEN DECELERATION OF A FLUID COLUMN**

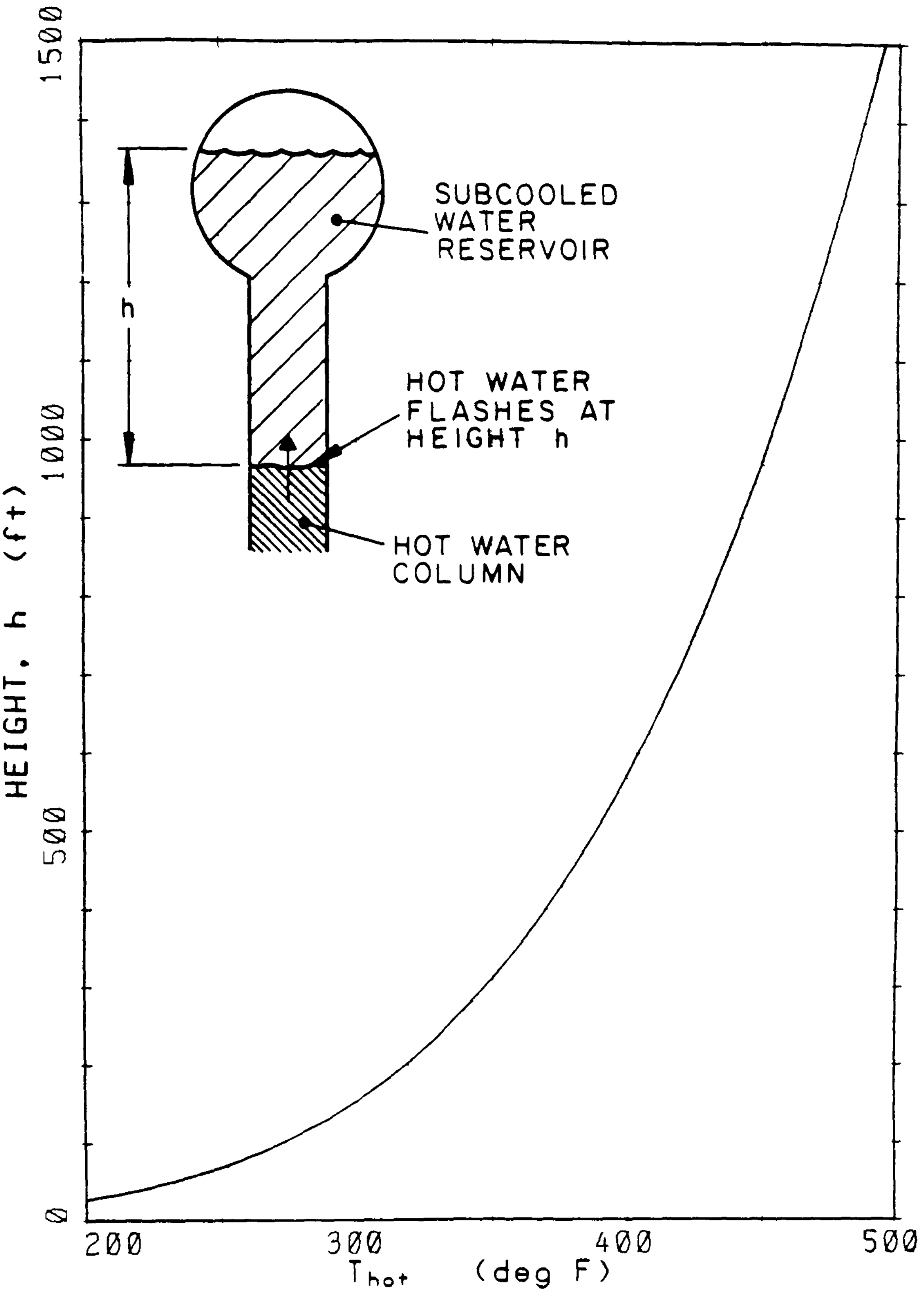

Figure C.9 THE HEIGHT BELOW A COLD WATER SURFACE AT WHICH A HOT WATER COLUMN WILL FLASH TO STEAM

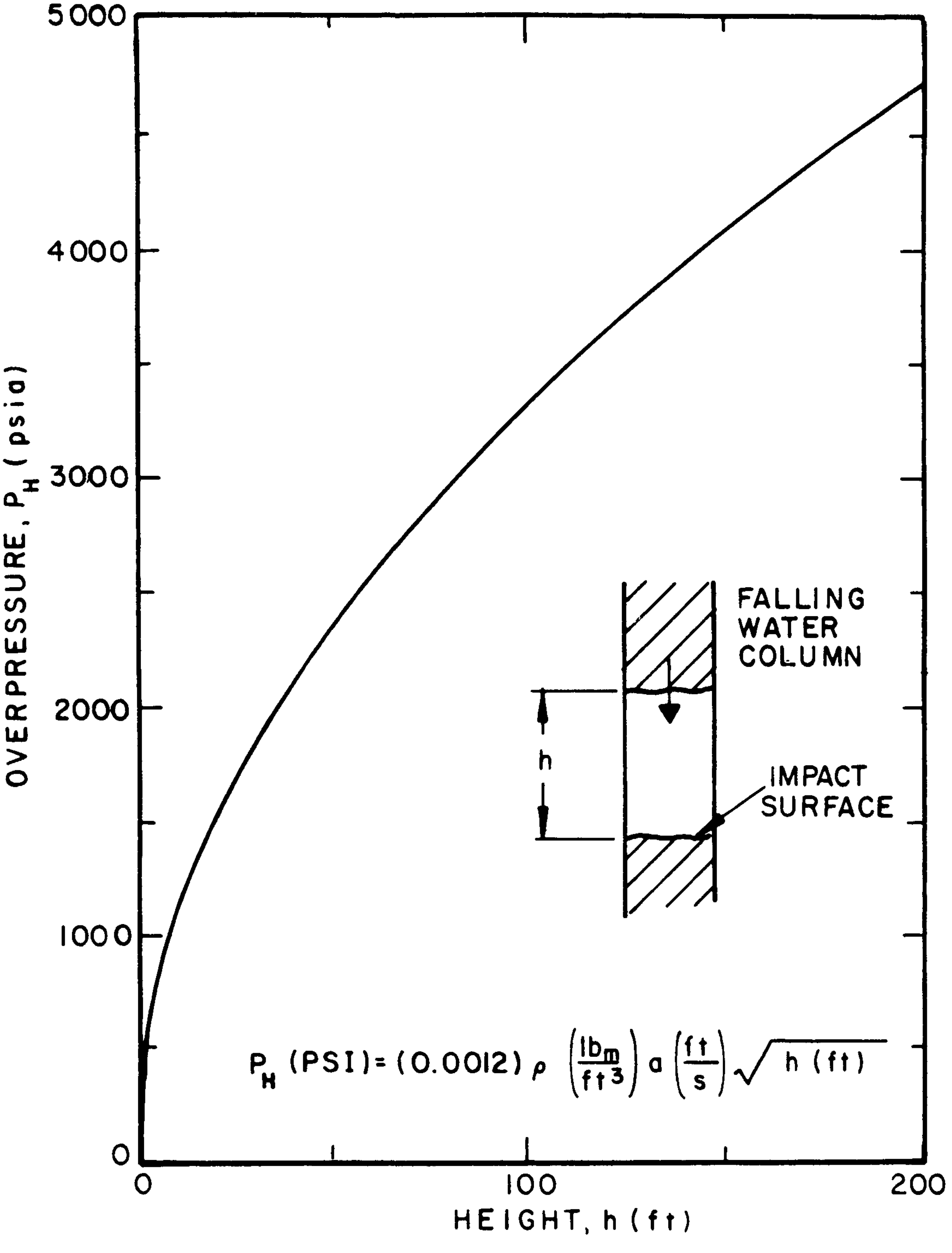

Figure C.10 WATERHAMMER OVERPRESSURES RESULTING FROM IMPACT OF A FALLING COLUMN OF WATER

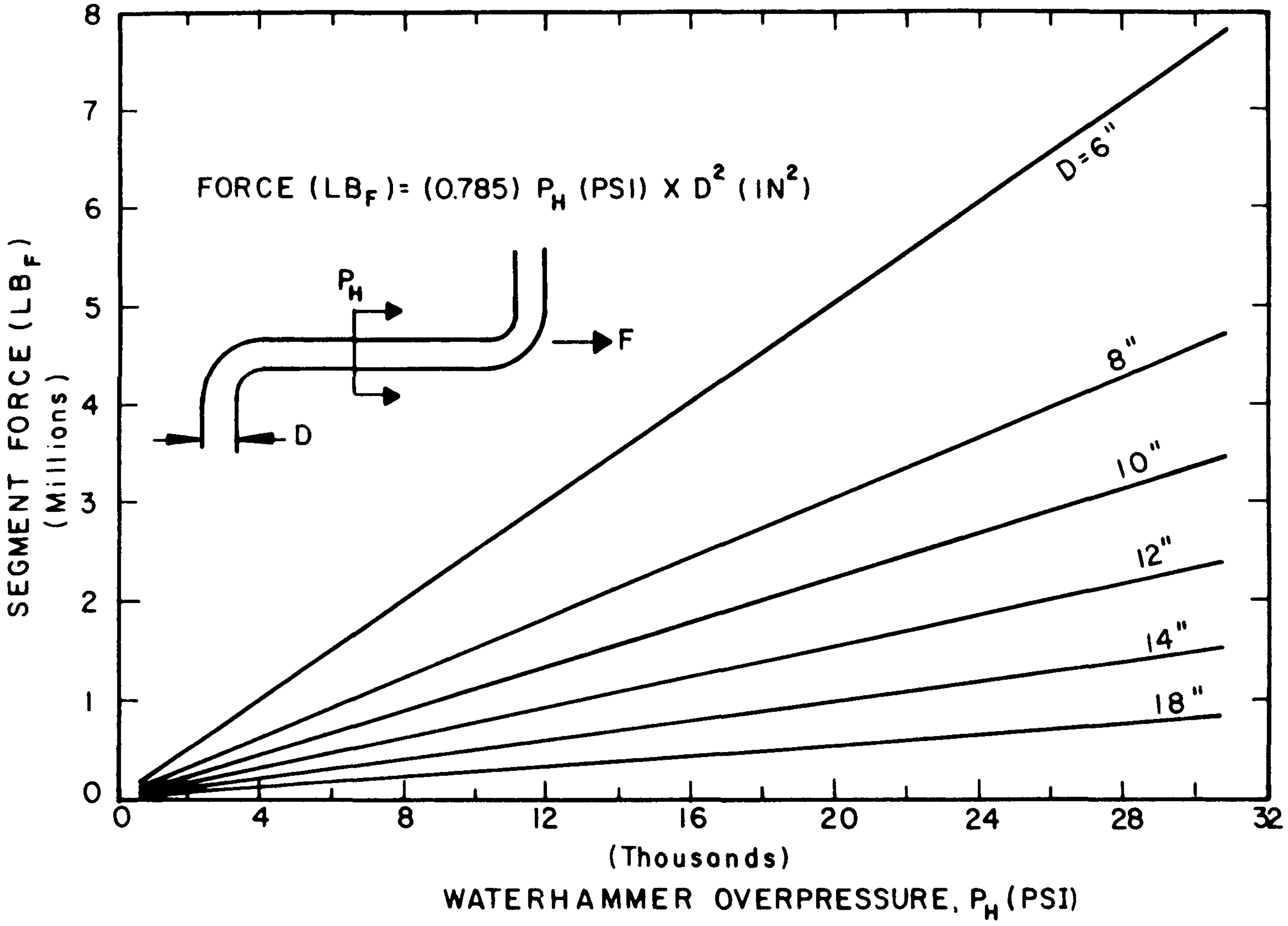

Figure C.11 SEGMENT FORCES DEPEND ON WATERHAMMER OVERPRESSURE AND PIPE DIAMETER

APPENDIX D

PHYSICAL PROPERTIES

This appendix presents thermodynamic and transport properties of water and steam under saturated conditions.

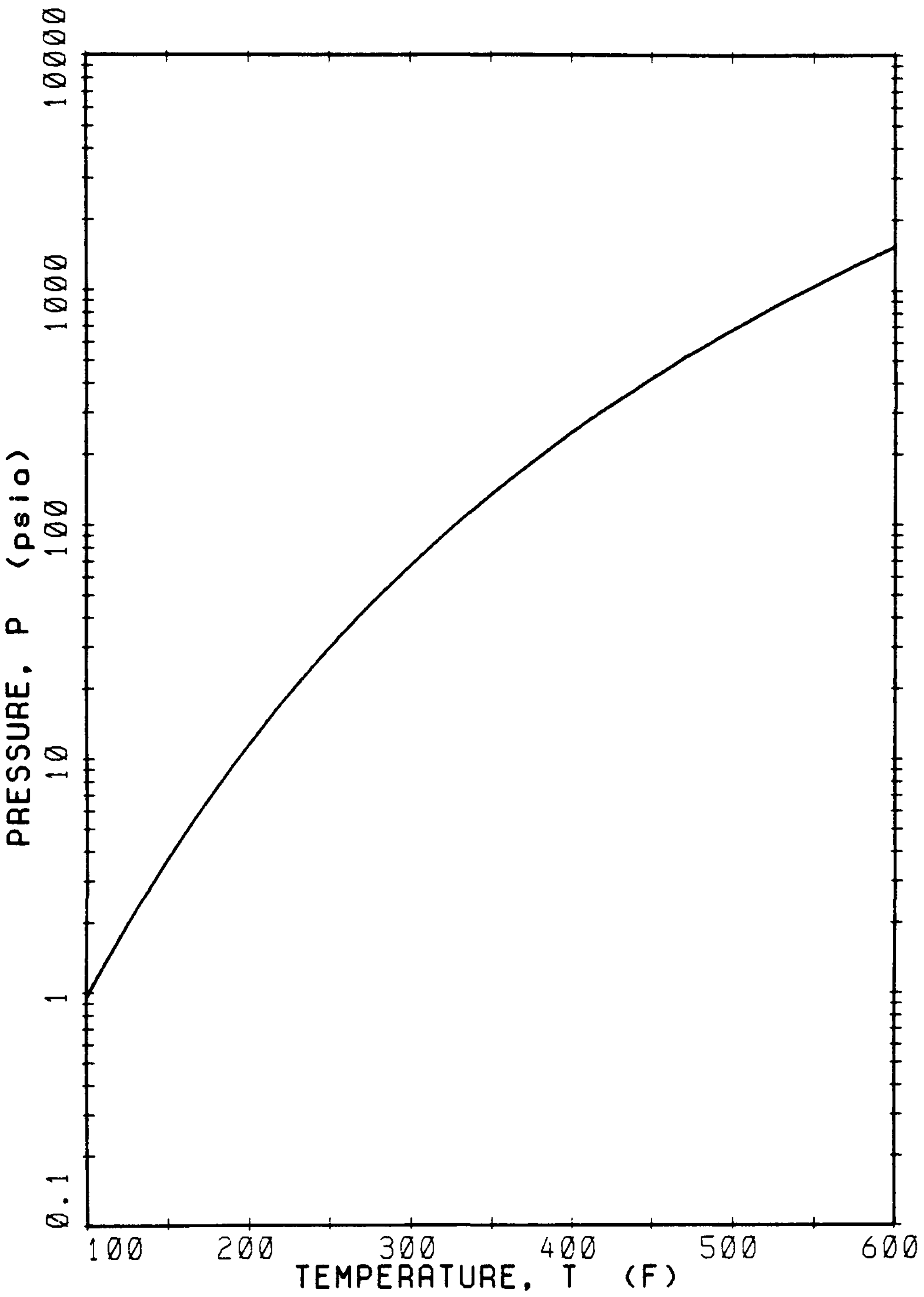

Figure D.1 SATURATION LINE FOR WATER

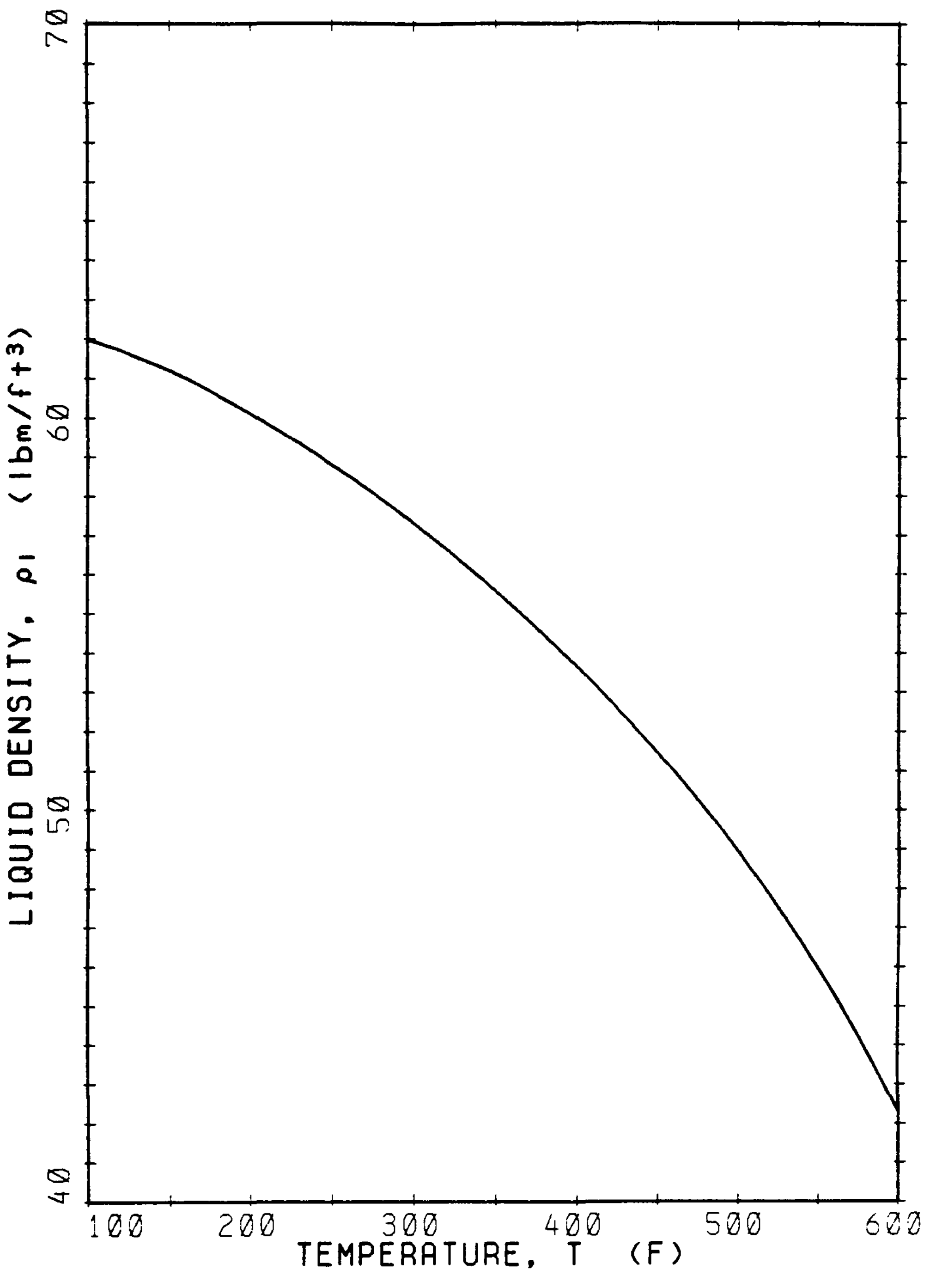

Figure D.2 LIQUID DENSITY AT SATURATION

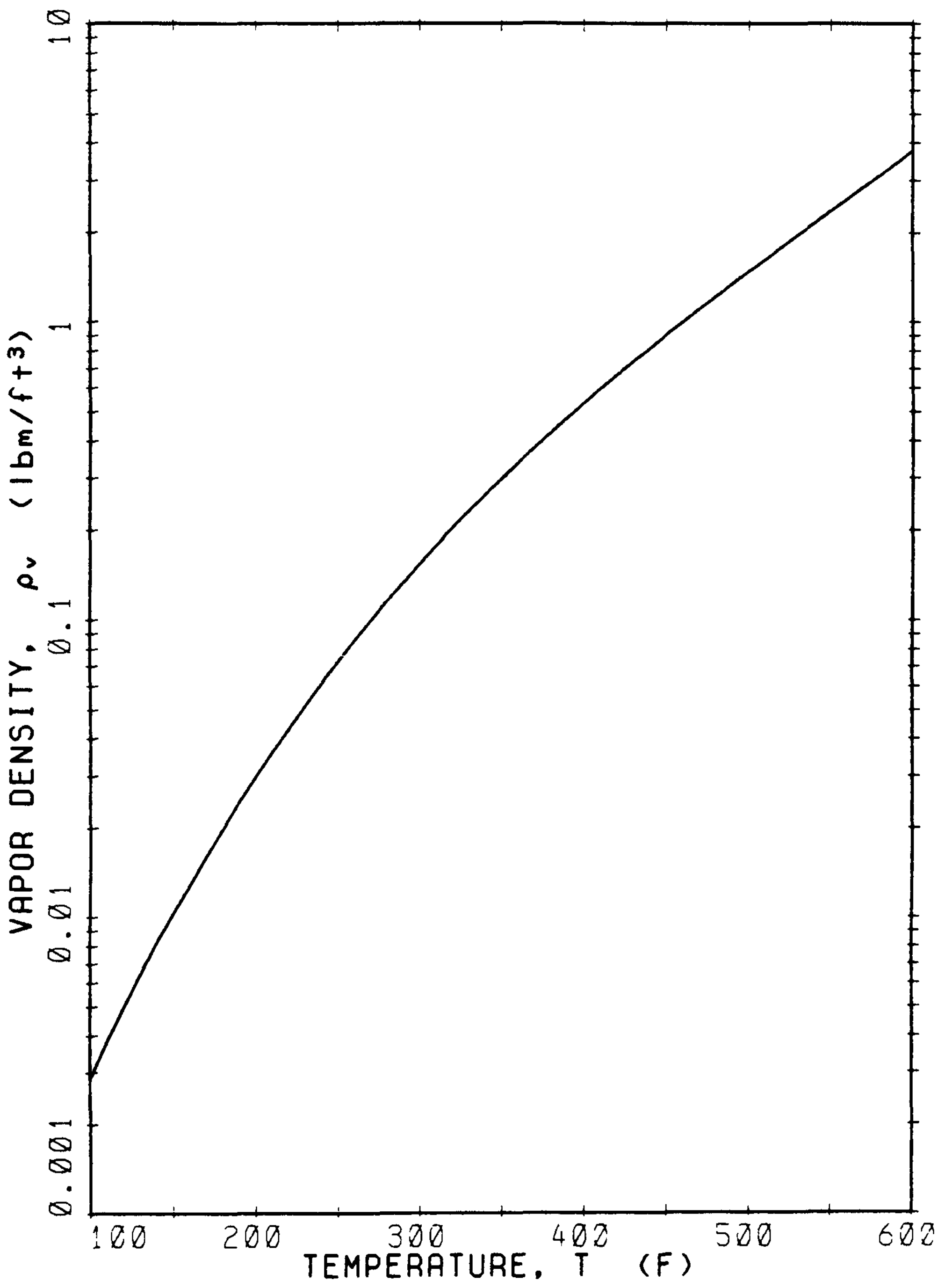

Figure D.3 VAPOR DENSITY AT SATURATION

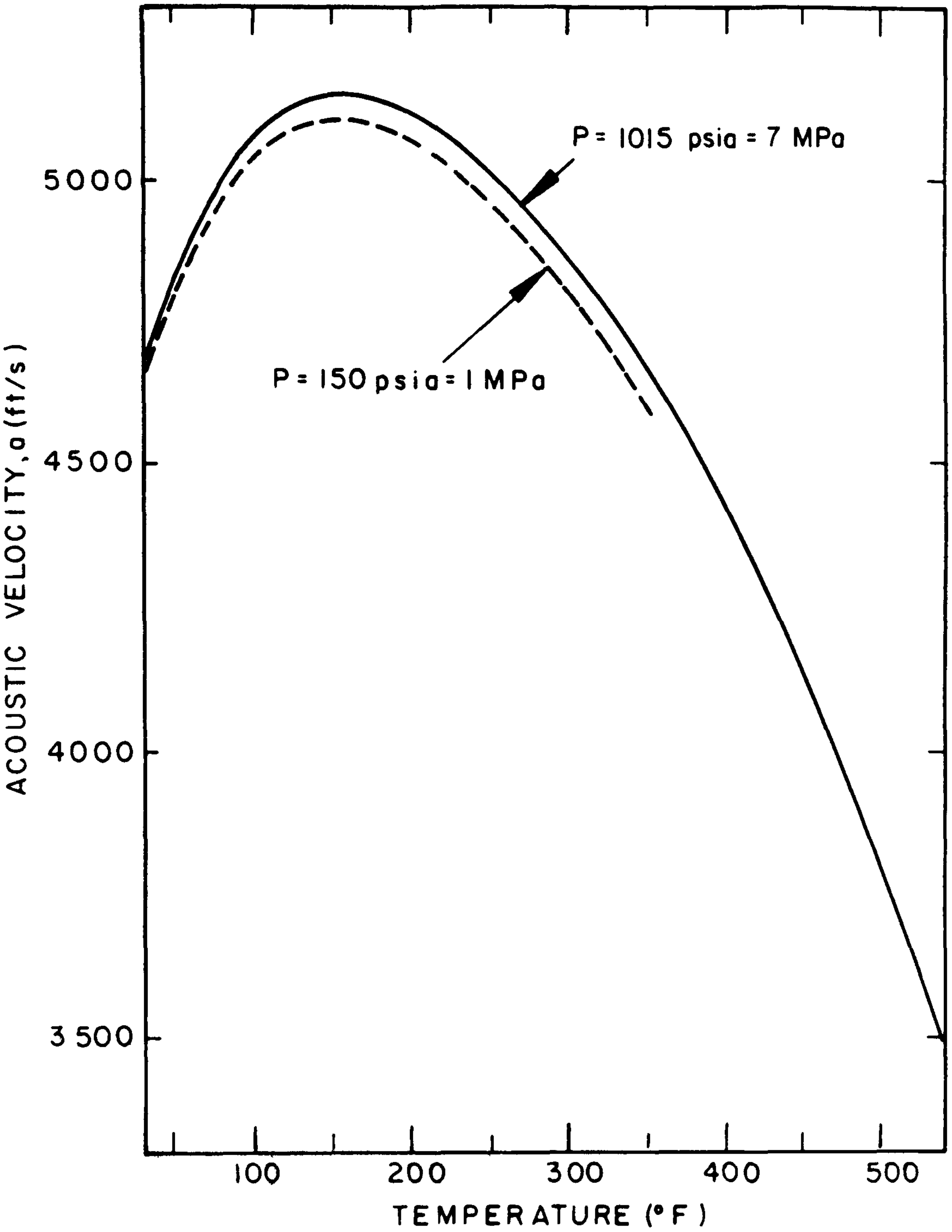

Figure D.4 ACOUSTIC VELOCITY (a) IN SATURATED LIQUID WATER

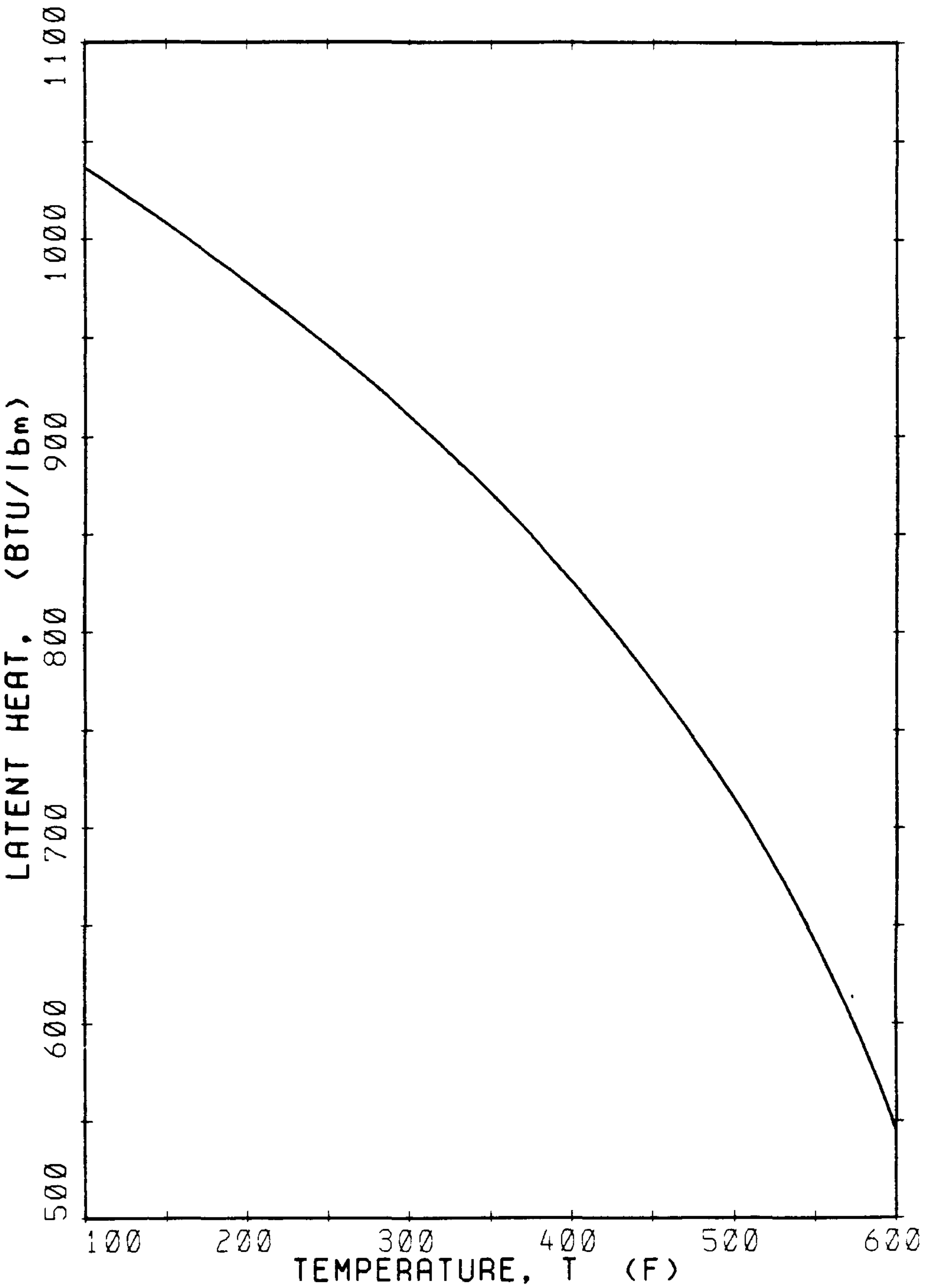

Figure D.5 LATENT HEAT OF CONDENSATION

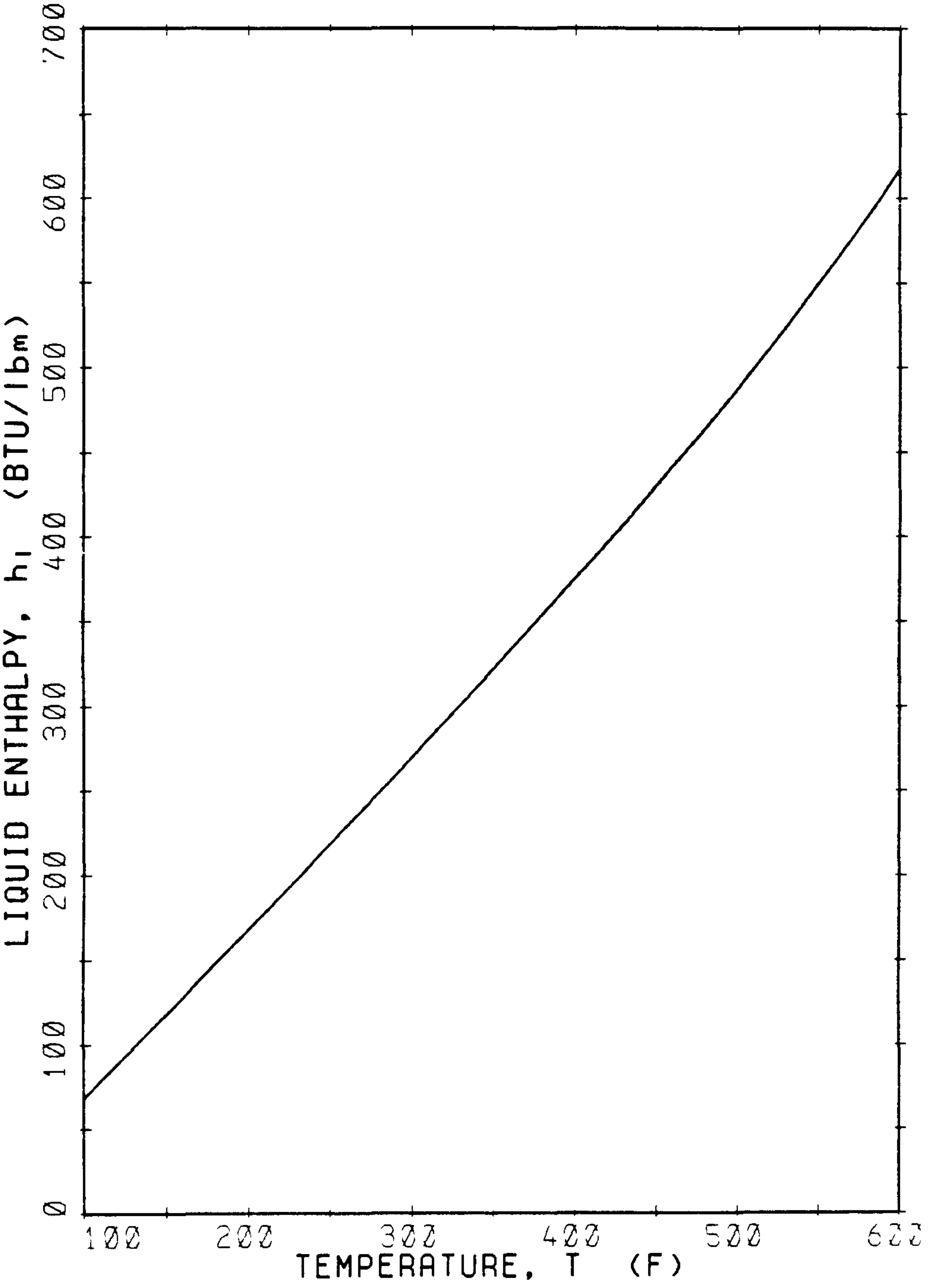

Figure D.6 LIQUID ENTHALPY AT SATURATION

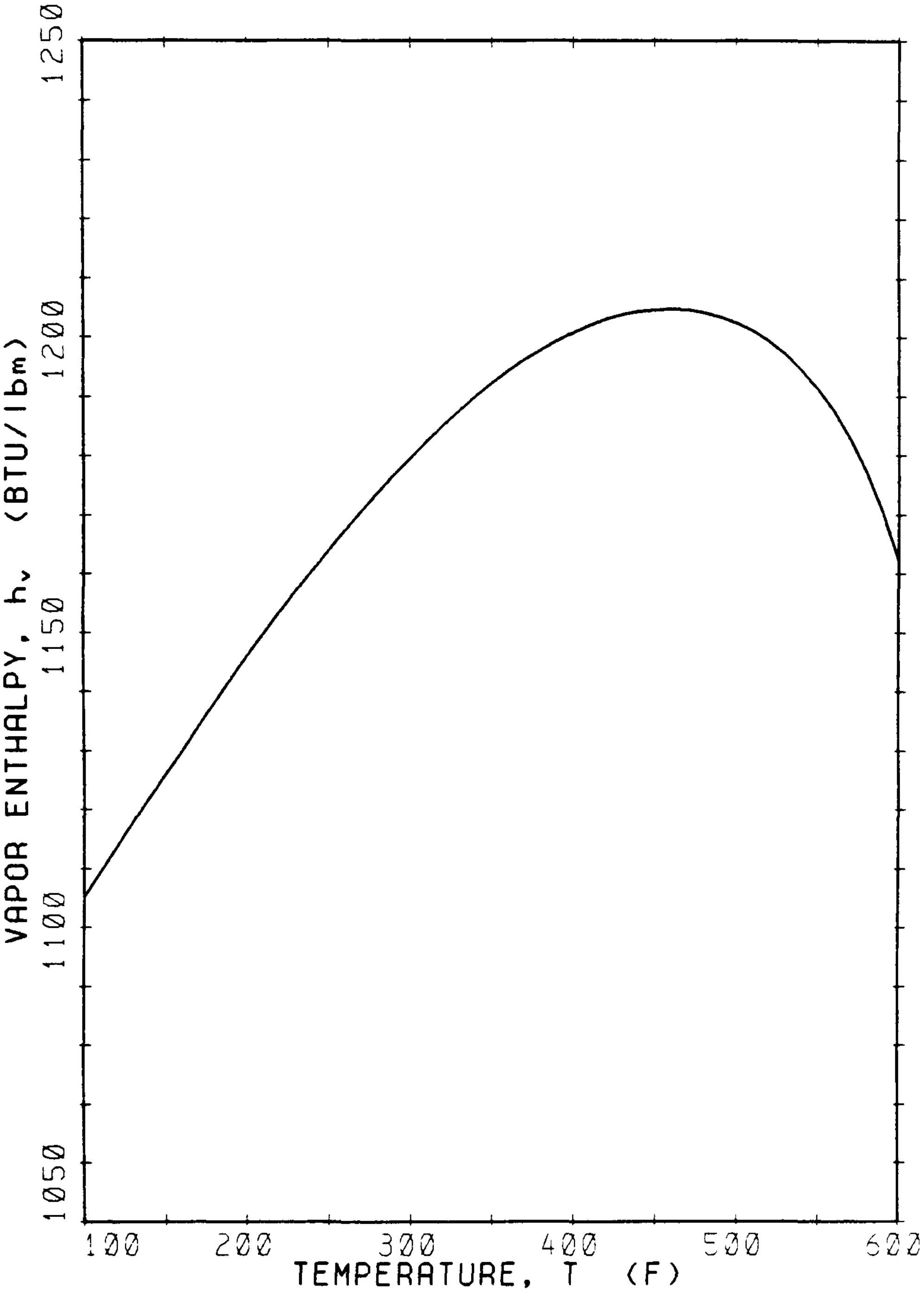

Figure D.7 ENTHALPY OF SATURATED VAPOR

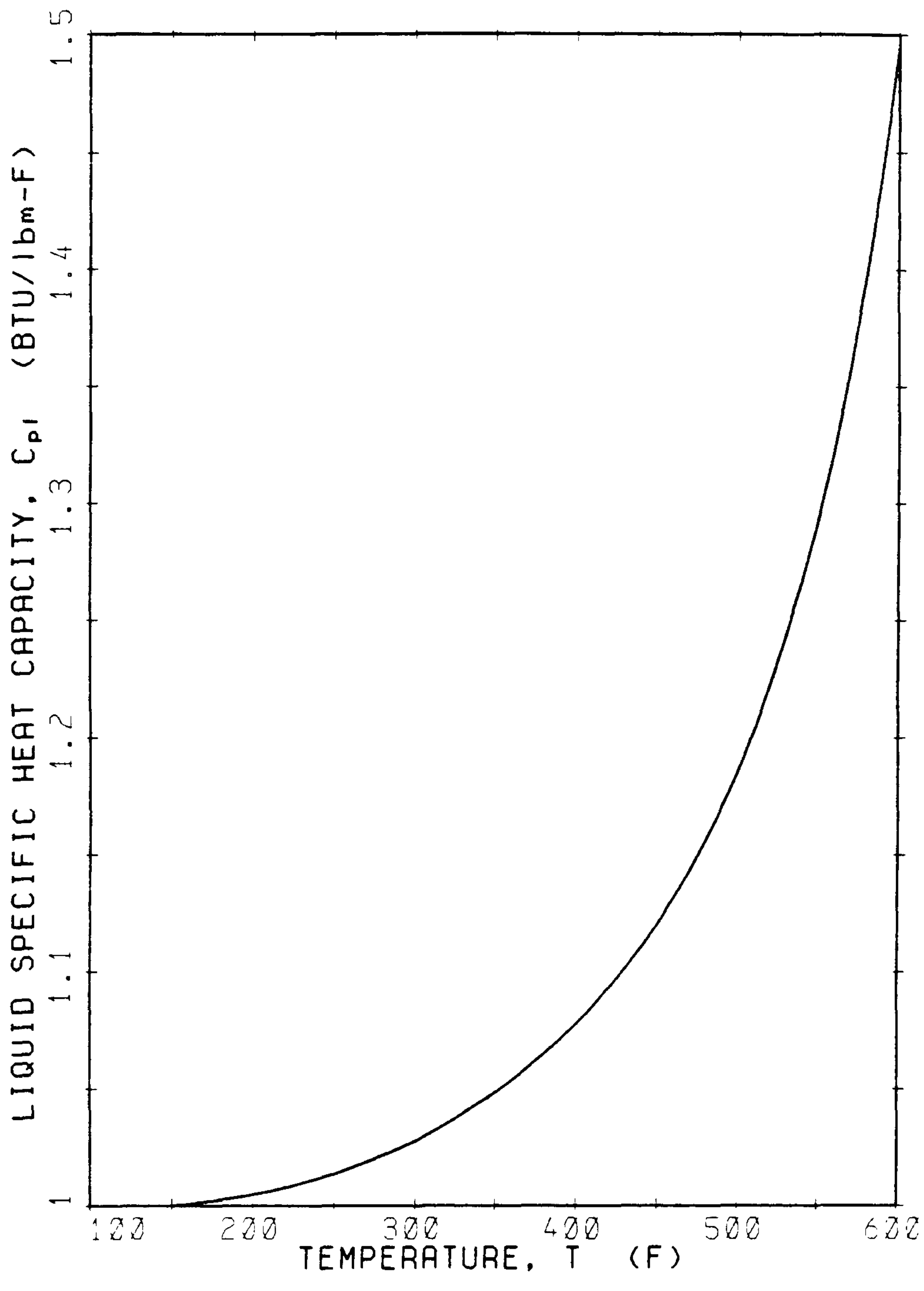

Figure D.8 SPECIFIC HEAT OF SATURATED LIQUID

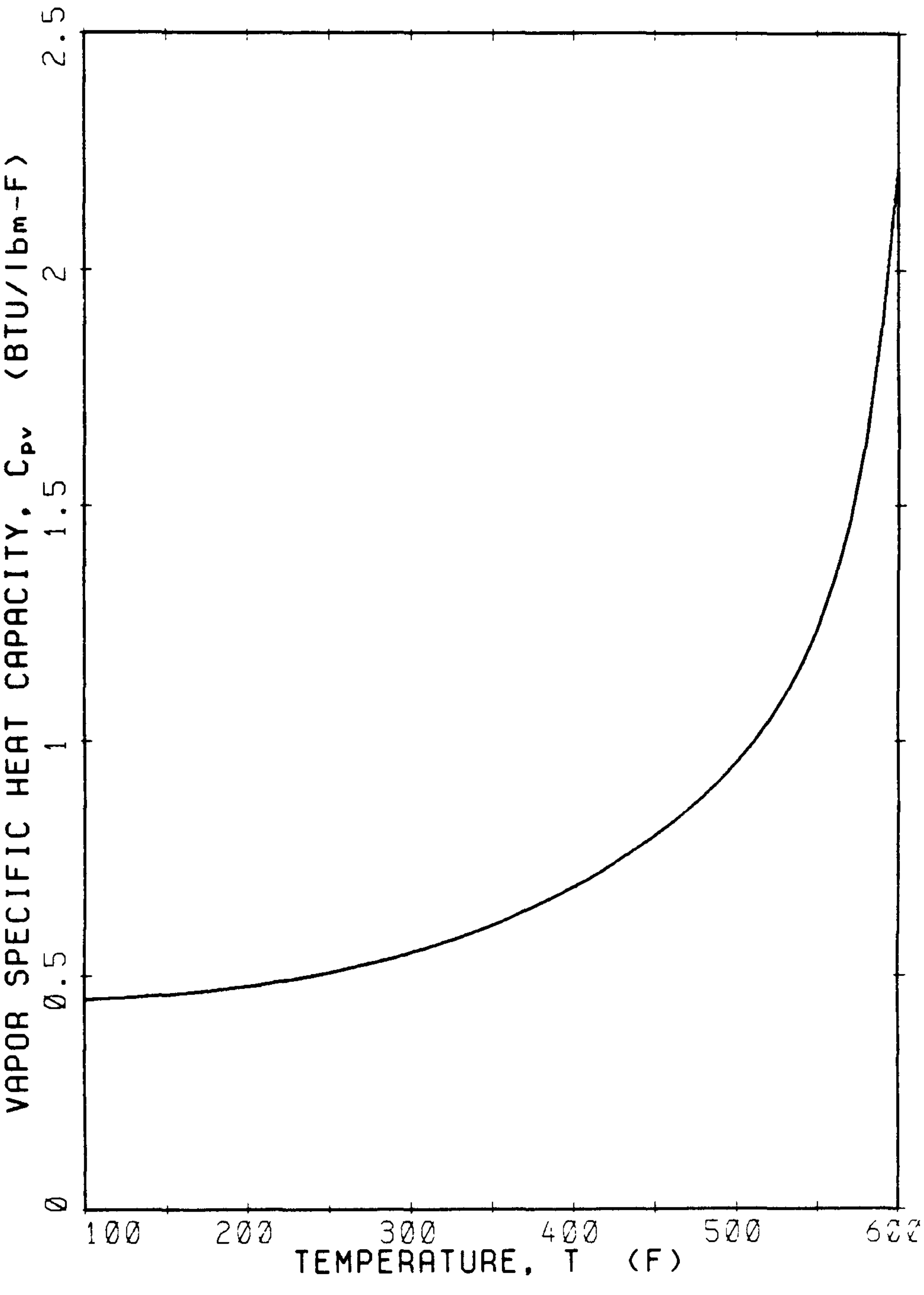

Figure D.9 SPECIFIC HEAT OF SATURATED VAPOR

APPENDIX E

BIBLIOGRAPHY

This Appendix contains an extensive bibliography of documents useful for diagnosis, evaluation and analysis of condensation–induced waterhammer. Section E.1 is devoted to documents relevant to the diagnosis of such events. Documents in this bibliography cover the following topics:

- Reviews of past waterhammer events (including nuclear and non–nuclear piping systems),
- Descriptions of plausible yet hypothetical condensation–induced waterhammer events,
- Guidelines for event diagnosis,
- Descriptions of nuclear reactor systems and operation, and
- Mitigation techniques.

Section E.2 covers theoretical analysis. The major topics are:

- Bubble flow
- Condensation
- Column separation
- Steam void collapse

Additional topics include acoustics, accumulators, blowdown, flashing, hydraulics, multiphase flow and steam hammer. Literature dealing with single phase conventional waterhammer is listed for completeness. The organization of this bibliography is presented in Table E.1.

E.1 BIBLIOGRAPHY FOR EVENT DIAGNOSIS

PAST EVENTS/NUCLEAR – BWRs

Memorandum for Karl. V. Seyfrit, Chief, Reactor Operations Analysis Branch, from Eric J. Leeds, Reactor Systems Engineer, Reactor Systems Section 1, Reactor Operations Analysis Branch, U.S. NRC; Subject: BROWNS FERRY NUCLEAR PLANT HPCI SYSTEM PERFORMANCE ASSESSMENT; AEOD/T508, August 14, 1985.

PAST EVENTS/NUCLEAR – PWRs

Block, J.A. et. al.; *An Evaluation of PWR Steam Generator Water Hammer*; NUREG–0291, Creare Inc. for U.S. NRC, June 1977.

Memorandum for Karl Seyfrit, Chief, Reactor Operations Analysis Branch, from Eugene Imbro, Lead Engineer, Reactor Systems 3, Reactor Operations Analysis Branch, U.S. NRC; Subject: TECHNICAL REVIEW REPORT, WATER HAMMER IN THE MAIN FEEDWATER SYSTEM RESULTING IN A FEEDWATER LINE BREAK; AEOD/T337, November 21, 1983.

Hildebrandt, P.C.; *Observations on Steam Generator Water Hammer*, "Workshop Proceedings: Steam Generator Waterhammer", EPRI WS–78–132, (Palo Alto, CA, Oct. 24–25, 1978), EPRI, June 1979, pp. 11–1 –11–5.

Sherburne, P.A. and Rush, G.C. ; *Waterhammer Considerations in Once Through Steam Generators*, "Workshop Proceedings: Steam Generator Waterhammer", EPRI WS–78–132, (Palo Alto, CA, Oct. 24–25, 1978),EPRI, June 1979, pp. 3–1 – 3–19.

South Texas Project Units 1 and 2; Highlights of Weekly Information Report [NRC], Week ending March 20, 1987.

PAST EVENTS/NUCLEAR – Compendia & Statistics

Memorandum for Ellis Merschoff, Chief, Reactive Inspection Section, Office of Inspection and Enforcement from Edward Yachimiak, Reactive Inspection Section, Office of Inspection and Enforcement, U.S. NRC; Subject: GENERIC CHECK VALVE FAILURE EVALUATION; July 14, 1986.

Basin, S.L. and Burns, E.T.; *Characteristics of Pipe System Failures in Light Water Reactors*; EPRI NP–438, Electric Power Research Institute, August 1977.

Bush, S.H., Patton, E.M. and Wheller, C.L.; *Water Hammers in BWRs*; EPRI NP–2590–LD, Sept. 1982.

Chapman, R.L. et. al.; *Compilation of Data Concerning Known and Suspected Water Hammer Events in Nuclear Power Plants (CY 1969 - May 1981)*; EGG-CAAD-5629, NUREG/CR–2059, EG&G Idaho Inc. for U.S. NRC, May 1982.

Chapman, R.L., Hanner, O.M.,Jr. and Wells, M.E.; *Review and Evaluation of Actual and Potential Water Hammer Events in Nuclear Plants*; CAAP–TR–042 (Rev. 1), EG&G Idaho, Inc. for U.S. NRC, Sept. 1979.

Uffer, R.A. et. al.; *Evaluation of Water Hammer Events in Light Water Reactor Plants*; NUREG/ CR–2781, QUAD–1–82–018, EGG–2203, Quadrex Corp. & EG&G Idaho for U.S. NRC, 1982.

REPORTS ON USI–A1 WATERHAMMER

Serkiz, A.W.; VALUE–IMPACT ANALYSIS FOR USI A–1, "WATER HAMMER"; NUREG–0993, For Comment, U.S. NRC, May 1983.

Serkiz, A.W.; REGULATORY ANALYSIS FOR USI A–1, "WATER HAMMER"; (Formerly Value–Impact Analysis for USI A–1, "Water Hammer"), NUREG–0993, Rev. 1, U.S. NRC, March 1984.

Serkiz, A.W.; *Evaluation of Water Hammer Occurrence in Nuclear Power Plants*; Technical Findings Relevant to Unresolved Safety Issue A–1, NUREG–0927, Rev. 1, March 1984.

U.S. NRC; *Water Hammer in Nuclear Power Plants*; NUREG–0582, July 1979.

U.S. NRC; *Report of the U.S. Nuclear Regulatory Commission Piping Review Committee*; NUREG–1061, Vol.4, Dec. 1984.

Uffer, R.; *Water Hammers in Direct Contact Heater Systems*; Innovative Concepts in Power Piping Design, E. Van Stijgeren, ed., PVP–Vol. 74, H00260, New York, NY: ASME, June 1983, pp. 41–45.

Valandani, P., Uffer, R. and Secton, D.; Water Hammer; *Flow Induced Vibration and Safety/Relief Valve Loads*; NUREG/CR –3939, U.S. NRC, Sept. 1984.

PAST EVENTS/NON–NUCLEAR – Compendia & Statistics

Gibbcons, W.S. and Hacknesy, B.D.; *Survey of Piping Failures for the Reactor Primary Coolant Pipe Rupture Study*; Prepared for Atomic Energy Commission by General Electric Co., May 1964.

Phillips, C.A.G. and Warwick, R.G.; *A Survey of Defects in Pressure Vessels Built to High Standards of Construction and its Relevance to Nuclear Primary Circuit Envelopes*; AHSB (S) R 162, United Kingdom Atomic Energy Authority, 1968.

Smith, T.A. and Warwick, R.G.; *The Second Survey of Defects in Pressure Vessels Built to High Standards of Construction and its Relevance to Nuclear Primary Circuits*; SRD R 30, United Kingdom Atomic Energy Authority, 1974.

HYPOTHETICAL EVENTS

Bruske, S.J. et. al.; *Effects of Control System Failures on Transients and Accidents At a General Electric Boiling Water Reactor. Main Report*; FIN No. A6477, EG&G Idaho for U.S. NRC, July 1984.

Jackobek, A.B. and Griffith, P.; *Investigation of Cold Leg Water Hammer in a PWR Due to the Admission of Emergency Core Cooling (ECC) During a Small Break LOCA*; NUREG/CR–3895, MIT for U.S. NRC, Sept. 1984.

Saffell, B.F., Jr.; *Supplemental Water Hammer Analysis and Systems Review*; EGG–CAAP–5133, EG&G Idaho, Inc. for NRC, July 1980. (Task 4.5 report)

Saha, P. et. al.; *An Evaluation of Condensation-Induced Water Hammer in Preheat Steam Generators*; BNL/NUREG–51248, NUREG/CR–1606, U.S. NRC, Sept. 1980. (Task 4.3 report).

Singh, B.K.; *Investigation of Condensation Induced Waterhammer in CE Steam Generators*, "Workshop Proceedings: Steam Generator Waterhammer", EPRI WS–78–132, (Palo Alto, CA, Oct. 24–25, 1978), EPRI, June 1979, pp. 5–1 – 5–15.

EVENT DIAGNOSIS – WATERHAMMER

Memorandum to J. O'Brien, Chairman, Task Committee on Other Dynamic Loads and Load Combinations from A.W. Serkiz, Task Manager, Generic Issues Branch, U.S. NRC; TRANSMITTAL OF DRAFT "Staff Recommencations on Water Hammer Loadings on Piping Components and Fittings"; Draft No. 1 of Section 7 for use in preparation of "Staff Recommendations on Event Combinations", April 24, 1984.

EVENT DIAGNOSIS – General

Makay, E. and Mucha, E.; *Fluid Transient in Power Plant Systems*; Power, July 1972, pp. 74–75.

U.S. NRC; INCIDENT INVESTIGATION MANUAL; August 1986.

U.S. NRC; Chapter 0513, NRC INCIDENT INVESTIGATION PROGRAM, NRC MANUAL, Approved August 8, 1986.

REACTOR SYSTEMS AND OPERATION

Babcock & Wilcox; BABCOCK–205 NSS DESIGN SUMMARY, SP129A 1M 8–78, 1978.

U.S. NRC; *Standard Technical Specifications for Westinghouse Pressurized Water Reactors*; NUREG–0452, Rev.4, November 1981.

Westinghouse Electric Co.; *The Westinghouse Pressurized Water Reactor Nuclear Power Plant*, Water Reactor Div., Pittsburgh, PA, 1984.

Memorandum for Stuart Rugin, Chief, Reactor Operations Analysis Branch, Office for Analysis and Evaluation of Operational Data from Peter Lam, Chief, Reactor Systems Section 2, Office for Analysis and Evaluation of Operational Data; Subject: INADVERTANT DRAINING OF REACTOR VESSEL DURING SHUTDOWN COOLING OPERATION; AEOD/E609, August 8, 1986.

General Electric; *General Description of a Boiling Water Reactor*, BWR/6, General Electric Co., San Jose, CA, Sept. 1980.

Han, J.T. and Anderson, N.; *Prevention and Mitigation of Steam Generator Water Hammer Events in PWR Plants*; NUREG–0918, U.S. NRC, Nov. 1982.

U.S. NRC; *Standard Technical Specifications for General Electric Boiling Water Reactors*; NUREG–0123, October 1976.

MITIGATION

Chapman, R.L., Hanner, O.M.,Jr. and Wells, M.E.; *Review and Evaluation of Actual and Potential Water Hammer Events in Nuclear Plants*; CAAP–TR–042 (Rev. 1), EG&G Idaho, Inc. for U.S. NRC, Sept. 1979.

Han, J.T. and Anderson, N.; *Prevention and Mitigation of Steam Generator Water Hammer Events in PWR Plants*; NUREG–0918, U.S. NRC, Nov. 1982.

Serkiz, A.W.; *Evaluation of Water Hammer Occurrence in Nuclear Power Plants*; Technical Findings Relevant to Unresolved Safety Issue A–1, NUREG–0927, For Comment, U.S. NRC, May 1983.

Serkiz, A.W.; *Evaluation of Water Hammer Occurrence in Nuclear Power Plants*; Technical Findings Relevant to Unresolved Safety Issue A–1, NUREG–0927, Rev. 1, March 1984.

U.S. NRC; *Water Hammer in Nuclear Power Plants*; NUREG–0582, July 1979.

Uffer, R.A. et. al.; *Evaluation of Water Hammer Events in Light Water Reactor Plants*; NUREG/ CR–2781, QUAD–1–82–018, EGG–2203, Quadrex Corp. & EG&G Idaho for U.S. NRC, 1982.

Singh, G.; *Waterhammer in Steam Generators and Other Related Systems*, "Workshop Proceedings: Steam Generator Waterhammer", EPRI WS–78–132, (Palo Alto, CA, Oct. 24–25, 1978), EPRI, June 1979, pp. 4–1 – 4–35.

Table E.1: ORGANIZATION OF WATERHAMMER ANALYSIS BIBLIOGRAPHY

Topics:

Acoustics; speed of sound
Accumulators

Bubble Collapse
Blowdown
Bubble Flow

Condensation–induced
- analysis
- codes
- experimental
- survey of phenomena
- rapid condensation
- onset of slugging
- slug flow
- stratified flow

Column Separation

Flashing

Hydraulics

Multiphase Flow

Steam hammer

Single–phase
Single–phase/codes

Steam void collapse
- experimental
- theory

ACOUSTICS; Speed of Sound

Ruggles, A.E., Scarton, H.A. and Lahey, R.T., Jr.; *An Investigation of the Propagation of Pressure Perturbations in Bubbly Air/Water Flows*, "First International Multiphase Fluid Transients Symposium", H.H. Safwat, J. Braun and U.S. Rohatgi, eds., FED–Vol. 41, (ASME WAM, Anaheim, CA, Dec. 7–12, 1986), New York, NY: ASME, 1986, pp. 1–9.

Swaffield, J.A., Gasiorek, J.A. and Johal, K.S.; *Mathematical Models to Predict the Celerity of Pressure Waves in Two Component Gas/Liquid Flow*, "Fluid Transients and Acoustics in the Power Industry", C. Papadakis, ed., ASME, (WAM, San Francisco, CA, Dec. 10–15, 1978), New York, NY: ASME, 1978, pp. 53–57.

Swaffield, J.A., Gasiorek, J.M. and Kohal, K.S.; *Measurements of Speeds of Propagation of Pressure Transients in Two Component Gas/Liquid Mixtures*, "Fluid Transients and Acoustics in the Power Industry", C. Papadakis, ed., ASME, (WAM, San Francisco, CA, Dec. 10–15, 1978), New York, NY: ASME, 1978, pp. 59–65.

Wylie, F.B.; *Free Air in Liquid Transient Flow*; "Proc. of the 3rd Int. Conf. on Pressure Surges", Vol. 1, Paper B1, BHRA, (Canterbury, England, March 1980), Cranfield, Bedford, England: BHRA Fluid Engineering, 1980, pp. 27–42.

ACCUMULATORS

Cheng, S.C., Gorman, D.J. and Kulkarni, K.; *Surge Tank Pressure Transients During Multiple Stages*; ASME Paper 75–FE–30, May 1975.

Chaudry, M.H.; *Applied Hydraulic Transients*; New York, NY: Van Nostrand Reinhold, 1979.

Fok, A.T.K.; *Design Charts for Air Chamber on Pump Pipe Lines*; J. Hydraulics Div., Trans. ASCE, Vol. 104, Sept. 1978, pp. 1289–1303.

Kino, I.; *Waterhammer Calculation of a Pipeline with Accumulator*; Hydraulic Pneumatic Power, Jan. 1970, pp. 42–46.

Niyogi, K.K. and Chandra, V.; *Roles of Vacuum Breaker and Air Release Devices in Reducing Waterhammer Forces*, "Forum on Unsteady Flow—1985", FED.–Vol. 27, P.H. Rothe, ed., papers presented at Winter Annual Mtg., (Miami Beach, FL, Nov. 17–22, 1985), New York, NY: ASME, 1985, pp. 7–9.

Sisson, B.; *Nomograph Sizes Accumulators to Suppress Line Shock*; Heating/Piping/Air Conditioning, June 1980, pp. 371–372.

Zahid, Z.; *Using Accumulators to Smooth Hydraulic Transients*; Machine Design, July 7, 1977, pp. 75–77.

BUBBLE COLLAPSE

Biasi, L., Prosperetti, A. and Tozzi, A.; *Collapse of a Condensing Bubble in Compressible Liquids*, Chem. Engrg. Science, Vol. 27, 1972, pp. 815–822.

Board, S.J. and Kimpton, A.D.; *Spherical Vapour Bubble Collapse*; Chemical Engrg. Science, Vol. 29, 1974, pp. 363–371.

Hickling, R. and Plesset, M.S.; *Collapse and Rebound of a Spherical Bubble in Water*, The Physics of Fluids, 7(1), Jan. 1964, pp. 7–14.

Levenspiel, O.; *Collapse of Steam Bubbles in Water*, Ind. and Engrg. Chem., 51(6), June 1959, pp. 787–790.

Li, W.–H.; *Thermal Effect on the Growth and Collapse of Cavities*; Cavitation & Hydraulic Machinery: Proc. IAHR–Symp., F. Numachi, ed., (Sendai, Japan, 1962), Paper A–1, 1962, pp. 1–16.

BLOWDOWN

Aust, E., et al.; *Vibration Phenomena in Large Scale Pressure Suppression Tests*, paper no. GKSS–82/E/23, CONF 8205131–2, presented at Int. Conf. on Vibrations in Nuclear Plants, Keswick, England, May 1982.

Travis, J.R. and Torrey, M.D.; *Thermal Hydraulics of a Feed-Water Pipe Breakage With a Back-Pressure Check Valve*, DE85 007703, LA–UR–85–457, presented at Int. Symp. on Fundamental Aspects of Gas–Liquid Flows, (ASME Winter Annual Mtg., Miami, FL, Nov. 17–21, 1985), 1985.

Winters, W.S., Jr.; *Nonequilibrium Blowdown in Long Pipes*; PhD, U. Michigan, 1978.

BUBBLE FLOW

Beattie, D.R.H.; *Pressure Pulse and Critical Flow Behavior in Distributed Gas-Liquid Systems*, "Proc. 2nd Int. Conf. on Pressure Surges", paper no. D3, BHRA, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. D3–31–D–3–50.

Dukman, H.K.M. and Vreugdenhil, C.B.; *The Effect of Dissolved Gas on Cavitation in Horizontal Pipe-Lines*, J. Hydraulic Research, 7(3), 1969, pp. 301–314.

Enever, K.J.; *Surge Pressures in a Gas-Liquid Mixture with a Low Gas Content*; "Proc. 1st Int. Conf. on Pressure Surges", BHRA, Paper C1, (Cantebury, England, Sept. 6–8, 1972), Cranfield, Bedford, England: BHRA Fluid Engineering, 1973, pp. C1–1–C1–12.

Ewing, D.J.F.; *Allowing for Free Air in Waterhammer Analysis*; "Proc. of the 3rd Int. Conf. on Pressure Surges", Vol. 1, Paper C2, BHRA, (Canterbury, England, March 25–17, 1980), Cranfield, Bedford, England: BHRA Fluid Engineering, 1980, pp. 127–146.

Fanelli, M. and Reali, M.; *A Theoretical Determination of the Celerity of Water Hammer Waves in a Two-Phase Fluid Mixture*, Energia Elettrica, 52(4), Apr. 1975, pp. 186–194.

Gel'fand, B.E. and Timofeev, E.I.; *Investigation of Water Hammer in Hydrodynamic Shock Tubes*, High Temperatures, 21(2), March 1983, pp. 258–262.

Goel, M.L. and Francisco, J.M.; *Transient Pressure (Waterhammer) Loads in Candu Emergency Coolant Injection (ECI) System*, "First International Multiphase Fluid Transients Symposium", H.H. Safwat, J. Braun and U.S. Rohatgi, eds., FED–Vol. 41, (ASME WAM, Anaheim, CA, Dec. 7–12, 1986), New York, NY: ASME, pp. 19–27.

Jakeman, D., Smith, B.L. and Heer, W.; *Propagation of Pressure Waves Through Air-Water Mixtures*, Report no. EIR–534, DE85 703126, Eidgenosessisches Inst. fuer Reaktorforschung, Wuerenlingen, Switzerland, Nov. 1984.

Kazama, T.; *Column Separation and Waterhammer in Binary Mixture*, submitted to Massachusetts Institute of Technology for Master's degree, June 1983.

Kranenburg, C.; *The Effect of Free Gas on Cavitation in Pipelines Induced by Waterhammer*; "Proc. 1st Int. Conf. on Pressure Surges", BHRA, Paper C4, (Cantebury, England, Sept. 6–8, 1972), Cranfield, Bedford, England: BHRA Fluid Engineering, 1973, pp. C4–41 – C4–52.

Kranenburg, C.; *Gas Release During Transient Cavitation in Pipes*; J. Hydraulic Div., ASCE, Paper HY–10, 1974, pp. 1383–1398.

Martin, C.S.; *Entrapped Air in Pipelines*; "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. F2, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. F2–15–F2–28.

Martin, C.S. and Padmanabhan, M.; *The Effect of Free Gases on Pressure Transients*; Final Report, Grant GK–38570, Georgia Inst. Tech., Atlanta, GA, for NSF, Washington, DC, June 1976.

Martin, C.S., Padmanabhan, M. and Wiggert, D.C.; *Pressure Wave Propagation in Two-Phase Bubbly Air-Water Mixtures*; "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. C1, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. C1–1–C1–16.

Martin, C.S. and Wiggert, D.C.; *Critique of Hydraulic Transient Simulation in Cooling Water Systems*, "First International Multiphase Fluid Transients Symposium", H.H. Safwat, J. Braun and U.S. Rohatgi, eds., FED–Vol. 41, (ASME WAM, Anaheim, CA, Dec. 7–12, 1986), New York, NY: ASME, 1986, pp. 29–40.

Moody, F.J.; *Time-Dependent Pipe Forces Caused by Blowdown and Flow Stoppage*; ASME paper no. 73–FE–23, (Applied Mechanics and Fluids Engrg. Conf., ASME, Atlanta, GA, June 20–22, 1973), J. Fluids Engrg., 95(1, #3), Sept. 1973, pp. 422–428.

Moody, F.J.; *Unsteady Piping Forces Caused by Hot Water Discharge From Suddenly Opened Safety/Relief Valves*, ASME paper no. 81–WA/NE–16, presented at WAM, ASME, Washington, DC, Nov. 15–20, 1981.

Moody, F.J.; *Impact Pressure From Sudden Arrival of Gas/Liquid Mixtures at a Relief Valve Discharging Gas*, "Fluid Transients in Fluid–Structure Interaction—1985", FED–Vol. 30, paper presented at WAM, ASME, (Miami, FL, Nov. 17–22, 1985), 1985, pp. 55–61.

Phu, T.D.; *Water-Hammer Waves in Bubbly Pipe Flows*, Thesis submitted to U. New South Wales, Australia, April 1981.

Ruggles, A.E., Scarton, H.A. and Lahey, R.T., Jr.; *An Investigation of the Propagation of Pressure Perturbations in Bubbly Air/Water Flows*, "First International Multiphase Fluid Transients Symposium", H.H. Safwat, J. Braun and U.S. Rohatgi, eds., FED–Vol. 41, (ASME WAM, Anaheim, CA, Dec. 7–12, 1986), New York, NY: ASME, 1986, pp. 1–9.

Song, Charles C.S.; *Two-Phase Flow Hydraulic Transient Model for Storm Sewer Systems*; "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. C2, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. C2–17–C2–34.

Thorley, A.R.D.; *Pressure Surge Analysis and Control*; Chartered Mechanical Engineer, 25M(1), Jan. 1978, pp. 67–70.

Tullis, J.P., Streeter, V.L. and Wylie, E.B.; *Waterhammer Analysis with Air Release*, "Proc. 2nd Int. Conf. on Pressure Surges", paper no. C3, BHRA, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. C3–35–47.

Wiggert, D.C., Rao, P.V. and Martin, C.S.; *Modelling of Two-Component Flows*, "Proceedings of the 3rd Int. Conf. on Pressure Surges", Vol. 2, H.S. Stephens, A.R.D. Thorley and J.A. Hanson, eds., BHRA, (Cranfield, Bedford, March 1980), Cranfield, Bedford, England: BHRA Fluid Engineering, 1980, pp. 489–494.

CONDENSATION–INDUCED

Moody, F.J. and Shin, Y.W.; *Two-Phase Flow and Waterhammer Loads in Vessels, Piping, and Structural Systems*; PVP–Vol.91, (1984 Pressure Vessel and Piping Conf., June 1984), ASME, 1984.

Rehder, W.A.; *The Effect of Air in Damping Water Borne Pressure Pulses*; MS Thesis, U.S. Naval Postgraduate School, 1964.

Safwat, H.H.; *Analysis of the Safety Relief Valve Discharge Transients of a Boiling Water Reactor*; "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. E1, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. E1–1–E1–17.

Safwat, H.H.; *Analysis of the Safety Relief Valve Discharge Transients of a Boiling Water Reactor*, "Proc. of the 2nd Int. Conf. on Pressure Surges", BHRA, (London, England, Sept. 2–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1976, pp. E1 1 E1–17.

CONDENSATION–INDUCED/ANALYSIS

Chiu, C. and Reilly, J.T.; *Plant Availability Improvement by Elimination of Water Hammer*; paper presented at Workshop on Water Hammer in Nuclear Power Plants, EPRI, Boston, MA, July 9–10, 1986.

Chiu, C., Tuttle, D. and Serkiz, A.W.; *Water Hammer in a PWR Horizontal Feedwater Line*, American Nuclear Society Trans., Vol. 52, 1986, pp. 589–591.

Makay, E. and Mucha, E.; *Fluid Transient in Power Plant Systems*; Power, July 1972, pp. 74–75.

CONDENSATION–INDUCED/CODES

Krotiuk, W.J.; *WHAMMOCII--A Computer Code for Performing One or Two Phase Water Hammer Analysis*, "Fluid Transients and Fluid–Structure Interaction", PVP–Vol. 64, papers presented at the Pressure Vessel and Piping Conf., ASME, (Orlando, FL, June 27–July 2, 1982), New York, NY: ASME, 1982, pp. 44–62.

Pisces International; *Transient Hydraulic Analysis of Systems and Components*; PRO–83–19, Pisces Int., San Leandro, CA, 1983.

CONDENSATION–INDUCED/EXPERIMENTAL

Dolan, F.X., Rothe, P.H. and Hsu, S.T.; *Rapid Condensation with Coaxial and Cocurrent Injection of Vapor*, "First Inter– national Multiphase Fluid Transients Symposium", H.H. Safwat, J. Braun and U.S. Rohatgi, eds., FED–Vol. 41, (ASME WAM, Ananheim, CA, Dec. 7–12, 1986), New York, NY: ASME, 1986, pp. 41–49. Creare TN–367

Lee, S.C. and Bankoff, S.G.; *Stability of Steam-Water Countercurrent Flow in an Inclined Channel: Part II - Condensation-Induced Waterhammer*; J. Heat Transfer, Trans. ASME, Vol. 106, Nov. 1984, pp. 900–901.

CONDENSATION–INDUCED/SURVEY OF PHENOMENA

Griffith, P.; *Unsolved Problems in Reactor Thermal Hydraulics*, Paper no. 15.A, presented at 3rd Int. Topical Mtg. on Reactor Thermal Hydraulics, C. Chiu, G.J. Brown, eds., ANS, Newport, RI, Oct. 15–18, 1985.

Serkiz, A.W.; *Position Paper on Water Hammer and Other Dynamic Loads*; Report of the U.S. Nuclear Regulatory Commission Piping Review Committee. Evaluation of Other Dynamic Loads and Load Combinations, NUREG–1061, Vol.4, Dec. 1984, pp. B–114 - 155.

CONDENSATION–INDUCED/RAPID

Utamura, M.; *Mechanism of Pressure Oscillation Due to Steam Condensation in Water*; "Fluid Transients in Fluid=Structure Interaction—1985", FED–Vol. 30, paper presented at WAM, ASME, (Miami, FL, Nov. 17–22, 1985), 1985, pp. 85–95.

CONDENSATION–INDUCED/ONSET SLUGGING

Wallis, G.B. and Dobson, J.E.; *The Onset of Slugging in Horizontal Stratified Air-Water Flow*; Int. J. Multiphase Flow, 1(1), Oct. 1973, pp. 173–193.

CONDENSATION–INDUCED/STRATIFIED FLOW

Bjorge, R.W. ; *Initiation of Water Hammer in Horizontal or Nearly-Horizontal Pipes Containing Steam and Subcooled Water*; MIT–EL 83–002, MIT, Cambridge, MA, Feb. 1983; prepared for Boston Edison Co. of Ma, PB83–188250; also PhD Thesis, Jan. 1983.

Block, J.A.; *Condensation-Driven Fluid Motions*, Int. J. Multiphase Flow, 6(1–2), 1980, Section 5.3, pp. 126–127.

Chiu, C., Tuttle, D. and Serkiz, A.W.; *Water Hammer in a PWR Horizontal Feedwater Line*, American Nuclear Society Trans., Vol. 52, 1986, pp. 589–591.

Gwinn, J.M. and Wander, P.J.; *Startup Hammer in Service Water Systems*; ASME Paper 74–WA/PWR–8, 1974.

Rothe, P.R., Wallis, G.B. and Crowley, C.J.; *Waterhammer in the Feedwater Systems of PWR Generators*, "Fluid Transients and Acoustics in the Power Industry", C. Papadakis, ed., (ASME WAM, San Francisco, CA, Dec. 1978), ASME Publ. H00123, 1978, pp. 75–85.

Samra, R.S.; *Feedwater System Transient Analysis for a PWR*, Flow Induced Vib., presented at 3rd Nat. Congress on Pressure Vessel & Piping Tech., ASME, (San Francisco, CA, June 1979), New York, NY: ASME, 1979, pp. 137–145.

Sherburne, P.A. and Rush, G.C.; *Waterhammer Considerations in Once Through Steam Generators*, "Workshop Proceedings: Steam Generator Waterhammer", EPRI WS–78–132, (Palo Alto, CA, Oct. 24–24, 1978), EPRI, June 1979, pp. 3–1 – 3–19.

COLUMN SEPARATION

Aga, J., Karterud, T.J. and Nielsen, T.K.; *Testing of Transient Flow and Column Separation in Crude Oil Pipelines*; "Proc. of the 3rd Int. Conf. on Pressure Surges", Vol. 1, Paper C1, BHRA, (Canterbury, England, March 25–27, 1980), Cranfield, Bedford, England: BHRA Fluid Engineering, 1980, pp 113–126.

Atzeni, A., Cao, C. and Piga, E.; *Transients with Cavitation in Cooling Water Systems For Steam-Power Plants*; "Proc. 1st Int. Conf. on Pressure Surges", BHRA, Paper D3, (Canterbury, England, Sept. 6–8, 1972), Cranfield, Bedford, England: BHRA Fluid Engineering, 1973, pp. D3–33–D3–52.

Binnie, A.M. and Thackrah, D.B.; *Water Hammer in a Pumping Main and its Prevention*; Proc. IME, Vol. 165, 1951, p. 43+.

De Bernardinis, B. and Siccardi, F.; *Transients in Low Pressure Pumping Systems with Column Separation: A Simulation Program*, "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. G2, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. G2–15–G2–26.

Fox, J.A. and McGarry, M.; *Pressure Transients in Pipelines Transporting Volatile Liquids*, "4th Int. Conf. on Pressure Surges", H.S. Stephens, et al., eds., BHRA, paper no. B1, (Bath, England, Sept. 21–23, 1983), Cranfield, Bedford, England: BHRA Fluid Engineering, 1983, pp. 39–58.

Ilic, V. and Marshall, J.; *An Experimental Analysis of Liquid Depressurisation with Mass Transfer*, "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. E3, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. E3–35–E3–40.

Kalkwijk, J.P.T. and Kranenburg, C.; *Cavitation in Horizontal Pipelines Due to Water Hammer*; J. Hydraulics Div., Proc. ASCE, Vol. 97, HY 10, Oct. 1971, pp. 1585–1605.

Kazama, T.; *Column Separation and Waterhammer in Binary Mixture*, submitted to Massachusetts Institute of Technology for Master's degree, June 1983.

Kot, C.A. and Youngdahl, C.K.; *The Analysis of Fluid Transients in Piping Systems, Including the Effects of Cavitation*, Fluid Transients and Acoustics in the Power Industry, C. Papadakis, ed., ASME, (WAM, San Francisco, CA, Dec. 10–15, 1978), New York, NY: ASME, 1978, pp. 45–52.

Kranenburg, C.; *Gas Release During Transient Cavitation in Pipes*; J. Hydraulic Div., ASCE, Paper HY–10, 1974, pp. 1383–1398.

La Barbera, P., Risso, P. and Siccardi, F.; *Severe Liquid Column Separation Effects in a Cooling Circuit of a Nuclear Power Plant: Experimental Measurements and Numerical Simulation*, "Fluid Transients and Acoustics in the Power Industry", C. Papadakis, ed., ASME, (WAM, San Francisco, CA, Dec. 10–15, 1978), New York, NY: ASME, pp. 339–349.

Li, W.–H.; *Mechanics of Pipe Flow Following Column Separation*, J. Engrg. Mech. Div., Proc. ASCE, Paper no. EM 4, Aug. 1962, pp. 97–118.

Li, W.–H. and Walsh, J.P.; *Pressure Generated by Cavitation in a Pipe*, J. Engrg. Mech., ASCE, Vol. 90, Paper no. EM 6, Dec. 1964, pp. 113–133.

Lin, F.N., Moore, W.I. and Walker, S.W.; *Selected Thermodynamic and Fluid Flow Data From the Space Shuttle Liquid Oxygen Servicing System*, Proc. 9th Int. Cryog. Engrg. Conf., ICEC9, (Kobe, Japan, May 11–14, 1986), Surry, U.K.: Butterworth & Co., pp. 782–785.

Marsden, N.J. and Fox, J.A.; *An Alternative Approach to the Problem of Column Separation in an Elevated Section of Pipeline*; "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. F1, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. F1–1–F1–13.

Martin, C.S.; *Experimental Investigation of Column Separation with Rapid Closure of Downstream Valve*; "Proc. 1st Int. Conf. on Pressure Surges", BHRA, Paper B3, H.S. Stephens, et. al., eds., (Bath, England, Sept. 21–23, 1983), Cranfield, Bedford, England: BHRA Fluid Engineering, 1983, pp. 77–88.

Martin, C.S. and Wiggert, D.C.; *Critique of Hydraulic Transient Simulation in Cooling Water Systems*, "First International Multiphase Fluid Transients Symposium", H.H. Safwat, J. Braun and U.S. Rohatgi, eds., FED–Vol. 41, (ASME WAM, Anaheim, CA, Dec. 7–12, 1986), New York, NY: ASME, 1986, pp. 29–40.

Papadakis, C.N. and Hollingshead, D.F.; *Air Release in the Transient Analysis of Condensers*, "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. G1, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. G1–1–G1–14.

Provoost, G.A.; *Investigation into Cavitation in a Prototype Pipeline Caused by Water Hammer*, "Proc. 2nd Int. Conf. on Pressure Surges", paper no. D2, BHRA, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. D2–13–D2–29.

Ramakrishnan, T.K.; *Vapour Pockets and Pressure Surges in Pipelines*; 4th Canadian Congress of Applied Mechanics, Montreal, Quebec, 1973, pp. 685–686.

Ruus, E., Karney, B. and El–Fitiany, F.A.; *Charts for Water Hammer in Low Head Pump Discharge Lines Resulting from Water Column Separation and Check Valve Closure*, Canadian J. Civil Engrg., 11(4), Dec. 1984, pp. 717–742.

Safwat, H.H.; *Measurement of Transient Flow Velocities for Water Hammer Applications*; ASME Paper 71–FE–29, May 1971.

Safwat, H.H.; *Photographic Study of Water Column Separation*; J. Hydraulics Div., Proc. ASCE, April 1972, pp. 739–750.

Safwat, H.H.; *Water Column Separation and Cavitation in Short Pipelines*; ASME Paper 75–FE–33, 1975.

Safwat, H.H.; *Experimental Study of Pressure Surges in Condenser Cooling Water Systems*; "Proc. 1st Int. Conf. on Pressure Surges", BHRA, Paper D2, (Cantebury, England, Sept. 6 8, 1972), Cranfield, Bedford, England: BHRA Fluid Engineering, 1973, pp. D2 17 D2 32

Safwat, H.H. and De Kluyver, J.P.; *Digital Computations for Waterhammer-Column Separation*; "Proc. 1st Int. Conf. on Pressure Surges", BHRA, Paper C5, (Cantebury, England, Sept. 6–8, 1972), Cranfield, Bedford, England: BHRA Fluid Engineering, pp. C5–53 – C5–68.

Sheer, T.J. ; *Computer Analysis of Waterhammer in Power Station Cooling Water Systems*; "Proc. 1st Int. Conf. on Pressure Surges", BHRA, Paper D1, (Cantebury, England, 1972), Cranfield, Bedford, England: BHRA Fluid Engineering, 1973, pp. D1–1 – D1–16.

Simpson, A.R. and Wylie, E.B.; *Problems Encountered in Modeling Vapor Column Separation*; "Fluid Transients in Fluid–Structure Interaction—1985", FED–Vol. 30, paper presented at WAM, ASME, (Miami, FL, Nov. 17–22, 1985), 1985, pp. 103–107.

Sridharan, K. and Kencharaddi, I.H.; *Case Studies of Water-Hammer Problems in Pumping Mains*, J. Indian Water Works Assn.,17(1), Jan.–Mar. 1985, pp. 51–57.

Streeter, V.L. and Wylie, E.B.; *Vapor Column Separation in Piping Systems*, presented at Century 2 Symp., ASME, Aug. 1980, Session 26, Water Hammer Analysis, no papers published.

Swaffield, J.A.; *Column Separation in an Aircraft Fuel System*; "Proc. 1st Int. Conf. on Presure Surges", BHRA, Paper C2, (Cantebury, England, Sept. 6–8, 1972), Cranfield, Bedford, England: BHRA Fluid Engineering, 1973, pp. C2–13–C2–28.

Swaffield, J.A.; *A Study of the Influence of Air Release on Column Separation in an Aviation Kerosine Pipeline*, Proc. Instn. Mech. Engrs., 186(56/72), 1972, pp. 693–703.

Tanahashi, T. and Kasahara, E.; *Comparisons Between Experimental and Theoretical Results of the Waterhammer with Water Column Separations*; Bull. JSME, 13(61), July 1970, pp. 914–925.

Thorley, A.R.D.; *State-of-the-Art Review of Pressure Surge Studies*; 6th Australasian Hydraulics and Fluid Mechanics Conf., Adelaide, Australia, Dec. 1977, pp. 546–550.

Thorley, A.R.D.; *Pressure Surge Analysis and Control*; Chartered Mechanical Engineer, 25M(1), Jan. 1978, pp. 67–70.

Thorton, R.E.; *High Gas Temperatures Associated with Pressure Surges in a Pipelne*, "4th Int. Conf. on Pressure Surges", BHRA, H.S. Stephens, et al., eds., paper no. B2, (Bath, England, Sept. 21–23, 1983), Cranfield, Bedford, England: BHRA Fluid Engineering, 1983, pp. 59–76.

Vaidyaraman, P.P. and Anderson, A.G.; *Two-Phase Flow in Long Vertical Pipes*; "Proc. 1st Int. Conf. on Pressure Surges", BHRA, paper no. C3, (Canterbury, England, Sept. 6–8, 1972), Cranfield, Bedford, England: BHRA Fluid Engineering, 1973, pp. C3–29–C3–39.

Wylie, E.B.; *Simulation of Vaporous and Gaseous Cavitation*, "Numerical Methods for Fluid Transient Analysis", FED. Vol. 4, ASME, C.S. Martin, M.H. Chaudhry, eds., 1983, pp. 47–52.

Wylie, E.B. and Streeter, V.L.; *Column Separation in Horizontal Pipelines*, Proc. Jt. Symp. Des. and Oper. of Fluid Mach., IAHR, Colorado State Univ., Fort Collins, CO, Vol. 1, pp. 3–12, 1978.

Yamaguchi, K. and Ichikawa, T.; *Pressure Surge Due to Oil Column Separation in Pipelines*; "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. F3, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. F3–29–F3–46.

Yow, W. et. al.; *Column Separation and Rejoining Field Study*; "Unsteady Flow Forum 1985", FED. Vol. 27, P.H. Rothe, ed., presented at Winter Annual Mtg., (Miami Beach, FL, Nov. 17–22, 1985), New York, NY: ASME, 1985, pp. 18–20.

FLASHING

Heer, W. and Jakeman, D.; *The Origin and Magnitude of Pressures in Vapour Explosions*, Report no. EIR–Bericht Nr. 521, DE85 703125, Eidgenoessisches Inst. fuer Reaktorforschung, Wuerenlingen, Switzerland, June 1984.

Ilic, V. and Marshall, J.; *An Experimental Analysis of Liquid Depressurisation with Mass Transfer*, "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. E3, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. E3–35–E3–40.

Vaughan, G.J.; *On the Interpretation of Pressure Surges in Liquids Caused by Vapour Explosions*, "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. E2, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. E2–19–E2–34.

HYDRAULICS

Basfeld, M. and Muller, E.–A.; *The Hydraulic Ram*, Forsch, Ingauieurwes, (Germany, Fed. Rep. of), 50(5), 1984, pp. 141–147.

Wallis, G.B., Crowley, C.J. and Hagi, Y.; *Conditions for a Pipe to Run Full When Discharging Liquid into a Space Filled with Gas*, J. Fluids Engrg., Vol. 99, 1977, pp. 405–413.

MULTIPHASE FLOW

Martin, C.S.; *Entrapped Air in Pipelines*; "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. F2, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. F2–15–F2–28.

Martin, C.S., Padmanabhan, M. and Wiggert, D.C.; *Pressure Wave Propagation in Two-Phase Bubbly Air-Water Mixtures*; "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. C1, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. C1–1–C1–16.

Song, Charles C.S.; *Two-Phase Flow Hydraulic Transient Model for Storm Sewer Systems*; "Proc. 2nd Int. Conf. on Pressure Surges", BHRA, paper no. C2, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. C2–17–C2–34.

Tullis, J.P., Streeter, V.L. and Wylie, E.B.; *Waterhammer Analysis with Air Release*, "Proc. 2nd Int. Conf. on Pressure Surges", paper no. C3, BHRA, (London, England, Sept. 22–24, 1976), Cranfield, Bedford, England: BHRA Fluid Engineering, 1977, pp. C3–35–47.

STEAM HAMMER

Luk, C.–H.; *Effects of the Steam Chest on Steamhammer Analysis for Nuclear Piping Systems*; ASME Paper 75–PVP–61, 1975.

SINGLE–PHASE

American Society of Mechanical Engineers; *Symposium on Water Hammer*; June 1933, 3rd Printing, ASME, 1961.

Anderson, A.; *Menabrea's Note on Waterhammer: 1958*; J. Hydraulics Div., Trans. ASCE, Jan. 1976, pp. 29–39.

Angus, R.W.; Transactions Amer. Soc. Civil Engrs., Vol. 104, 1939, pp. 340–401.

Bergeron, L.; *Water Hammer in Hydraulics and Wave Surges in Electricity*, ASME, New York, NY: John Wiley and Sons, Inc., 1961.

Chaudry, M.H.; *Applied Hydraulic Transients*; New York, NY: Van Nostrand Reinhold, 1979.

Driels, M.; *Predicting Optimum Two-Stage Valve Closure*; ASME Paper 75–WA/FE–2, 1975.

Hatfield, F.J., Davidson, L.C. and Wiggert, D.C.; *Acoustic Analysis of Liquid-Filled Piping by Component Synthesis: Experimental Validation and Examination of Assumptions*, "Fluid Transients and Fluid–Structure Interaction", PVP–Vol. 64, Y.W. Shin, F.J. Moody and M.K. Au–Yang, eds., papers presented at the Pressure Vessel and Piping Conf., (Orlando, FL, June 27–July 2, 1982), New York, NY: ASME, 1982, pp. 106–115.

Jaeger, C.; *The Theory of Resonance in Hydropower Systems. Discussion of Incidents and Accidents Occurring in Pressure Systems*; J. Basic Engrg, Trans. ASME, 85(4), Dec. 1963, pp. 631–640.

Jaeger, C.; *Water Hammer Effects in Power Conduits - Part 1*; Civil Engrg and Public Works Review, 43(500), Feb/May 1948, pp. 74–76.

Jaeger, C.; *Fluid Transients in Hydro-Engineering Practice*, London, England: Blackie & Son Limited, 1977.

Joukovsky, N.; See Simin, O., Rec. ID 603.

Kirik, M.J. and Gradle, R.J.; *A Model for Check Valve/Feedwater System Waterhammer Analysis*, ASME Paper no. 80–C2/PVP–27, presented at the Century 2 Pressure Vessels & Piping Conf., San Francisco, CA, Aug. 12–15, 1980.

Lawson, J.D., O'Neil, I.C. and Graze, H.R.; *Pressure Surges in Fire Services of Tall Buildings*, "Hydraulics and Fluid Mechanics", R. Silvester, ed., proc. 1st Australian Conf., (U. Western Australia, Dec. 6–13, 1962), New York, NY: Macmillan Co., 1964, pp. 353–368.

Marchal, M., Flesch, G. and Suter, P.; *Calculating the Waterhammer in Storage Pump Installations with Electronic Digital Computers*; Sulzer Research No. 1968, [date?], pp. 67–74.

Martin, S.C.; *Waterhammer in Steam Generators and Feedwater Piping*, "Workshop Proceedings: Steam Generator Waterhammer", EPRI WS–78–132, EPRI, (Palo Alto, CA, Oct. 24–25, 1978), 1979, pp. 1–1 – 1–46.

Moody, F.J.; *Additional Waterhammer Considerations in Energy Industries*; ASME Paper 80–C2/ PVP–154, August 1980.

O'Keefe, W.; *Match Hydraulic-Transient Analysis to Powerplant Water-System Needs*; Power, 125(8), August 1981, pp. 73–75.

Otwell, R.S., Wiggerst, D.C. and Hatfield, F.J.; *The Effect of Elbow Restraint on Pressure Transients*; Topics in Fluid Structure Interaction, H. Chung and M.D. Bernstein, eds., (1984 Pressure Vessels and Piping Conf.), ASME, 1984, pp. 27–40.

Parmakian, J.; *Water Hammer Analysis*; New York, NY: Dover Publications, 1963.

Pearsall, I.S.; *The Velocity of Water Hammer Waves*; Symp. on Surges in Pipelines, London, England, Paper 2, Proc. IME, 180(3E), Nov. 1965, pp. 12–20.

Perez, H.; *Resonant Waterhammer: A Case Study*; Int. J. Water Power & Dam Construction, April 1982, pp. 42–43.

Ruus, E., Karney, B. and El–Fitiany, F.A.; *Charts for Water Hammer in Low Head Pump Discharge Lines Resulting From Water Column Separation and Check Valve Closure*, Canadian J. Civil Engrg., 11(4), Dec. 1984, pp. 717–742.

Ruus, E. and Karney, B.; *Charts for Water Hammer in High Head Pump Discharge Lines Resulting From Pump Failure and Check Valve Closure*, Canadian J. Civil Engrg., 12(1), March 1985, pp. 137–149.

Safwat, H.H.; *Measurement of Transient Flow Velocities for Water Hammer Applications*; ASME Paper 71–FE–29, May 1971.

Safwat, H.H., Arastu, A.H. and Noman, A.; *Study of Check Valve Slamming in a BWR Feedwater System Following a Postulated Pipe Break*, "Forum on Unsteady Flow 1985", FED.–Vol. 27, P.H. Rothe ed., presented at Winter Annual Mtg., (Miami Beach, FL, Nov. 17–22, 1985), New York, NY: ASME, 1985.

Sharp, B.B.; *Water Hammer Problems and Solutions*; London, England: Edward Arnold Publ. Ltd., 1981.

Silvester, R.; *Hydraulics and Fluid Mechanics*, Proc. 1st Australian Conf., (U. Western Australia Dec. 6–13, 1962), New York, NY: The Macmillan Co., 1964.

Simin, O.; *Water Hammer*, [compilation of N. Joukovsky's work in Moscow, 1897], Proc. Amer. Water Works Assoc., Vol. 24, 1904, pp. 341–424.

Smith, J.; *Controlling Water Hammer*; National Engineer, 82(4), April 1978, pp. 6–7.

Streeter, V.L.; *Transients in Pipelines Carrying Liquids or Gases*; Transportation J., Proc. ASCE, Vol. 97, paper no. TE 1, Feb. 1971, pp. 15–29.

Strong, B.R., Jr., Leung, J.H. and Tan, L.–B.; *Control Rod Drive Water Hammer in Boiling Water Reactors*, American Nuclear Society Trans., Vol. 44, June 1983, pp. 621–622.

Swaffield, J.A.; *The Influence of Bends on Fluid Transients Propagated in Incompressible Pipe Flow*, Proc. Instn. Mech. Engrs., Vol. 183, Pt. 1, #29, 1968–1969, pp. 603–614.

Tarantine, F.J. and Rouleau, W.T.; *Waterhammer Attenuation with a Tapered Line*; J. Basic Engrg, Trans. ASME, 91(3), Sept. 1969, pp. 341–352.

Thirriot, C.; *What to Hope From Analytical Methods for Solving Pressure Surge Problems?*, "Proc. of the 1st Int. Conf. on Pressure Surges", Paper A7, BHRA, (Canterbury, England, Sept. 6–8, 1972), Cranfield, Bedford, England: BHRA Fluid Engineering, 1973, pp. A7–77.

Thorley, A.R.D.; *State-of-the-Art Review of Pressure Surge Studies*; 6th Australasian Hydraulics and Fluid Mechanics Conf., Adelaide, Australia, Dec. 1977, pp. 546–550.

Thorley, A.R.D.; *Influence of Variations of Transient Velocity on Resonating Frequencies*; ASME Paper 71–WA/FE–20, Nov. 1971.

Thorley, A.R.D. and Guymer, C.; *Pressure Surge Propagation in Thick-Walled Conduits of Rectangular Cross Section*; ASME Paper 75–WA/FE–15, J. Fluids Engrg, Trans. ASME, Sept. 1976, pp. 455–460.

Twyman, J.W.R., Thorley, A.R.D. and Hewavitarne, R.; *Wave Propagation in Plastically Deforming Ducts*, Paper E6, "Proceedings of the 3rd Int. Conf. on Pressure Surges", Vol. 2, H.S. Stephens, A.R.D. Thorley and J.A. Hanson, eds., BHRA, (Canterbury, England, March 1980), Cranfield, Bedford, England: BHRA Fluid Engineering, 1980, pp. 473–488.

van de Sande, E., et al.; *Resonance in the Water Circuit of a Cooling Tower*, PB84–213362, Kema Scientific & Technical Reports, 1(2), 1983, pp. 11–17.

Walker, J.; *Perturbation Solutions for Steady One-Dimensional Waterhammer Waves*; ASME Paper 74–FE–20, J. Fluids Engrg, Trans. ASME, June 1975, pp. 260–262.

Wiggert, D.C., Hatfield, F.J. and Otwell, R.S.; Fluid Structure Interaction in Piping Systems; Druckstossberechnung Von Rohrleitungssystemen, 5./6., Dec. 1983.

Wylie, E.B.; *Fundamental Equations of Waterhammer*, J. Hydraulic Engrg., 110(4), Apr. 1984, pp. 539–542.

Wylie, E.B. and Streeter, V.L.; *Fluid Transients*, New York, NY: McGraw–Hill Inc., 1978.

Zienkiewicz, O.C.; *Transmission of Waterhammer Pressure Through Surge Tanks*; Proc. IME, 168(3), 1954, p. 629.

SINGLE–PHASE/CODES

A–Moneim, M.T.; *Numerical Fluid-Structure Interaction Analysis of Piping Systems*, "Fluid Structure Interaction Phenomena in Pressure Vessel and Piping Systems", PVP–PB–026, ASME, 1977, pp. 107–121.

Harper, C.R., Hsieh, J.S. and Luk, C.H.; *An Analysis of Waterhammer Loads in a Typical Nuclear Piping System*; ASME Paper 75–PVP–53, 1975.

Martin, C.S. ; *Pressure Transients in Pipe Lines and Hydraulic Machinery*, users manual for this computer program, May 1976.

Martin, C.S. and Jackson. H.C.; *Combined Surge Tank and Waterhammer Analysis by Digital Computer*; Water Power, 24(4), April 1972, pp. 123–129.

Mitra, A.K. and Rouleau, W.T.; *Radial and Axial Variations in Transient Pressure Waves Transmitted Through Liquid Transmission Lines*; "Numerical Methods for Fluid Transient Analysis", C.S. Martin And M.H. Chaudhry, eds., ASME Publ. FED–Vol.4, 1983, pp. 39–46.

Mitry, A.M.; *Analysis and Computer Simulation for Transient Flow in Complex System of Liquid Piping*; "Fluid Transients in Fluid–Structure Interaction—1985", FED–Vol. 30, paper presented at WAM, ASME, (Miami, FL, Nov. 17–22, 1985), 1985, pp. 115–122.

Rutkowski, A. et al.; *Hydrodynamic and Structural Effects Due to the Feedwater Line Blowdown with Check Valve Slam*, "Fluid Transients and Fluid–Structure Interaction", PVP–Vol. 64, Y.W. Shin, F.J. Moody and M.K. Au–Yang, eds., papers presented at the Pressure Vessel and Piping Conf., (Orlando, FL, June 27–July 2, 1982), New York, NY: ASME, 1982, pp. 155–173.

Schwirian, R.E.; *Multidimensional Waterhammer Analysis Using a Node-Flow Link Approach*; "Fluid Transients in Fluid–Structure Interaction—1985", FED–Vol. 30, paper presented at WAM, ASME, (Miami, FL, Nov. 17–22, 1985), 1985, pp. 69–77.

Strong, B.R., Jr., Leung, J.H. and Tan, L.–B.; *Control Rod Drive Water Hammer in Boiling Water Reactors*, American Nuclear Society Trans., Vol. 44, June 1983, pp. 621–622.

Wiedermann, A.H.; *An Elastic-Plastic Pipe Response Model for Small Thickness to Diameter Ratio Pipes in Water Hammer Analysis,* "Fluid Transients and Fluid–Structure Interaction", PVP–Vol. 64, Y.W. Shin, F.J. Moody and M.K. Au–Yang, eds., papers presented at the Pressure Vessel and Piping Conf., (Orlando, FL, June 27–July 2, 1982), New York, NY: ASME, 1982.

Wiggert, D.C. et. al.; *Modeling of Transient Two-Component Flow Using a Four-Point Implicit Method*; "Numerical Methods for Fluid Transient Analysis", C.S. Martin and M.H. Chaudhry, eds., ASME Publ. FED–Vol.4, 1983, pp. 23–28.

Wiggert, D.C., Hatfield, F.J. and Stuckenbruck, S.; *Analysis of Liquid and Structural Transients in Piping by the Method of Characteristics*; "Fluid Transients in Fluid–Structure Interaction—1985", FED–Vol. 30, Publ. G00314, paper presented at WAM, ASME, (Miami, FL, Nov. 17–22, 1985), 1985, pp. 97–102.

STEAM VOID COLLAPSE/EXPERIMENTAL

Gruel, R.L.; *Steam Bubble Collapse and Water Hammer in Piping Systems: Experiment and Analysis*; BS and MS, MIT, June 1980.

Hurwitz, W.M.; *Piping Network Response to Steam Generated Water Hammer*; MS, MIT, May 1980.

Koltookian, S.A.; *Peak Pressure in a Steam Bubble Collapse Induced Waterhammer*; MIT Report, Cambridge, MA, April 1976.

Krakauer, J.A.; *Peak Pressure in a Steam Bubble Collapse Induced Waterhammer*; MIT Report, Cambridge, MA, April 1976.

Moore, M.J.; *Water Hammer in a PWR Steam Generator*; MIT Report, Cambridge, MA, 1976.

Rumancik, J.A. and Cermak, J.O.; *Investigation of Bubble Collapse Water Hammer in Split Flow Preheat Steam Generators,* "Workshop Proceedings: Steam Generator Waterhammer", EPRI WS–78–132, (Palo Alto, CA, Oct. 24–25, 1978), EPRI, June 1979, pp. 6–1 – 6–24.

Signor, C.W.; *What We Learned About Water Hammer*; ASHRAE J., 2(4), April 1960, pp. 69–71.

Smith, E.T. and Dubry, E.E.; *Water Hammer Experiments*; Proc. Int. District Heating Assoc., 1951, pp. 130–133.

STEAM VOID COLLAPSE/THEORY

Gruel, R.L.; *Steam Bubble Collapse and Water Hammer in Piping Systems: Experiment and Analysis*; BS and MS, MIT, June 1980.

Howard, N.M.; *Understanding Feedwater Line Pressure Surges*, "Workshop Proceedings: Steam Generator Waterhammer", EPRI WS–78–132, (Palo Alto, CA, Oct. 24–25, 1978), EPRI, June 1979, pp. 9–1 – 9–16.

Hurwitz, W.M.; *Piping Network Response to Steam Generated Water Hammer*; MS, MIT, May 1980.

Hurwitz, W.M.; *Theoretical Analysis of Steam Bubble Collapse, Wave Propagation and Structural Response for Water Hammer Transients in a Piping Netowrk*, "Fluid Transients and Fluid–Structure Interaction", PVP–Vol. 64, Y.W. Shin, F.J. Moody and M.K. Au–Yang, eds., papers presented at the Pressure Vessel and Piping Conf., (Orlando, FL, June 27–July 2, 1982), New York, NY: ASME, 1982, pp. 137–154.

Jones, O.C.,Jr. et. al.; *Condensation Induced Water Hammer in Steam Generators*; Two–phase Flow Dynamics, A.E. Bergles and S. Ishigai, eds., Japan–U.S. Seminar, 1979, Washington, DC:: Hemisphere Publ. Corp., 1981, pp. 255–270.

Martin, S.C.; *Waterhammer in Steam Generators and Feedwater Piping*, "Workshop Proceedings: Steam Generator Waterhammer", EPRI WS–78–132, EPRI, (Palo Alto, CA, Oct. 24–25, 1978), 1979, pp. 1–1 – 1–46.

Singh, G.; *Waterhammer in Steam Generators and Other Related Systems*, "Workshop Proceedings: Steam Generator Waterhammer", EPRI WS–78–132, (Palo Alto, CA, Oct. 24–25, 1978), EPRI, June 1979, pp. 4–1 – 4–35.