DEPRESSURIZATION AND DEFORMATION CHARACTERISTICS OF A BURSTING PIPE: THE EFFECT OF SURROUNDING FLUIDS

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Nomenclature

\[ a \] acoustic speed in pressurizing fluid
\[ A \] cross-sectional area of pipe
\[ c \] length of strain gage
\[ d \] length of pipe wall flap
\[ D_h \] hydraulic diameter
\[ e \] internal energy of leakage flow
\[ e' \] stagnation enthalpy
\[ E \] energy
\[ E \] modulus of elasticity
\[ f \] friction factor
\[ F \] energy absorbed per unit area during crack extension
\[ G \] mass flow rate per unit area
\[ G_l \] leakage mass flow rate
\[ g \] gravitational acceleration
\[ h \] pipe wall thickness
\[ H \] fluid enthalpy
\[ l \] length variable
\[ L \] crack length
\[ L \] length variable
\[ n \] thickness of wall ligament
\[ N \] total number of readings in a sample
\[ P \] fluid pressure
\[ P_0 \] initial pipe pressure
\[ \bar{P} \] dimensionless pressure variable
\[ q \] energy flux
\[ Q \] volumetric internal heat generation
\[ r \] spatial variable

\[ ^1 \text{Dimensional quantities are evaluated in S.I. units.} \]
**NOMENCLATURE**

$R$  
pipe radius

$s$  
entropy

$sd$  
sample standard deviation

$t$  
time

$T$  
fluid temperature

$u$  
fluid velocity

$U$  
internal energy

$\dot{U}$  
specific internal energy

$v$  
specific volume

$V_t$  
crack tip speed

$V_w$  
speed of point on pipe flap

$w$  
position on pipe flap

$W$  
width of crack

$x, y, z$  
cartesian coordinates

$X_i$  
individual readings

$\bar{X}$  
sample mean value

**Greek Symbols**

$\alpha$  
breach opening area

$\beta$  
flap opening angle

$\beta_0$  
reference value for $\beta$

$\gamma$  
specific heat ratio

$\Gamma$  
longitudinal elastic wave speed

$\delta$  
breach opening width

$\epsilon$  
uncertainty in result

$\varepsilon$  
strain in pipe wall

$\theta$  
opening angle

$\lambda$  
pressure decay length

$\rho$  
fluid density

$\rho_s$  
pipe wall material density

$\rho_w$  
density of water
NOMENCLATURE

\( \sigma_0 \) initial pipe wall hoop stress
\( \sigma_y \) yield stress of pipe wall material
\( \tau \) dimensionless time parameter
\( \Xi \) energy per unit length
\( \Sigma \) dimensionless depressurization rate
\( \Upsilon \) shear stress

Sub/superscripts

\( a \) axial stretching
\( e \) elastic strain
\( f \) fracture
\( k \) kinetic
\( l \) leakage
\( p \) potential
\( r \) reflected
\( t \) crack tip
\( w \) surrounding water
\( x \) incident
\( 0 \) initial or reference value
\( (\cdot) \) time differentiation
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In the safety analysis of industrial plants containing pressurized pipes, it is important to understand the physical processes associated with pipe rupture. This is necessary to assess the consequences of pipe rupture on the safe operation of the system. The physical mechanisms associated with pipe rupture include:

- depressurization of the contained fluid,
- pipe wall deformation,
- motion of the surrounding fluid,
- crack tip propagation,
- phase change of the contained fluid.

The coupling of the structural response of the pipe wall to the depressurization of the contained fluid and the motion of the surrounding fluid complicates the experimental and theoretical study of the axial rupture process. Thus, many aspects of the pipe rupture process remain poorly understood, because they are difficult to measure or predict.
The extensive use of pipelines for the transportation of natural gas has resulted in the investigation of axial rupture in gas-pressurized pipelines by means of small-scale and full-scale pipe experiments. Full-scale tests however, tend to be very expensive and cumbersome and the amount of useful data produced is limited. Smaller scale tests have proven more rewarding but there is still the problem of relating the results to the rupture of full-scale pipelines.

Although crack propagation in gas-pressurized pipes discharging into air has been extensively investigated, very limited data is available on the details of liquid-pressurized pipe rupture. Liquid-pressurized pipe failure has different rupture characteristics. Also of interest are the rupture characteristics of both liquid and gas pressurized pipes submerged in water.

Information on submerged liquid-pressurized failure has relevance to the safe design of nuclear reactors. In a pressure tube nuclear reactor, pressure tubes are used to contain and transport high temperature, high pressure coolant. A 600 MW(e) reactor contains 400 such tubes. These tubes are submerged in a liquid moderator which serves to maintain the nuclear chain reaction. Because of its role as primary containment for pressurized coolant, the integrity and reliability of the pressure tubes are essential for the safe operation of the reactor. The various damage mechanisms resulting from the axial rupture of a pressure tube are dependent on the breach opening characteristics of the failure. Data on liquid-pressurized pipes discharging into air pertains to the primary coolant piping system of nuclear reactors.

The purpose of the present investigation was the study of axial rupture of pressurized pipes. The primary objective was to determine the effect of different types of pressurizing and surrounding fluids and the pressurizing fluid temperature on
the physical processes associated with pipe rupture. Gas-pressurized tests were performed in air to provide a comparison with reported data, and underwater to determine the effect of the surrounding water. These underwater tests are of relevance to offshore pipelines. Liquid-pressurized tests were performed in air and underwater to determine the effect of surrounding water and operating conditions.

The two limiting cases of pipe rupture are:

1. circumferential or double-ended guillotine rupture which results from the propagation of a crack around the circumference of the pipe (Figure D.1),

2. axial or fishmouth rupture resulting from the propagation of a crack along the longitudinal axis of the pipe (Figure D.1).

Of the two pipe rupture modes, axial rupture is considered most likely to occur in piping systems. This is because, in a thin-walled pressurized pipe, an axial crack is oriented normal to the maximum principal stress direction. Also, axial rupture has the greatest potential for damage due to the discharge of the pressurized fluid. Whereas the circumferential break is limited to the amount of fluid determined by the pipe radius, a significant length of pipe can be ruptured in an axial break.

An apparatus was designed and constructed for producing liquid and gas pressurized pipe rupture. Rupture was initiated by the pressurization to failure of the pipe wall material at the bottom of a part-through groove machined in the outer surface of the pipe wall. High speed photography of the breach development process was a principal consideration in the design process. Flexibility was retained in all the design features so that different types of pressurizing and surrounding fluids could be used with minimum modification.

\[1\] The figures are in Appendix D.
CHAPTER 1. INTRODUCTION

The photographic records and transient strain and pressure data obtained in the present small diameter pipe experiments have no direct quantitative value for the actual prediction of the rupture characteristics of full-scale pipes. It was hoped however that the information obtained would help in the selection of realistic pipe rupture mechanisms to be used in a theoretical model of pipe rupture.

The emphasis of the present work was on the fluid-structure interaction phenomena associated with pipe rupture. Thus, fracture mechanics parameters which influence the pipe rupture process were not investigated. This would involve the use of various pipe materials (i.e. having different values of fracture toughness) as well as varying the pipe wall thickness and the size of the initial defect. The present experimental work used a standard test pipe. The pipe wall material, initial defect geometry and defect location were the same in all test runs. Therefore, conclusions drawn from the study are limited to the plane stress (thin-walled pipes) mode of pipe rupture and to a blunt axial defect in the external diameter of an internally pressurized pipe.
Chapter 2

Literature Review

The majority of failures in pipes initiate from defects or flaws. These flaws (Figure D.2a) are either inherent in the pipe material or introduced during fabrication. When a pipe containing a flaw is pressurized, the flaw may grow through the pipe wall. The penetration of the pipe wall results in a through-wall crack (Figures D.2b,c). If the crack length is below some length, called the critical length, fluid leakage occurs providing an early warning well in advance of complete pipe failure. This behavior is termed leak-before-break. If the leaking pipe is not repaired or replaced, the through-wall crack undergoes stable growth. Rapid unstable crack extension occurs when the crack has attained the critical length (Figures D.2c,d). Whereas stable crack growth occurs slowly (duration of minutes or hours), unstable crack growth proceeds rapidly (duration of milliseconds) resulting in a large breach or opening. This rapid opening process is referred to as pipe rupture.

The scope of this literature review is limited to the axial rupture of pressurized pipes, that is, events that occur after the period of stable (slow) crack growth. Because of its importance, most of the literature available is on the study of rupture in full-scale gas pipelines. The pipe wall material is carbon steel with a yield strength
range of 310–448 MPa. The pipe radius to wall thickness ratio \(R/h\) of the line pipe varies from 35 to 50 and the nominal hoop stress to yield stress ratio \(\sigma/\sigma_y\) from 0.5 to 0.8.

Pipe rupture is usually initiated by two methods: detonating an explosive charge placed in contact with a starter groove and overpressurization. For a given starter groove geometry and location, experiments show that the method of rupture initiation is not important as far as the characteristics of the subsequent pipe rupture are concerned.

The main area of interest in this work is the effect of pressurizing and surrounding fluids on ductile pipe rupture. Accordingly, whenever possible, the importance of past work is assessed with this in mind. The literature on ductile rupture of pressurized pipes falls under two categories: gas-pressurized pipe rupture [1–44] and liquid-pressurized pipe rupture [45–57]. The following is an overview of the previous experimental studies of direct relevance to this work.
CHAPTER 2. LITERATURE REVIEW

2.1 Gas-Pressurized Pipe Rupture

One of the earliest investigations of full-scale pipeline rupture is that of McClure et al. [1]. They carried out pneumatic burst tests using pipes of 610 to 915 mm diameter and a range of $R/h$ values from 21 to 60. Temperature was identified as an important parameter affecting rupture propagation. The rupture was found to propagate predominantly in either a ductile or brittle manner depending on the pipe wall temperature. For the pipe material used (plain carbon steel, grade X-52), a brittle to ductile transition temperature of 16 °C was determined.

During brittle rupture, several cracks were observed to travel together in the pipe wall material. The most frequently observed crack pattern was spiral and rupture was accompanied by little plastic deformation. The measured crack speeds for the brittle rupture (610 m/s) was in excess of the measured acoustic speed in the gas (345 m/s). (This means there is no depressurization ahead of the rupture and the initial wall hoop stress is maintained). Ductile rupture on the other hand was observed to travel more slowly (250 m/s). This is because a greater proportion of the available strain energy is used in producing new plastic zone at the tip of the advancing crack. The ductile rupture was observed to propagate in a straight line. Based on the observation that the crack speed during ductile rupture is lower than the acoustic speed, it can be concluded that there is depressurization ahead of the rupture indicating fluid depressurization may be important in the pipe rupture process. In the remaining portion of this thesis, the term pipe rupture is used to mean ductile pipe rupture.

In the same work, McClure et al. tested several pipe specimens at various nominal hoop stress levels for a range of $\sigma/\sigma_y$ from 0.31 to 0.85. The tests were at one
temperature and measurements of crack speed were made. They concluded from these measurements that the stress level did not influence the crack speed. McClure et al. also conducted tests on pipes having identical wall material and diameter but different $R/h$ ratios (22.9 and 36.9). Only a slight difference in crack speed was observed. Based on this limited data, they concluded that the pipe wall thickness has negligible effect on crack speed during pipe rupture.

Similar observations were made by Baum [2,3]. He conducted gas pressurized tests using small diameter pipes (102 mm diameter, $R/h=32$, mild steel grade BS980 CDS2) with variations in imposed stress level covering a factor of two change in failure stress ($\sigma/\sigma_y$ from 0.35 to 0.79). The crack tip speed during rupture was observed to lie in the narrow band of 200–230 m/s. The same was found to hold true for the crack lip speed. The crack lips refer to the free edges of the separated pipe wall formed behind the crack tip (Figure D.3). A crack lip speed of $\sim 140$ m/s was measured for the mid point of the free edge. Baum also found no dependence of the crack tip and crack lip speeds on the initial flaw length. Flaw lengths of one, two and four pipe radii were used.

Baum [2] proposed a model for breach area growth rate by assuming that the area growth rate is dictated solely by the rupture pressure and the inertia of the pipe walls. He also assumed that the top of the rupturing pipe can be approximated by rigid flaps, hinged at a chord length $R$ from the flaw, which rotate under the action of the pipe pressure (Figure D.4). A fixed flap length of $4R$ along the pipe was assumed in the calculation of breach area with time (plan area of breach assumed to be rectangular). The predicted breach area growth rate for the early stages of breach growth were found to agree with their measured area growth rates (obtained from high speed photographs of the developing breach). Based on this agreement,
Baum concluded that the initial stage of breach growth is dictated by the inertia of the pipe walls. The measured area growth rate was underpredicted by the inertia controlled breach growth model in the later stages of area growth (that is, breach opening area $a > OATTR^2$). It is apparent that this discrepancy is due to the decay of internal pipe pressure with time being neglected; more importantly, the assumed geometry does not include any effect of end restraint (the observed breach area geometry is diamond shaped instead of the assumed rectangular shape). Finally, the model does not account for plastic deformation at the hinge.

Close study of rupture propagation during the burst testing of large diameter gas pressurized pipes is dangerous on account of the large amounts of energy released. Also, full-scale testing of gas pipelines is particularly expensive and time consuming. To overcome these problems and minimize the potential dangers involved, several small scale tests [2-5] have been performed to study rupture propagation. The test pipe material is usually mild steel and pipe sizes range from 50 to 150 mm in diameter but the $R/h$ and $\sigma/\sigma_y$ ratios are the same as in full scale pipeline tests. No further dimensionless scaling parameters have been used to design these experiments or help correlate the results. In most full-scale burst tests [6-19], information on crack speed was obtained by the use of crack detectors. Crack detectors consist of a series of conducting wires placed transverse to the propagating crack. Data on the breach opening area history is not available from such tests. Small scale tests enable the direct observation of the breach development. High speed photography is the most common experimental technique used. From the cine film, the variation of the breach opening area with time and the crack speed can be obtained. Using high speed photography in this way, Baum [2,3] and Sturm [20,21] determined in a series of experiments that the rupture attains a constant peak speed by the time
CHAPTER 2. LITERATURE REVIEW

the crack has travelled a distance of one pipe radius.

Emery et al. [22] carried out pneumatic rupture studies on small diameter pipes (50.8 mm diameter, \( R/h = 35 \)) to supplement and validate a continuing numerical study of pipe rupture. Static and dynamic crack extension rates, breach opening rates and internal pressure transients were measured during pipe rupture. Transient breach openings were recorded by high-speed photography. The work of Emery et al. is of interest in this study since the same pipe geometry (diameter and \( R/h \) ratio) and grade of steel (1010) were used. The experimental data was used to check their split ring model of pipe rupture which is described below in more detail.

Emery et al. have proposed several numerical models of axial pipe rupture over the past decade [23,24]. In earlier work [23], a finite difference representation of cylindrical shell deformation and a finite difference transient fluid code for fluid depressurization were proposed to evaluate the rupture characteristics of pressurized pipes. The cylindrical shell (pipe) was subdivided into a series of nodal points by a mesh in the axial and circumferential coordinates (essentially a two-dimensional representation). Some of the assumptions made in deriving the shell equations for displacements and rotations at the nodal points in the mesh are: plane sections remain plane and work hardening of the pipe material can be ignored. The crack tip was permitted to advance along the pipe whenever the transverse strain ahead of the crack exceeded a prescribed value (2%). This critical strain value was quoted for A103 steel. Emery et al. do not comment on the applicability of this critical strain value to other materials. A constant fluid pressure was assumed in calculating the breach opening history. These calculations were limited by computer memory and speed requirements. Because of this limitation only short pipes (less than 3 pipe radii) could be treated. No comparisons of crack opening width (predicted by the
shell code) were made with experimental data for the reasons mentioned above. The transient fluid flow code was based on a continuity-momentum-energy solution originally derived by Meyer [25] and utilized by Rose et al. [26] in a single-phase coolant blowdown numerical code. Fluid flow through the breach was treated by assuming the exiting fluid removes axial momentum from the pipe but causes no pressure variation across the pipe cross-section. The fluid code was used with a prescribed crack opening shape to predict the depressurization transient accompanying axial rupture. By using appropriate equations of state, the code was adapted to handle gas depressurization. The fluid code is described in more detail in Appendix A. The fluid code was also used to determine the depressurization history in the split ring model which is described next.

In order to reduce the prodigious computer memory and speed requirements for the shell code described previously, Emery et al. [24] proposed a split ring model of pipe rupture. This model is based on the assumption that the pipe consists of a series of disconnected two-dimensional rings which open in response to the fluid pressure (Figure D.5). The model development was based on suggestions by Kanninen [27,28] and Freund [29,30,31] that the deformation of the shell around the crack tip is characterized by zero axial and circumferential strain. Assuming no shear transfer between the rings, a two-dimensional dynamic finite element code was used to predict the ring motion. Whenever the crack opening angle attained a prescribed value ($\theta = 13^\circ$), the crack tip was advanced one ring width. Once again, it is difficult to determine if this value can be used for other pipe materials. Emery et al. simulated axial pipe rupture for conditions obtained in their experimental work [22]. The simulation overpredicted the observed crack speeds by a factor of five. On the basis of these results they concluded that the ring model did not accurately
reflect the motion of the pipe walls during pipe rupture. The discrepancy between
the experimental data and predictions was attributed to the lack of restraining forces
due to the neglect of axial tensile straining. Experimental data [7,10,22] indicates
extensive straining along the edges of the flaps behind the crack tip. This contradicts
the assumption of zero axial strain. Since neglecting the axial strain allows each
ring to be treated independently, its consideration will require the simultaneous
solution or coupling of the rings. Thus the intrinsic simplicity of the model is lost.
Emery et al. suggest that an alternative would be the inclusion of energy dissipation
mechanisms identified through an energy rate balance analysis [32–40] into the ring
model. The energy rate balance equation originally suggested by Poynton [32,33]
and applied to a rupturing pipe by Emery et al. [22] is as follows:

\[ \Xi_p = \Xi_a + \Xi_k \]  

(2.1)

where

\( \Xi_p \) = potential energy provided by internal pipe pressure,

\( \Xi_a \) = energy dissipated in axial straining,

\( \Xi_k \) = kinetic energy of pipe walls.

Full details on the evaluation of the above terms are given in Chapter 5.

Of the above energy dissipation modes (\( \Xi_a \) and \( \Xi_k \)), the energy absorbed in axial
straining is not accounted for in the split ring model. The split ring model was
modified to include the energy absorbed in axial stretching of the pipe walls as
calculated from Equation (2.1). Details of the implementation of the above energy
partition scheme in the ring model were not available at the time of writing. The
modified model, when used with the one-dimensional transient fluid code predicted
crack speeds and pressure transients during gas-pressurized pipe rupture which com-
pared satisfactorily with their experimental results (Figure D.6). The dependence of the predicted crack speed on how the input energy is divided amongst the various energy dissipation modes (axial straining of pipe walls, kinetic energy imparted to pipe walls) is the focus of the ongoing work of Emery et al.

The literature reviewed so far pertains to the rupture of gas-pressurized pipes in air. Gas-pressurized pipes are however used in a variety of situations in which they are submerged in media other than air. Examples are, gas pipelines buried in soil, underwater pipelines and pressure tubes in gas-cooled, heavy water-moderated nuclear reactors. The effect of soil backfill has been studied by several investigators. The presence of soil and water backfill around a pipe results in a smaller opening area \[32,41,42\]. This is evident in photographs of the final opening configuration of the composite (half backfilled, half exposed) pipes used by Poynton [32]. Poynton did not measure crack speed. Maxey [43,44] studied the rupture of two large diameter (559 and 1067 mm, \(R/h=32\), mild steel grade 5LX52) underwater gas pipelines. The tests were performed in a 10 m deep water-filled quarry. A lower crack speed was measured (226 m/s versus 305 m/s) than in an identical exposed pipe. He did not measure the internal depressurization transient and did not record the breach development.

Later in this work, the energy balance analysis is extended to account for the presence of surrounding water in underwater pipe rupture.
2.2 Liquid-Pressurized Pipe Rupture

The experimental investigations on axial rupture of liquid-pressurized pipes have been limited to primary coolant piping and pressure tubes for nuclear reactors. These studies mainly focus on either rupture initiation or the consequences of the pipe rupture.

The only experimental depressurization data available on liquid-pressurized pipe rupture are data on "blowdown" tests. These studies pertain to the circumferential mode of pipe rupture. Several investigators [45-57] have performed analytical and experimental studies of the sudden depressurization of pressurized hot water. Quick opening devices or rupture disks were used to create a circumferential pipe rupture. Transient temperatures and pressures were measured along the test pipe. The common observation was that depressurization was accompanied by an almost linear drop of pressure with time during the initial stages. The pressure was found to fall below the saturation pressure at the initial water temperature. Following this undershoot below saturation, the pressure recovered to a steady level. The steady pressure was lower than the saturation pressure at the initial liquid temperature (Figure D.7). The pressure recovery was attributed to the flashing to vapor of the water as it passed from a subcooled to a superheated state.

The sudden depressurization of single-phase pressurized fluids occurs in other fields of study (for example, shock tubes). The phenomenon is well understood and there exists a large body of work on analytical techniques to determine the resulting pressure transients [58,59]. A solution technique frequently used is the method of characteristics. This method has been extended by Hancox and Banerjee [51] to the two-phase flow that is encountered in the blowdown of hot water. A sample of their
results plotted on a distance-time plane is shown in Figure D.8. The figure shows
the path followed by pressure waves generated by the sudden depressurization. The
discontinuous change in the slope of the pressure waves signifies a transition from
water to a water-steam mixture and is due to the sharp reduction in acoustic speed
in the two-phase region. The result is for the blowdown of a closed end cylindrical
pipe filled with high enthalpy water, which is suddenly opened at one end to the
atmosphere. The geometry (4 m, 32 mm diameter) and initial condition (6.9 MPa,
243 °C) were selected in order to compare the predicted pressure transient against
the experimental data of Edwards and O’Brien [48]. Predicted and experimental
pressure histories at the closed end of the pipe are shown in Figure D.7. It is
evident that the method of characteristics is inadequate for predicting the short
term pressure response of two-phase blowdown. The solution technique described is
limited to a constant area pipe and considers pressure as only a function of the axial
coordinate. However, in the axial pipe rupture case, the problem is complicated by
the motion of the crack and the change in pipe cross sectional area due to pipe wall
deformation.

In a study of the consequences of pressure tube rupture on in-core components,
Hill et al. [55] performed a visualization study on the axial rupture of submerged
pressure tubes. The principal means of investigation was high speed photography
of the discharge patterns from pressure tubes. They observed in a qualitative way
that rupture in a pressure tube submerged in water resulted in lower crack speeds
and smaller breach opening areas than in the exposed case.

No experimental data could be found on the coupled breach opening and depres­
surization data for liquid-pressurized pipe rupture. Furthermore, no visualization
data exists on the breach development process and the crack speeds involved.
2.3 Scope of the Present Investigation

It is apparent from the preceding review of earlier experimental investigations that very limited data is available on the details of liquid-pressurized axial pipe rupture and on the effect of surrounding fluids on the rupture characteristics of both liquid and gas pressurized pipes. Liquid-pressurized pipe rupture has different depressurization characteristics than the better studied gas-pressurized case. This points to the need for well defined pipe rupture experiments which will permit the verification of pipe rupture models.

The purpose of the present study was the systematic investigation of the influence of pressurizing fluid, external environment and the pressurizing fluid temperature on the axial rupture of a pressurized pipe. The following were the specific objectives of the investigation.

- Build a pipe rupture facility capable of handling different pressurizing and surrounding fluids and obtain transient pressure, strain and breach opening data for various internal and external fluid combinations.

- Obtain visualization data on the development of axial rupture in pressurized pipes.

- Determine the effects of pressure medium and surrounding medium on the breach opening characteristics.

- Gain further insight into the mechanism responsible for axial rupture in pressurized pipes and suggest possible models for further theoretical development.

The fracture mechanics aspects of the pipe rupture process were not investigated in the present study.
Chapter 3

Description of the Experiment

3.1 Experimental Apparatus

The experimental apparatus was designed to satisfy the following objectives: the measurement of transient pressure and strain and the direct observation of the pipe breach development process. Another important requirement was the capability to handle different pressurizing and surrounding fluids. The design pressure and temperature were 15 MPa and 70 °C respectively.

The design and fabrication of the experimental set-up involved the following primary steps.

- Selection of the material, the wall thickness and length of the test pipe.
- Selection of a groove cutting technique to provide a uniform and repeatable groove geometry. The optimum groove dimensions had to be determined.
- Selection of a rupture initiation method.
- Design of the test section heating arrangement, location of temperature de-
tectors, pressure transducers and strain gages and selection of pressure and strain readout devices.

- Design of a containment system to provide an external water environment yet provide access to the pipe for high speed photography.

- Design of auxiliary systems such as a liquid-filling system, pipe and vessel evacuation systems, test loop heater controls and a pressurization system.

- Design of a trigger and synchronization unit for the simultaneous acquisition of photographic, transient pressure and strain data.

A photograph of the general layout of the pipe rupture facility used in this study is shown in Figure D.9.
3.1.1 General Features

The general features of the apparatus are shown schematically in Figure D.10. The pressurizing fluid was circulated by a centrifugal pump driven at constant speed with an A.C. motor. The fluid flow was controlled by a series of valves and a pump by-pass system. The main components of the experimental set-up were the test section and the pressurization system. These two components were connected by stainless steel tubing. A section of the tubing was wrapped in heating tape for maintaining the system temperature. The pressurization system comprised a free piston pressurizer connected at one end to a compressed air supply and at the other to the test loop. The pressurization system was used to vary the pressure of the fluid in the loop. The test section consisted of the test pipe and end fittings located in a containment vessel. The containment vessel had two transparent viewing ports. Most of the instrumentation used was located in the test section.

Pressurizing Fluids

The pressurizing fluids (air, water and Freon) used were selected for different reasons. Water provided an inexpensive means of testing the performance of the experimental apparatus and studying single-phase depressurization. Pneumatic tests, provided data for comparison with published data. Freon-11 (critical pressure 4.4 MPa, critical temperature 198 °C and boiling point 23.8 °C) was used in the subcooled tests. The selection of Freon was made for several reasons; a subcooled state can be reached at fairly low temperatures and pressures thus simplifying the experimental apparatus; it is chemically stable, non-toxic, non-carcinogenic, non-mutagenic, non-teratogenic, non-flammable and non-corrosive.
Freon also offers the possibility of modeling the coolant in a pressure tube nuclear reactor on the basis of thermodynamic similarity. Generally, for steam-water systems which are encountered in nuclear reactors, the large physical size, high temperature and high pressure and large power requirements make full-scale studies costly and cumbersome. Fluid-to-fluid modeling is one method used to alleviate high testing costs [60]. In the experimental studies of two phase flow and heat transfer, it has been found expedient to replace water, which has a large latent heat, with lower latent heat fluids such as fluorocarbons. Based on his scaling experiments, Mayinger [61] proposes Freon as a suitable modeling fluid for scaling steam-water mixtures.

The major disadvantage of using Freon in the present study was the cost. This was compounded by the fact that some of the Freon inventory used in each experimental run was lost due to evaporation and contamination. This inadvertent contribution to the depletion of the ozone layer\(^1\) is deeply regretted.

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\(^1\)Industrial chemicals such as chlorofluorocarbons (CFCs e.g. Freons) are thought to be responsible for the destruction of the stratospheric ozone layer. Depletion of the ozone layer caused by these synthetic chemicals would result in increased ultraviolet radiation reaching the earth's surface, with potentially significant adverse implications for human and plant life. In addition, as "green house gases," CFCs contribute to global warming and resulting dangers for agriculture and rising sea levels. A recent treaty signed by most industrial nations seeks to limit global production and consumption of CFCs [62].
3.1.2 Test Specimen

A standard test pipe, 50.8 mm outer diameter, 0.89 mm wall thickness and 1016 mm long was used in this study. The wall material was Grade 1010, cold rolled, electrically welded carbon steel. The material properties 221 MPa yield strength, 310 MPa tensile strength, 15% elongation and Rockwell 55B hardness. The pipe wall material was chosen to allow comparison with the air-pressurized tests of Emery et al. [22].

Crack propagation was channeled along a part-through groove machined along the outer surface of the pipe. The groove was 0.36 mm deep (40% wall thickness) and 250 mm long with a vee shaped cross section. Figure D.11 is a schematic of a pipe specimen showing the groove geometry. This particular groove geometry was chosen because it was found in earlier experiments that the crack did not propagate into virgin pipe material. These experimental runs in which aluminum alloy (6061-T6, 50.8 mm diameter and 1.24 mm wall thickness) test pipes were used resulted in the curving of the crack in the circumferential direction at the end of the starter groove. This circumferential flap mode of pipe failure is shown in Figure D.12. The use of grooves to ensure directional stability of cracks is standard practice [22,63]. The pneumatic burst tests used a 0.71 mm (80% wall thickness) deep groove in an attempt to lower the failure pressure thus reduce the amount of energy released. An underwater experimental run involving a gas-pressurized standard test pipe resulted in considerable damage to equipment. This was a result of the shock wave produced by the rapid release of high pressure gas.

Special precautions had to be taken during the groove cutting process in order to produce a uniform groove. These included extremely slow feeds and the use of a
specially designed depth micrometer with a pointed rod to check the groove depth [22]. The above ensured that pipe flexibility and variations in pipe straightness and hardness did not lead to a non-uniform cut. This was vital to prevent the premature failure of test pipes. Premature failure produced no useful data since the rupture process had to be synchronized with the data acquisition process. The estimated tolerance for the depth of the groove (Figure D.11) was ±0.05 mm.

Fluid-induced buckling, shown in Figure D.13, was observed in pipes which were deformed during shipping. This phenomenon has been investigated by Mills [64]. Straight pipes containing fluid under pressure can buckle in a manner similar to an axially loaded column, even though there is negligible axial compressive force on the pipe. This behavior can be explained by the unavoidable nonuniformities in pipe material and symmetry which can cause a certain amount of lateral deflection. This lateral deflection increases with pressure until buckling occurs. The incidence of buckling was reduced by a thorough visual inspection of all pipe specimens to eliminate deformed specimens. Fluid-induced buckling of pipes has been reported by other investigators [22].
3.1.3 Test Section

The test section was located inside a steel containment vessel (Figure D.14). The vessel, a decommissioned decompression chamber, was cylindrical in shape (1.2 m in diameter and 2.1 m long) with end caps. In addition to holding water during underwater tests, the vessel acted as a protection barrier against potential fragmentation missiles from the rupturing pipe. Flanges were welded to holes cut in the vessel to provide viewing ports and support for end fittings which held the test pipe. Transparent polycarbonate sheets were used for the viewing ports. The clearances between the polycarbonate sheet and flange were sealed using neoprene gasket material. A safety relief vent was provided to prevent the overpressurization of the vessel as well as a drain to evacuate the vessel.

The test pipe was held in place by two end fittings. The end fittings were bolted to flanges at either end of the containment vessel. One end fitting was retractable allowing the easy insertion and removal of test pipes. Figure D.15 shows the end fitting in the retracted and fully inserted positions. The other end fitting held and centered a 12.7 mm diameter hollow steel transducer holder. The annular space in the transducer holder was used for passing the transducer cable out of the test section. Both fittings were fabricated from a 66.7 mm outer diameter, 5.5 mm wall thickness steel pipe. The ends of the test section were sealed with pipe caps. The test pipe was held in position in the end pieces by a set of Buna-N O-rings. Buna-N is the O-ring material with the least swelling when exposed to Freon. The O-rings were changed frequently to guard against ring failure during pressurization. The pipe end condition eliminated forces in the axial direction meaning the pipe was only subject to hoop stress loading.
This design of the test section had the primary objective of facilitating the easy removal and replacement of test pipes. The particular test pipe/end support arrangement was chosen to ensure a long enough test section. This resulted in an adequate period for monitoring the pressure transient before it was disturbed by the leading edge of the rarefaction wave returning to the measurement position upon reflection from the closed end of the test section.

The pressure transducers, strain gages and temperature detectors used in the experiment were all located in the test section. Tube fittings were connected to each end of the test section to deliver and return the pressurizing fluid.
3.1.4 Test Loop and Pressurization System

The test section was connected to the pressurization system by Grade 316 stainless steel tubing. The tubing was 12.7 mm in diameter and 0.9 mm wall thickness. The pressurization system consisted of a compressed air supply connected through an accumulator and a solenoid valve to the pressurizer (Figure D.10). The pressurizer is a thick walled steel pressure cylinder containing a free aluminum piston. The pressurizer was required only in the liquid pressurized tests. Because of the small volume displacement of the pressurizer, the compressed air supply had to be connected directly to the test section to achieve high pressures during the air-pressurized tests. The loop was designed to permit the use of different pressurizing fluids with minimum modification.

A circulation pump and heating tape were necessary for the hot Freon tests. The circulation pump was a Crane Chempump centrifugal canned rotor pump. The pump and driving electric motor are built together into a single hermetically sealed unit. The test loop was heated by a length of heating tape wrapped around the loop. The entire loop was insulated with fiber-glass insulation. To accommodate the resulting thermal expansion during the hot Freon tests, the loop was not rigidly fixed.

After the apparatus was assembled, the test loop was hydrostatically tested at 10 MPa for several hours to check for leakage. An ungrooved pipe was used as a test specimen. Compression fittings were used for all connections between pieces of tubing. All compression fittings (elbows, unions and tees) and valves used were rated at 15 MPa. The modular design features of the apparatus resulted in great ease of assembly, maintenance and retrofitting.
3.1.5 Controls and Instrumentation

The pressure within the apparatus was maintained by a free-piston pressurizer which was connected to the test loop at one end and the compressed air supply reservoir at the other. The pressure in the compressed air side was controlled by a pressure regulator and vent (Figure D.10). A Heise bourdon tube gage (calibrated against a deadweight tester and accurate to within 0.1% of the full scale reading) was used to monitor the pressure in the pressurizer. A diaphragm pressure gage in the discharge port of the circulation pump monitored the pressure in the test loop.

The fluid temperature during the hot Freon tests was controlled by passing the fluid through heated lengths of tubing. The heater was formed by wrapping heating tape around one meter length of the test loop. The heating rate in the tape was controlled with a variable A.C. transformer. Temperature measurements were made using platinum resistance temperature detectors (RTDs). The RTDs (Omega Model PR-11) were connected through a six position selector switch to a digital readout meter (Omega Model 199P2). The digital meter had a 0.1 °C resolution. The RTD/readout meter combination was calibrated against an ASTM precision thermometer. The sensitive element of the RTD was mounted in the loop by means of a fitting designed to withstand the high operating pressures.

To measure the internal depressurization transient, two pressure transducers were located in the test section. One, a Kistler 603B1 piezoelectric transducer was mounted at the end of a transducer holder centered in the test section. The transducer was located at the mid-length of the test pipe to measure the pressure transient within the immediate rupture zone. The other, a Kistler 6123A3 was mounted flush with the inner pipe wall surface close to the end of the test sec-
Figure D.16 shows the location of the pressure transducers (PT-) in the test section. The high natural frequencies of the piezoelectric transducers permit the measurement of the high frequency pressure variations. The 603B1 has a natural frequency of 500 kHz and a rise time of 1 μs, the 6123A3 a natural frequency of 110 kHz.

The sensing element of the transducers consists of stacked quartz plates. The plates are sealed into a stainless steel cylinder with a stainless steel diaphragm at one end. The diaphragm is welded to the transducer body to provide a hermetic seal for underwater applications. Pressure applied to this diaphragm compresses the quartz stack generating an electrical charge output proportional to the pressure applied. The quartz plates in the stack, interleaved with gold electrodes, are so oriented and connected that individual charge signals are added. The high impedance charge signal was sent through a low noise coaxial cable and converted to a low impedance voltage signal by a dual-mode charge amplifier (Kistler Model 5004). The voltage signal was transmitted through another coaxial cable to an oscilloscope.

Piezoelectric pressure measuring systems have very high impedance in the charge mode. The high impedance, while providing a desirable long time constant, was a disadvantage for underwater work since the slightest film of moisture across its microdot connection could short the transducer signal. However, this danger was reduced by sealing the gage connections with water-repellent silicone grease and heat shrink cable. When the sealing was compromised, transducer and cable had to be cleaned and baked for several hours at 121 °C to restore insulating properties. The time constant for quartz pressure transducers is sufficiently long for a quasi-static calibration using a dead weight tester. Simpson [65] compared the static and dynamic calibration (performed in shock tubes) of piezoelectric transducers and
found good agreement. Recalibration following a baking of the gage showed that the sensitivity was not affected.

Dynamic axial strains were measured by a pair of high elongation strain gages oriented axially along the machined groove. The gages were Showa Type N11-FA-5-120-11, 5 mm gage length, 120 Ω resistance, 4% maximum measurable strain, polyester backed and self temperature compensated for steel up to a maximum of 80 °C. The gages were bonded to the test specimen with M-Bond 200 adhesive after carefully degreasing then cleaning the pipe surface with a conditioner and neutralizer. The strain transmission requirement of the adhesive demands a high shear modulus over the operating temperature range, and negligible viscoelastic effects. For the underwater tests, the gages had to be waterproofed using a layer of M-Coat W-1 microcrystalline wax. The transient strain signals were fed into a pair of Ellis Associates Model BAM-1 bridge amplifiers. The BAM-1 is designed to handle dynamic signals over a frequency range of 0 to 20 kHz. The bridge was powered by a direct current, constant voltage supply. DC voltage is preferable for dynamic strain measurements because of the wide frequency response and system stability. Systems powered by DC voltage are however susceptible to electromagnetic interference so adequate shielding is required. Figure D.16 shows the location of the strain gages on the test pipe. The gages were located as close as possible to the machined starter groove.

Transient signals from the charge and bridge amplifiers were transmitted to a pair of Nicolet Type 3091 digital oscilloscopes. The 3091 provided 12-bit analog-to-digital resolution with a buffer memory capacity of 4096 data words (4 KB) per channel. Each channel samples analog signals at a fixed rate of 1 MHz but the effective rate is determined by the sweep rate selected. An effective sampling rate
of 50 kHz was used in most of the experimental runs. The data stored on the 3091 was transferred to diskettes via a 16-bit microcomputer. The oscilloscopes were triggered by an external battery circuit which operated on the voltage drop resulting from the opening of the solenoid valve (the opening of the solenoid valve initiates pressurization of the test pipe). To synchronize the data acquisition with the pipe rupture event, a variable time delay circuit was added to the trigger circuit. A delay time was set, based on preliminary tests, to make optimal use of the fixed memory of the oscilloscope. An electrical circuit, closed either by the events synchronization switch of the high speed camera or a manual push button activated the solenoid valve. Figure D.17 is a pictorial view of the layout of the measuring equipment showing the control panel and various instrumentation.

Electrical noise was a problem in the data acquisition system. The use of separate regulated power supplies and common grounding of components greatly improved the signal-to-noise ratio and reduced interference or cross talk between measuring circuits. This resulted in relatively clean signals free from erratic noise signals.
3.1.6 High Speed Photography

Photographic recording of the rupturing pipe was obtained by two different camera systems. The primary photographic system was a RedLake Laboratories Model K20S4E HyCam motion picture camera with a terminal framing rate of 11,000 frames/second. The HyCam is a high speed camera designed for acquisition of photographic data pertaining to high speed or transient phenomena. The HyCam uses high speed spool film and a rotating shutter to achieve an exposure time of 80 µs. 30.5 m (100 ft) spools of 16-mm Kodak 7224 4-X negative black-and-white (ASA 400) were used. Illumination was provided by a single 2 kW quartz-halogen lamp positioned to give flat frontal lighting. The lamp had a Fresnel lens that produced a concentrated beam of adjustable intensity. Also a neon timing light was used to put timing marks of millisecond interval on the film. A timing light generator, which produced accurately calibrated electrically pulses for the purpose of triggering the neon glow light, was connected to the HyCam. The timing marks were used to determine the framing rate.

Because of the high framing rate required to capture the rupture process, the transit time of a 30.5 m (100 ft) film was of the order of one second. As a result, the pipe rupture had to be triggered through the HyCam. Hyzer [66] recommends automatic synchronization between camera and event when reaction times of less than half a second were needed to capture the event on film. Further complicating the situation was the effect of loud noise on decision making. Loud noises occurring when a decision is made, produce a significant deterioration in the ability to perform simple tasks (e.g. operating an on/off switch) by reducing response rates [67]. Fortunately, the HyCam has an events synchronization capability; a microswitch
with normally closed and normally open contacts that can be actuated at any pre-
determined point in the film run. The events synchronizer was used to open the 
solenoid valve thus initiating the pressurization sequence which led to pipe rupture.

The camera was mounted on a tripod, 2 m away from the test pipe. A 25 mm, 
f/1.4 Kern-Paillard lens was connected to the optical head of the HyCam. It was 
focused on a 150 mm section of the test pipe showing the full diameter of 50.8 mm. 
Good depth of field was obtained with this arrangement. Focusing was optimized 
by the use of a painted orthogonal grid on the pipe.

Photography in the case of underwater rupture proved to be difficult due to 
the attenuation of incident light mainly by scattering and absorption. Scattering 
results in reduced image definition and contrast [68]. The effect of absorption was 
partially overcome by “push”-processing the film to a higher than rated film speed 
of 800 ASA. A lesser problem was the effect of refraction but this required only a 
changed lens setting to compensate for the difference in optical paths.

The other camera system was a 35-mm single-lens-reflex (SLR) camera posi-
tioned normal to the test pipe to record the fluid jet issuing from the breach. Only 
a single frame of the flow field was possible for each experimental run. Two differ-
ent mechanisms were used to trip the shutter of the camera. The first was a sound 
activated release mechanism which utilized a condenser microphone and a trigger 
circuit plugged into the electronic shutter release socket of the camera. The second 
was a break wire technique which used a single strip of conducting nickel paint 
across the crack path. The drop in voltage on breakage of the wire provided the 
trigger to trip the shutter. The second method proved to be the more reliable of the 
two methods. Because of the low intensity of light, a Fujicolor ASA 400 negative 
color film was used.
CHAPTER 3. DESCRIPTION OF THE EXPERIMENT

3.2 Experimental Procedure

3.2.1 Initial Preparation

Surface preparation of the test pipe started with the bonding of two strain gages to the pipe wall at locations along the machined groove. This was done after careful cleaning of the pipe surface in a procedure described in Section 3.1.5.

The exterior of the pipe surface was then coated with several layers of fast-drying white enamel paint. This was necessary to increase the contrast between the test pipe and the background. The paint acts as a diffuse coating to tone down the bright highlights on the reflective metal surface. The paint also served to insulate the electrical circuits subsequently painted on the pipe from the metal substrate. A perpendicular black paint grid 12.7 mm by 6.4 mm was then painted on the pipe surface. This provided a reference scale for quantitative measurements from the high speed photographs obtained.

Next, a series of thin nickel strips was painted normal to the machined groove to form a breakwire circuit. The paint strips 12.7 mm apart formed a resistive grid which produced step changes in grid resistance as the crack tip successively interrupted the legs of the grid. The paint was applied by means of a template fashioned out of vinyl tape; it dried quickly and had good adhesion. Grounding of the grid was prevented by the insulation of the grid from the metal pipe provided by the paint coat. Because the pipe failure produced two crack tips, the breakwire circuit was painted on only half of the test pipe. The other side of the pipe had a single strip of nickel paint across the machined groove. This provided a signal to trigger the opening of the shutter of the 35-mm camera. For underwater tests, the external break wire circuits were waterproofed using a layer of mineral wax.
3.2.2 Test Procedure

The test pipe was fixed in position in the test section. The containment vessel was readied by bolting the polycarbonate sheets to the viewing ports. Before the apparatus was filled with pressurizing fluid, all loop connections were tested for tightness. The free piston in the pressurizer was moved across its length towards the compressed air side. The pressurizer was then filled with water or Freon. This was a relatively simple operation because the pressurizer was in an upright position. The test section and connecting tubing were manually filled at the highest point in the loop. A vent placed strategically in the test loop, allowed escape of displaced air. Filling was done slowly to ensure complete purging of trapped air. Once the test loop was full, the vent in the test section was plugged. The inlet valve at the filling location was then closed.

With the filling procedure complete, the instrumentation was readied for the experimental run. First, the image of the test pipe on the film plane of the single frame and motion picture cameras were adjusted for position and focus. Focusing was carried out at maximum lens aperture. To maximize the depth of field, the smallest possible aperture for the available light and the fastest commercially available film were used. After film was loaded in the motion picture camera, it was important not to disturb its location and settings. This was because the optical path from the image to the objective passes through the film and the film happens to be opaque. The raw film was stored at low temperatures (below 10 °C). To prevent moisture condensation, the refrigerated film had to be thawed out before use. At room temperature this required an hour or so.

The leads of the strain gages were connected to bridge amplifiers in a half-
bridge configuration. This required the use of dummy gages which were bonded to an identical pipe. The bridge amplifiers were then balanced and connected to an oscilloscope. The charge amplifiers were reset and connected to an oscilloscope. Also, the break wire, high speed and 35-mm camera trigger circuits were connected to power supplies. The HyCam trigger circuit was checked using the manual switch. The oscilloscopes were then readied (zero voltage offsets and store next mode).

The appropriate danger area around the pipe burst facility was cleared of all non-essential personnel.

The pressurization sequence started with the following steps.

1. The solenoid valve was opened to connect the pressurizer to the compressed air supply reservoir.

2. The system pressure was increased to 5 MPa to check for possible leaks. If any were detected, the apparatus was evacuated and the leak fixed. The pressurization sequence was then restarted.

For the hot Freon tests, the loop heaters were turned on. The circulation pump was then activated to maintain a uniform fluid temperature in the loop. The temperature was monitored on the readout meter connected to the temperature detectors. During the Freon heating process, the pressure was monitored on the diaphragm pressure gage and maintained above the saturation pressure at the current temperature. This was achieved by the periodic bleeding of the Freon inventory. The heating was applied gradually to avoid high thermal stresses in the pipe walls. Close to the desired temperature, the solenoid valve was closed and the pressure on the gas side of the pressurizer increased to 9 MPa. This was slightly higher than the pipe failure pressure. The quartz halogen lamps were then turned on. The loop
heaters were turned off when the desired temperature was achieved. After a delay of a few seconds to allow for the removal of residual heat from the heaters, the pump was shut off and the valves across it closed. These last steps produced a more uniform axial temperature distribution and isolated the pump. The temperature reading on the digital meter was recorded.

The motion picture camera was then turned on. The camera unit had to be plugged into line power for at least 10 seconds before use to allow the electronic controls to stabilize. When the camera had run through a set length of film, it triggered the solenoid valve to open. The increase in pressure on the gas side of the free piston in the pressurizer compressed the fluid in the test pipe until pipe failure.

A relatively simple procedure was adopted to ensure the camera was running when pipe rupture occurred. A preliminary series of tests was carried out to determine the time taken from the initiation of pressurization to pipe rupture for the various testing conditions. The time delay was determined by the compressibility of the working fluid and the response time of the solenoid valve. The response time of the solenoid valve (Ascolectric Model 8223A3, 2-way, normally closed, internal pilot operated piston type valve) was determined to range from 50 to 75 ms. In subsequent tests, the delay length in the camera event synchronizer unit was set to compensate for the delay time. A persistent problem encountered during the experimental program was excessive leakage through the solenoid valve in the closed configuration. This leakage resulted in premature pipe failure with no useful data produced. The problem was alleviated by the disassembly and thorough cleaning of the valve before each test run.

For water-pressurized tests, the heating procedure described above was omitted. In the pneumatic burst case, the pressurization system was modified by replacing the
pressurizer with a flexible hose. This provided direct communication between the compressed air supply and the test section when the solenoid valve was open. The pressurization procedure was identical to that described above minus the heating and filling procedures.

The pipe rupture event lasted less than a second. At the end of the experimental run, pressurized gas in the gas side of the pressurizer was vented. The pressure and strain data stored on the oscilloscopes were transferred to a microcomputer. After each test, drifts and settings were checked to ensure the precision of measurements taken. The exposed film was retrieved and promptly dispatched for processing.
3.2.3 Test Conditions

Experimental runs were made for three different types of pressurizing fluid; air, water and Freon. The water-pressurized tests, performed at ambient temperature were necessary to check the performance of the test apparatus and the reproducibility of test data. The air-pressurized tests also done at ambient temperature provided data for comparison against published data. The Freon tests were done at varying bulk temperatures of 24, 35, 45, 55 °C. An upper temperature limit of 70 °C was imposed by the operational specification of the circulation pump and by the maximum strain gage operating temperature for self temperature compensation.

In order to determine the effect of surrounding water, tests were performed underwater for all the test conditions mentioned above. The failure pressure in water and Freon pressurized tests was 8.55±0.33 MPa (see Appendix B), since a generic test pipe was used. The air-pressurized tests were however at a lower pressure for reasons mentioned earlier.

Motion and still pictures, transient strain and pressure data were obtained for all the experimental runs. The motion pictures were taken at a maximum framing rate of 6000 frames per second, while the still photographs were taken with an exposure time of 25 μs. The high framing rates and short exposure times were necessary in order to sufficiently slow down the image on the film plane.
Chapter 4

Results

The results of 26 experimental runs performed using standard test pipes are described in this chapter. An equal number of tests were used to develop pipe rupture test procedures and associated instrumentation. Three experimental parameters were varied as follows:

1. Three types of pressurizing fluid were used. Eight of the tests were water pressurized, six were air pressurized and twelve were pressurized with Freon.

2. The second parameter of interest was the type of surrounding fluid. Experiments were performed underwater and in air. For all the tests, the surrounding fluid was initially at ambient pressure.

3. The initial Freon temperature was varied in the Freon-pressurized tests.

The experiments were carried out over a pressure range of 2.1 to 8.9 MPa and an initial temperature range of 24 to 55 °C. Simultaneous measurements of transient pressure and strain and high speed photographic recordings were made for most of the test runs. A summary of the test conditions used in the experimental runs
are shown in Table C.1. The letter-number code used in Table C.1 identifies the different experimental runs. The first letter designates the type of pressurizing fluid; the second denotes the type of surrounding fluid. The first number designates the initial temperature of the pressurizing fluid in degrees Celsius and the second designates the test number in that particular series. The omission of the test number indicates the first in a series of tests using the same pressurizing and surrounding fluids. The letters A, F, and W refer to air, Freon and water respectively. The surrounding water was at ambient pressure (0.1 MPa) and temperature (24 °C) for all of the runs. Incomplete pressure data was obtained for test runs F(24)A-2 and F(35)A-3 due to problems with the data acquisition system.

The experimental errors in the measured data are evaluated in Appendix B and results are presented in Table B.1.

\[1\] The tables are in Appendix C.
4.1 Depressurization Data

When pipe rupture occurs, rapid depressurization commences with a rarefaction (expansion) wave propagating into the high pressure fluid and initiating flow towards the breach. Simultaneously, a compression wave propagates into the fluid surrounding the pipe. At any axial location along the pipe, the pressure starts to drop on arrival of the rarefaction wave.

The depressurization transient was measured at two pressure transducer positions. The transducer at location PT–1 was mounted in the breach zone. However, the rupture did not propagate as far as the transducer at PT–2. A selection (one for each pressurizing and surrounding fluid combination) of measured pressure transients at the transducer locations is presented in Figures D.18 to D.29. The pressure and time variables are presented as dimensionless parametric groupings. The pressure magnitude was normalized with respect to the fluid pressure at rupture and referenced to ambient pressure. A dimensionless time variable, $\tau$, was used to incorporate compressibility effects, to account for the different pressurizing media used. The dimensionless variables are defined as follows [69,70]:

\[ P = \frac{P}{P_0} \quad \text{(4.1)} \]
\[ \tau = \frac{at}{R} \quad \text{(4.2)} \]

In Figures D.18 through D.29, zero time corresponds to the start of depressurization at transducer position PT–1. The reference zero time was arbitrarily chosen to coincide with the time at which a 0.5% decrease in the initial pressure occurred (Figure D.30).

The pressure transients measured at the transducer locations display certain
common features. Depressurization starts with slow drop in pressure followed by a rapid pressure decay to ambient pressure. At $P \sim 0.1$, the rate of pressure drop levels off. The entire pressure transient at each transducer location takes place over a range of $r \sim 60$. The only exception being the pressure measurement at PT–2 for the air-pressurized tests ($r \sim 300$). The pressure traces for the air-pressurized tests are shown in Figures D.28 and D.29. The abrupt cut off for the pressure record at PT–1 for Run F(55)W (see Figure D.27) is due to an incorrect voltage offset setting on the oscilloscope. However, useful data was obtained for the short term pressure response (i.e. $r < 20$).

For $r > 20$, the pressure transients measured at PT–1 show different characteristics. The behavior was observed to depend on the type of pressurizing and surrounding fluids used. The underwater water-pressurized tests (an example being Figure D.19) exhibit a repressurization “hump” for the pressure measured at location PT–1 at a value of $r \sim 30$. This value of $r$ corresponds to the travel path of a compression wave reflected from the containment vessel wall. The repressurization behavior is absent in all tests performed in air (Figures D.28 and D.29) and in all pressure measurements at PT–2. The pressure transducer PT–2 is located outside the containment vessel (away from the breach zone) therefore it is not exposed directly to the reflected compression wave.

The pressure traces measured in the Freon tests and shown in Figures D.22 to D.27 are characterized by repressurization-depressurization oscillations after the initial pressure dip. The pressure oscillations measured at PT–2 were of short period but soon reached a steady state. The oscillations associated with PT–1 had a longer period with an amplitude which took longer to damp out. The behavior was determined not to be apparatus generated because it was not observed in either
the water or air pressurized tests. The pressure oscillations at PT-1 occur at about the time of return of the reflected compression wave discussed earlier. This makes it difficult to discern effects of the reflected wave on the pressure trace measured at PT-1 for underwater Freon pressurized rupture.

Comparisons of the pressure transients for the various hot Freon tests are presented in Figures D.31 to D.34. The magnitudes of pressure in all cases are within 3% of each other. The Freon temperatures quoted in Table C.1 are those measured at the resistance temperature detector location RTD-1.

Figures D.35 through D.39 show the pressure histories for tests underwater and in air using the same pressure medium. The pressure magnitudes were found to agree within ±4%. In general, agreement is better for the pressure measurements at transducer PT-2 since wave reflection effects are absent.

The pressure histories for the different pressurizing fluids (water, Freon and air) used are compared in Figures D.40 to D.43. The pressure data measured at PT-1 for all the pressure media used almost collapse into a single curve. The pressure measured at transducer location PT-1 decays to zero at $\tau = 17$ for all the pressurizing fluids. The pressure data obtained at PT-2 exhibit different characteristics. The pressure trace for the air pressurized case decays at a much slower rate than for the liquid pressurized case. At $\tau \sim 20$, the pressure measured at PT-2 for liquid-pressurized pipe rupture (Figures D.18–D.27) is close to ambient whereas that for the air-pressurized case (Figures D.28 and D.29) has fallen only to a value of $P \sim 0.65$.

The pressure traces presented show no sign of the rarefaction wave reflected from the ends of the test section. Any effects of the reflected wave should show up as a pressure drop at a value of $\tau \sim 120$. 
4.1.1 System performance

Before any Freon and air-pressurized pipe rupture tests were performed, several water-pressurized tests were done to test the system performance. Components were then redesigned to improve the overall system performance. Instrumentation and experimental procedures were developed during these tests. One of the measures of system performance used was the reproducibility of measured data. Reproducibility was assessed by surveying obvious features and anomalies in runs performed under identical conditions and by comparing specific measurements for such runs. Figures D.44 and D.45 show the depressurization transient for three water-pressurized tests. The normalized pressure histories agree to within ±5%. The agreement was much better for tests performed in air than for the underwater tests. The poor agreement obtained for the underwater tests (Figure D.45) is due to the reflection of the outgoing compression wave from the containment vessel wall.
CHAPTER 4. RESULTS

4.1.2 Rarefaction wave speed

The leading edge of the rarefaction wave generated during pipe breach propagates at the acoustic speed into the undisturbed high pressure fluid. Subsequent elements of the wave propagate against the flow established by the preceding portion of the wave, with the result that their propagation speed is reduced as the pressure falls and the wave becomes less steep with distance. The speed of the rarefaction wave was determined from the pressure traces from the various experimental runs. The wave speed was evaluated as follows:

\[ a = \frac{|\Delta z|}{|\Delta t|} \]  \hspace{1cm} (4.3)

where \(|\Delta z|\) is the axial distance between the two pressure transducer positions and \(|\Delta t|\) is the time taken by the wave to travel between the transducers. The measurement procedure is demonstrated in Figure D.30. The wave speeds obtained for all test runs are presented in Table C.1. An error analysis was made for the measurement method and the accuracy obtained was ±2% of \(a\) (see Appendix B).
4.1.3 Depressurization rate

Pipe rupture is followed by a rapid drop in pressure. This rapid rate of depressurization is halted near ambient pressure.

A dimensionless depressurization parameter, $\Sigma$, was used to characterize the depressurization rate. The pipe depressurization characteristic is defined as:

$$\Sigma = -\frac{1}{P_0} \left( \frac{dP}{dt} \right)_1 \frac{R}{a}$$

(4.4)

where $(dP/dt)_1$ is the slope of the linear portion of the pressure transient.

The determination of this slope is shown schematically in Figure D.30. The measured depressurization rate ($\Sigma$) values at the two pressure transducer locations are given in Table C.1.

The depressurization histories measured at the two transducer positions are compared for the different test runs in Figures D.35 to D.39. While the histories follow the same trend, the depressurization rate at position PT–1 is at least twice as large as that measured at PT–2. A comparison of $\Sigma$ values for the gas-pressurized case in Table C.1 shows that the value measured at PT–1 is about six times that at PT–2. This is much larger than the factor of two obtained for the liquid pressurized tests.

A comparison between the measured depressurization transient at transducer location PT–2 for gas pressurized rupture and the theoretical prediction for a centered expansion wave [69] is given in Figure D.46. The comparison shows good agreement between theory and experiment. This agreement inspires confidence in the experimental techniques employed in this study. Centered expansion waves are of importance in the study of flow in a shock tube and in the analysis of suddenly opened pressure vessels [69].
4.2 Crack Speed Gage Data

A preliminary attempt to measure the crack speed involved the use of a crack speed gage. The gage consisted of a series of conducting wires placed transverse to the crack to form a grid. The ends of the grid lines were joined together and connected in parallel with a recording circuit. The resistance of the grid changes incrementally as the advancing crack tip breaks successive legs, so that connection into a voltage divider produces a voltage that changes incrementally with crack advance. The voltage output was recorded using an oscilloscope. Figure D.47 shows a typical voltage output from a crack speed gage. The average speed of the crack traversing the grid is given by the gradient of a position-time history curve. The distance between the grid lines was known and the time interval was given by the crack speed gage record.

The crack speed gage was insulated from the metal substrate by the paint coat applied to the pipe surface. This method of crack speed determination was discontinued because it proved to be highly unreliable. Erratic failure and premature debonding under dynamic and high temperature conditions frequently occurred. Also the installation of the gage proved to be a difficult task and the gage circuit was susceptible to electrical noise. More importantly, there was uncertainty as to whether the failure of the conducting paint strip indicated the arrival of the crack tip. This required the strips to break only after being subject to plastic deformation field that would be experienced near the tip of a running crack [71]. A high speed photographic method was used instead to obtain the crack speed data. This method is described in Section 4.4.
4.3 Pipe Wall Deformation

Transient strain data measured adjacent to the crack path at locations SG-1 and SG-2 are shown in Figures D.48 through D.57. The strain gages were mounted in an axial orientation to evaluate the plastic zone ahead of the crack tip and the flap opening behavior following the passage of the crack tip. As the crack approaches the measurement point, the axial strain increases rapidly at a rapid rate of \( \sim 50/s \) to a peak strain level. In some of the strain records (Figures D.50–D.55), there is a momentary halt in the straining process, followed by a further rapid increase in strain to a final peak value. The peak measured strain is in excess of the yield strains for the pipe material used. Typical pipe materials yield at a tensile strain (corresponding to the lower yield stress) of 0.15% in simple tension. The time scale on the strain plots (Figures D.48 to D.57) is referenced to the start of depressurization at pressure transducer position PT-1.

The negligible initial strain measured in most of the test runs is due to the pipe end conditions used in this study. The ends of the pipe are free resulting in a zero axial force boundary condition. This translates to a negligible axial strain. The strains resulting from the initial pressurization of the pipe are insignificant compared with strains developed as the crack passes through the gage position.

The peak strain values measured for the gas-pressurized cases (Figures D.56 and D.57) are at least twice as high as that for the liquid-pressurized tests (Figures D.48 to D.55). The peak strain levels for the in-air tests were consistently higher than for the underwater tests. The strain records for the Freon tests (see Figures D.50 through D.55) show a trend of increasing peak strain level with increasing initial Freon temperature.
4.3.1 Paint coat crack patterns

The brittle coating technique of experimental stress analysis [72] relies on the failure by cracking of a layer of brittle coating applied to the surface under investigation. When the component is loaded, the coating will crack as its threshold strain is exceeded. Cracking occurs where strain is greatest and thus provides a quick identification of stress concentrations. Equally important, cracks indicate the directions of maximum strain at these points as they are always aligned at right angles to the maximum principal tensile strain direction.

The circumferential orientation of the crack pattern as displayed in Figures D.58 and D.59 indicates the alignment of the principal strain direction with the axial direction. The brittle coating crack patterns were the unintentional, but fortuitous, product of the paint coating used to make the pipe surface more photogenic. The photographs shown in Figures D.58 and D.59 are of the area at the end of the machined starter groove. Examination of the crack lips along the crack path show crack patterns which are shorter in length and less distinct. Similar paint coat crack patterns have been reported by Emery et al. [22].

Only qualitative interpretations of the patterns can be made because no calibration was done prior to the experimental runs. The threshold cracking strain of the coating can be determined by loading a calibration strip in tension. The strips must be loaded with the same load-time history as the structural component so that there is no loss of sensitivity.
4.3.2 Post rupture geometry

The section shape of test pipes was obtained by cutting sections through the pipe at various distances from the crack tip and outlining the cross sections. Samples of the section shape are shown in Figures D.60 to D.62. These measurements were made to obtain a representative pipe deformation geometry and investigate the effect of zero base constraint. The deformed shapes (Figures D.60 to D.62) show a measurable radial deformation of the order of 2.5 mm. Also considerable ovaling was observed in the immediate vicinity of the crack tip.

During pipe rupture, a general downward motion of the bottom part of the pipe in the central portion of the pipe was observed. This was caused by the thrust of the escaping fluid. Because no base constraint was provided, this downward motion was not restrained resulting in the observed deflected shape. When a base constraint (for example, flat plate backing) is used, the downward motion of the pipe is constrained resulting in a flattening of the pipe wall in contact with the base [22]. The measured deformation in the liquid-pressurized pipe shown in Figure D.60 is considerably less than in the gas-pressurized rupture cases (Figures D.61 and D.62).

While the deformed shapes are not replications of the actual section shapes during pipe rupture, they provide some insight into the deformation of the pipe cross section and the mode of opening of the crack edges during pipe rupture.
4.4 Photographic Data

To obtain information on the breach development process, high speed motion pictures were taken of the immediate breach area. The information of interest was the breach extension rate, the crack lip speed and the breach opening rate.

Figures D.63 through D.66 show sequences of the high speed photographs; Figure D.63 shows water pressurized pipe rupture discharging into air; Figure D.64 shows Freon pressurized pipe rupture discharging into water; Figures D.65 and D.66 are for gas pressurized pipe rupture. The first visual evidence of rupture was the appearance of free edges generated by the failure of the ligament at the bottom of the machined starter groove. Breach growth then develops as a result of the combined effect of crack tip extension and free edge displacement. A feature of the breach opening geometry is that there is considerable crack tip propagation before any significant breach opening.

A representative selection (one for each pressurizing and surrounding fluid combination) of the crack tip extension, crack opening width and crack opening area histories is shown in Figures D.67 to D.78. The data was obtained by a frame-by-frame analysis of photographic data. Each rupture sequence was projected on a screen using a 16-mm projector with provisions for starting, stopping, single frame projection and reversing through remote control. The film was spliced into a continuous loop which could be run through the projector without the inherent delays of rewinding or reversing film through the projector. Each sequence was viewed repeatedly to pick out details missed the first time and the action sequence was projected backwards to reveal any anomalies. Measurements were scaled off the projected image. Dimensional scaling was provided by a reference grid, 12.7 mm by
6.4 mm, painted on the outside of the pipe surface. Temporal scaling was provided by the camera framing rate and was obtained from millisecond timing marks on the film edge.

The crack tip motion history was derived from the displacement of the crack tip between successive cine film frames. The average crack speed was given by the gradient of the position time curve. The horizontal velocity of the free edge of the breach along a line perpendicular to the pipe axis through the center of the breach (henceforth referred to as the crack lip speed, Figure D.3) was likewise obtained. Measured crack tip and crack lip speeds are set out in Table C.2. The measured crack speeds for gas-pressurized pipe rupture agree with reported values [22]. Data for the crack tip motion exhibit an initial acceleration followed by a linear distance time relationship. In all cases the crack achieved a constant peak speed before a value of $\tau = 10$.

The plan view of the breach opening area was determined from frame to frame. For the liquid-pressurized tests, the issuing jet tended to obscure the breach area after a few frames ($\leq 6$) so only the initial area history was obtained. The plan area does not account for the curvature of the pipe wall and therefore underestimates the true breach area. The estimated discrepancy between the plan and true areas was $\sim 3\%$ which was smaller than the estimated accuracy of the plan area ($\sim 5\%$). Thus, the plan and true area may be taken as identical. The plan area, $\alpha$, is expressed as a fraction of the pipe cross sectional area $A(= \pi R^2)$. The estimated errors in the reported values of $\delta$, $L$ and $\alpha$ are given in Table B.1.

Because the camera viewed the test pipe at an angle to the pipe axis (film plane not parallel to object plane), some non-linearity was introduced. This was corrected by projecting the negatives at a similar angle when taking measurements.
CHAPTER 4. RESULTS

Film analytical techniques involve the translation of image detail to numerical data concerning the shape, size and displacement of the image as it changes from frame to frame. This is a subjective process and often requires the ability to detect the presence of poorly resolved images. The accuracy of the measurement procedure was also reduced by the limited camera framing rate achieved.

Comparison of the in-air and underwater tests in Figures D.79 to D.84 indicate a lower crack opening area rate for the underwater case. The final breach opening area for experimental runs showing the effect of the surrounding water is shown in Figures D.85 and D.86. Also crack speed data presented in Table C.2 show a lower speed for the underwater case.

The effect of increased initial Freon temperature on the breach opening characteristics is illustrated in Figures D.87 and D.88. An increase in the rate of crack opening and with temperature was observed. A similar effect on crack tip speed is shown in Table C.2.

The effect of the type of pressure medium on crack opening rate is shown in Figures D.89 and D.90. This shows the extremely rapid opening rate for the gas-pressurized rupture in relation to the liquid-pressurized case.

Finally, composite figures showing the strain, opening area and depressurization transients are presented for a selection of experimental runs in Figures D.91 through D.100. The time origin used in these plots is the start of depressurization at transducer location PT-1. These composite plots provide a means of assessing the mechanisms responsible for pipe rupture. In most of the plots, peak strain is attained by a value of $\tau \sim 10$. This corresponds to a drop of the internal pipe pressure to about a tenth of its initial value and a breach opening area of half the final value. For the Freon pressurized tests (Figures D.93 through D.98), the momentary
halt in the strain trace correlates with the start of rapid depressurization.

4.4.1 Flow field observations

Single frame still photographs of the flow issuing from the breach during pipe rupture were taken for several experimental runs. Figures D.101 and D.102 show a selection of such photographs. Because of synchronization problems, a complete set of photographs for all the runs was not obtained. Synchronization between the pipe burst and shutter opening was achieved by using the sound generated by the pipe rupture to provide a control signal to trip the shutter of the 35-mm SLR camera. An alternate method used was the drop in voltage provided by a break wire across the crack path. Similar observations were reported by Hill et al. [55].
4.5 Numerical Predictions

Figures D.103 and D.104 show the comparison between experimentally measured pressure transients and the corresponding results predicted by the one-dimensional transient fluid flow code, UW-BURST (Appendix A). The depressurization histories are at the same fixed location (transducer location PT-1). The results show satisfactory agreement. Experimental crack tip speeds and crack opening shape were required as inputs for the code.

A crack was introduced in the center of the pipe and assumed to extend towards the end of the pipe with the corresponding observed experimental crack speed. Following Emery et al. [22], a parabolic representation of the experimental crack opening shape was used. The numerical computation described above was performed without including the area time rate of change terms present in the governing equations (Appendix A).

No attempt was made in this study to extend the predictive capability of the code to the subcooled Freon case as this was beyond the scope of the present study. This can be done by using the appropriate equations of state. However, because of the strong non-equilibrium effects associated with rapid two-phase depressurization, there are relatively few depressurization models available.
Chapter 5

Discussion

5.1 General

A factor limiting the usefulness of literature on pipe rupture is that most studies were done to investigate specific pipeline operating conditions. Usually, pertinent details on the experimental set up (e.g. notch geometry, base constraint, pipe end conditions) are not reported. Consequently, difficulties arise in the comparison and interpretation of published data.

An attempt was made in the present study to discern the extent to which measured data was influenced by the idiosyncrasies of the experimental apparatus used.

5.1.1 Dimensional effects of apparatus

The first point of consideration is the effect of reflected pressure waves on the pressure history measured during the breach opening transient.

Pipe rupture is accompanied by a rarefaction wave travelling into the high pressure fluid and a compression wave propagating into the surrounding fluid. The rigid
and free boundaries of the experimental test section result in the reflection of these waves. A compression wave reflects from a solid boundary as a compression wave, in order to decelerate the fluid to zero velocity at the boundary. For the same reason, an expansion wave reflects from a solid wall as an expansion wave [69]. To reduce the influence of the boundaries, it was necessary to increase the spatial extent of the test section to ensure that the reflected waves do not interfere with measured pressure data during the measurement period.

The effect of the reflected rarefaction wave was minimized by using a long test section (wave transit time large compared to the measurement time scale). Similarly, the effect of the reflected compression wave can be minimized by making the dimensions of the containment vessel large relative to the pipe diameter. In the present study, the experiment had to be designed around an existing containment vessel. Therefore, the pipe diameter was the only design variable. The trend to smaller pipes was balanced by several factors. As the spatial scale is decreased, the effective pressure transducer/probe holder size increases. For smaller pipes, the failure pressure is increased \((P_0 \propto 1/R)\). The result of the compromise was that the pressure decay measured at transducer position PT-1 was interrupted by the reflected compression wave at \(\tau \sim 35\). This effect was only significant for the liquid-pressurized underwater tests, an example of which is shown in Figure D.19.

The behavior of the compression wave when different pressurizing and external fluids are involved is more complicated. The acoustic equations relating the transmitted pressure, \(P_z\), and reflected pressure, \(P_r\), of a pressure pulse, \(P_i\), incident from medium 1 at the interface between medium 1 and medium 2 are given by [73]:

\[
\frac{P_z}{P_i} = \frac{2\rho_2 a_2}{\rho_1 a_1 + \rho_2 a_2} \quad (5.1)
\]
\[ P_z = P_i + P_r \]  

(5.2)

The relations assume both media to be perfectly elastic and isotropic.

Hence for an air to water interface,

\[ \rho_2 a_2 \gg \rho_1 a_1; \quad P_z = 2P_i, \quad P_r = P_i \]

while for pressure pulses travelling from water to air,

\[ \rho_1 a_1 \gg \rho_2 a_2; \quad P_z = 0, \quad P_r = -P_i \]

This means no waves incident on the escaping gas from the surrounding water in the underwater air-pressurized tests are transmitted. This shielding effect explains why no repressurization effects are observed for the underwater gas-pressurized pressure trace in Figure D.29. From the relations given above, there should be a reflected compression wave produced at the air to water interface for the outward travelling wave. The transit time for this wave is of the order of \( \tau \sim 4 \) (the time to travel across the pipe diameter and back). The effect of this reflected wave is not evident in the pressure transient for the underwater gas pressurized pipe rupture case (Figure D.29).

The consequence of the reflected compression wave is that pressure measurements at transducer location PT-1 beyond \( \tau \sim 35 \) are unreliable. This is the case for the liquid-pressurized underwater tests only. The effect on the experimental pressure measurements was minimal because the short term pressure response of interest in this study lasts for a duration of \( \tau \sim 20 \). The short term pressure transients at transducer location PT-1 are given in Figures D.40 and D.42 for the various pressurizing fluids.
5.1.2 Starter groove geometry

Pipe rupture was induced by the pressurization to failure of the ligament at the bottom of a starter groove. The failure pressures measured for the liquid-pressurized tests in which a standard test pipe was used are given in Table C.1. These results show a degree of scatter around a mean value \( P_0 = 8.55 \pm 0.33 \text{ MPa} \). The variability of the failure pressure results from two main sources [70].

1. Variations in ligament thickness along the length of the groove caused by variations in pipe wall thickness which cannot be followed exactly in the groove machining process. Although groove depth was monitored to ensure uniformity, there was no direct means of checking the size of the ligament below the machined groove (see Section 3.1.2).

2. Uncertainty in material properties due to variations in yield stress and tensile stress between batches of pipe wall material.

Although the burst pressures show some scatter, the experimental results obtained using standard test pipes are reproducible. This can be seen in Figures D.44 and D.45 which are comparisons of several water pressurized runs. This reproducibility means that the use of standard test pipes enables the parametric study of the effect of different surrounding and pressurizing fluids on pipe rupture.

The ductile fracture surface observed along the crack path (Figure D.105) provided assurance that the experimental tests model full-scale pipe rupture which shows ductile behavior. A fully ductile failure is characterized by a slant microscopic fracture surface which is inclined at 45° to the pipe surface. Work hardening, residual tensile strains caused by the groove machining process and high strain rates can induce a brittle mode of rupture in pressurized pipes.
5.1.3 Pipe boundary conditions

Two factors unique to the present experimental set up are relevant to the evolution of the cross sectional shape of the deformed pipe. These are the pipe end support and the pipe base constraint. As described earlier, the test pipe was inserted into two end fittings to form the test section. The test pipe was held in place by the compression of O-rings at each end (Figure D.16). This effectively eliminates the axial force meaning the pipe is subject only to circumferential (hoop) stress loading. This is reflected in the negligible initial axial strain observed for most of the transient strain records shown in Figures D.48 to D.57. The test pipe used in the experimental runs had no base constraint. The thrust of the escaping pressure fluid causes a downward motion of the bottom of the immediate pipe rupture zone. This downward motion is not constrained resulting in the deflection of the test pipe. The pipe is effectively simply supported at the O-rings. The downward deflection of the pipe is shown in the post rupture section shapes given in Figures D.60 through D.62.

Under the dynamic loading conditions experienced in pipe rupture, longitudinal stress waves are generated in the pipe wall. A longitudinal elastic wave propagating at speeds up to 5000 m/s \((\sqrt{\frac{\mathcal{E}}{\rho_s}})\) is followed by a plastic wave which travels at a lower speed. \(\mathcal{E}\) and \(\rho_s\) are the elastic modulus and density of the pipe wall material respectively. The elastic and plastic waves are reflected at the free end of the test pipe. The interaction between a number of different waves travelling in both directions may set up an extremely complex stress distribution pattern [74]. The reflected elastic wave would return to the strain gage position at a value of \(\tau \sim 11\) for the water pressurized case and \(\tau \sim 3\) for gas pressurized pipe rupture.
However, there are no distinct features in the strain records given in Figures D.48 through D.57 to indicate the presence of this wave. Because the extensive plastic deformation field in the rupture area, it may be difficult to detect the presence of small perturbations due to the elastic wave in the strain record. The plastic wave travels at a rate of 300 m/s \((\sqrt{\sigma_y/\rho_a}).\) This estimate is based on the propagation speed of a longitudinal displacement wave in a perfectly plastic material [2]. \(\sigma_y\) is the yield stress of the pipe wall material based on the prevailing strain rate. Because the plastic wave speed is comparable to the crack tip speed, no effects of the reflected plastic wave are expected in the measurement period. From the transient axial strain results, yield strain is achieved well in advance of the crack tip confirming the presence of the plastic wave travelling ahead of the crack tip.

Lastly, a comment on the dynamic response of strain gages. Strain gages can be used with sufficient accuracy for the measurement of dynamic strains with rise times of not less than 3\(\mu\)s. The rise time is given by \((0.5 + 0.8T/c)\mu\)s, where \(T\) is the length of the strain gage and \(c\) is the longitudinal elastic wave speed. This is the recommendation of Oi [75] after an extensive study of the transient response characteristics of strain gages. Since the duration of pressure transients in the present study is of the order of 100 \(\mu\)s, it can be concluded that the strains measured accurately reflect the pipe wall strain field.
5.2 Pressurizing Fluid

The rupture of pressurized pipes is dependent upon the depressurization characteristics of the fluid especially in the vicinity of the crack tip. The pressure in the crack flap region decays to zero over a value of $r = 17$. This behavior is exhibited in Figures D.91 to D.100. From the definition of $r$ in Equation 4.2, a pressure decay length, $\lambda$, can be defined.

$$\lambda = b \frac{V_t}{a} R$$  \hspace{1cm} (5.3)

where $V_t$ is the crack propagation speed and the pipe pressure decays to zero at $\tau = b$.

For example, in the gas-pressurized case given in Figure D.99, $b = 17$, Tables C.1 and C.2 give values of $a = 375$ m/s and $V_t = 281$ m/s. This results in a value of $\lambda = 13R$. A similar calculation for the water pressurized pipe rupture case gives $\lambda = 0.7R$.

The pressure decay length gives an indication of the distance behind the crack tip over which pressure acts on the pipe wall flaps. The implication of Equation (5.3) is that the net flap area over which the pipe pressure acts depends on the acoustic speed in the pressurizing fluid and the crack tip speed. The pressure acting on the flaps formed behind the crack tip has been proposed [7,40] as the primary driving force for breach development in gas-pressurized pipe rupture. This suggestion is supported by the experimental results obtained in this study. For example, the extent of breach opening is much larger (order of the magnitude) in the gas-pressurized case than in the liquid-pressurized case (Figures D.89 and D.90). This qualitatively agrees with the much longer pressure decay length obtained previously for gas pressurization as compared to liquid pressurization.
A feature of the experimental pressure results is that the pressure histories for the different pressurizing fluids almost collapse to a single curve when the dimensionless time and pressure variables defined in Chapter 4 are used (Figures D.40 and D.42). This suggests that some features of the fluid depressurization which occurs during axial pipe rupture are universal and that the pressure decay length is an important length scale of the depressurization process. However, because of the differences in acoustic and crack tip speeds (Tables C.1 and C.2), the pressure decay length in the case of gas pressurization is much longer than for the liquid pressurized case as demonstrated earlier. This accounts for the much more extensive breach in the gas-pressurized case. In gas-pressurized pipes, the crack tip speed is comparable to the acoustic speed. Thus, the crack tip is always running into a zone of high pressure resulting in a massive breach. For liquid-pressurized pipes, the acoustic speed is much higher than the crack tip speed. Therefore the pressure at the crack tip falls to the saturation pressure of the liquid. The breach opening is limited on account of the reduced driving force.

The collapse of the pressure traces for the different pressurizing fluids into a single curve should not be taken to indicate that the internal pipe depressurization transient is independent of the breach opening rate and extent. This is because the transit time for a transverse expansion wave to travel from the original rupture site to transducer location PT-1 is \( \tau \sim 2 \). During this period, the breach opening rate and extent is the same for all the pressurizing fluids (Figure D.89).

Another feature of the pressure traces is the apparent insensitivity of the shape and decay profile of the dimensionless pressure distributions (Figures D.40 and D.42) to the magnitude of internal pipe pressure (the initial pipe pressure is 8.3 MPa for liquid pressurized pipe rupture compared to 2.3 MPa in the gas pressurized case).
This conclusion is however tentative and requires a more systematic variation of initial pipe pressure to confirm the observation.

The rupture of a pressurized pipe results in a rarefaction (expansion) wave travelling into the high pressure fluid. As the rarefaction wave propagates down the pipe, it becomes progressively less steep with distance. This shows up distinctly in the traces in Figure D.39 for pressure measurements at PT–1 and PT–2. The initial gradients at transducer position PT–1, $2R$ from the center of the starter groove is twice that measured at PT–2, $60R$ further along the test section. This effect is referred to as wave broadening. The wave broadening effect increases with the compressibility of the pressure medium. This effect can clearly be seen in Figures D.41 and D.43. The wave broadening effect is accurately predicted by a theoretical treatment of a centered expansion wave (Figure D.46). The wave broadening effect has implications for the location of pressure transducers for measuring the internal pipe depressurization transient. To obtain the pressure acting on the pipe wall flaps the transducer must be located in the immediate rupture zone. This requirement is more important for gas-pressurized pipe rupture.
5.3 Energy Balance Analysis

In an attempt to obtain some understanding of the relative magnitudes and distributions of the various modes of energy production and dissipation during pipe rupture, an energy balance analysis was performed.

The first attempts to establish an energy rate equilibrium for a propagating axial rupture arose from a British Gas study [33]. The study considered the sources and sinks of energy from the fundamental energy rate balance appropriate to the axial rupture of a pressurized pipe:

\[ E_e + E_p = E_a + E_f + E_k + E_w \]  

For a crack propagating at constant speed, the operation of time differentiation is replaced by \( V_t \frac{d}{db} \) where \( V_t \) is the crack tip speed. Thus Equation (5.4) can be rewritten in terms of an increment in crack extension, \( db \), as

\[ \Xi_e + \Xi_p = \Xi_a + \Xi_f + \Xi_k + \Xi_w \]  

where \( \Xi_i = \frac{dE_i}{db} \).

The above energy balance is used in the present study to determine the relative magnitudes and distributions of the various modes of energy dissipation during pipe rupture. Of particular interest, is the inertial effect of surrounding water in underwater pipe rupture.

In order to solve the rate balance, it is necessary to obtain estimates of basic individual parameters: the pipe wall deformation pattern and fluid pressure acting on the pipe walls. The models of pipe deformation and axial depressurization used are necessarily simple in order to obtain a closed form analytical solution [22,33–40].
CHAPTER 5. DISCUSSION

Pipewall deformation: The geometric model used to describe pipe wall deformation postulates that the flaps behind the crack tip open in an involute shape [33]. The following assumptions were made:

1. The lower parts of the pipe are undeformed.

2. The upper parts of the pipe consist of linear flaps (Figure D.106)

3. The perimeter length of the pipe is constant.

4. The distortion of the cross section upstream of the crack tip can be ignored.

5. The plan view of the rupturing pipe is linear.

The geometric model of pipe deformation and symbols used are shown in Figure D.106. The angle, \( \theta \), indicates the direction of the horizontal projection of the crack edges referred to the longitudinal axis of the pipe. The variables \( x, \delta, \) and \( \beta \) are related by

\[
\delta = x \tan \theta = R (\sin \beta - \beta \cos \beta)
\]  

(5.6)

Again referring to Figure D.106, it can be seen that the horizontal component of the velocity of points on the edge of the pipe flap \( (\omega = d = \beta R) \) is

\[
V_x = \frac{d\delta}{dt} = \frac{dx}{dt} \tan \theta + \frac{x}{\cos^2 \theta} \frac{d\theta}{dt}
\]  

(5.7)

\[
= V_t \tan \theta + \frac{x}{\cos^2 \theta} \frac{d\theta}{dt}
\]  

(5.8)

where \( V_t \) is the crack tip speed. The opening angle, \( \theta \), is in general, time dependent. However, on the basis of experimental observation (Figure D.65), \( \theta \) was taken to be constant.
The velocity of a generic point on the flaps is

\[ V_w = \frac{V_t \tan \theta \ w}{\sin \beta \ \beta R} \]  

(5.9)

where it is assumed that the velocity normal to the deforming pipe wall has a maximum value at the edge of the pipe wall flap, and varies linearly to zero at the point of tangency with the original pipe circumference. The deformed geometry of the rupturing pipe is effectively defined by two geometric parameters, \( \beta \) and \( \theta \). This geometric model cannot be used for a detailed evaluation of local actions at every point, but, can lead to a fairly realistic evaluation of the global effects of the surrounding water.

Axial depressurization: The following assumptions were made [22]:

1. The pressure decay profile downstream of the crack tip is linear with no circumferential variation.

\[ \frac{P}{P_t} = 1 - \frac{\beta}{\beta_0} \]  

(5.10)

In Equation (5.10), it has been implicitly assumed that \( \beta_0 \) is a constant. The assumed pressure decay profile is a good approximation of the pressure profiles measured in this study (Figures D.91 to D.100).

2. The crack tip pressure, \( P_t \), was estimated from the measured pressure histories shown in Figures D.91 to D.100. The arrival time of the crack tip at the pressure transducer was determined from the crack speed and the distance between the original rupture site and the transducer location.

Expressions for the first five terms in Equation (5.5) have been reported in the literature [22]. These expressions are quoted below for the sake of completeness. The energy terms are for a unit crack extension.
Strain energy: The strain energy released during an incremental crack extension is given by
\[ \Xi_e = \frac{\sigma_i^2}{2\varepsilon} \pi h R = \frac{\pi P_t^2 R^3}{2\varepsilon h} \]  
(5.11)
The pressure \( P_t \) was used in the above expression instead of the line pressure \( P_0 \) because the energy release associated with the reduction of the pipe pressure from \( P_0 \) to \( P_t \) goes into accelerating the pressurized fluid. Only the elastic energy due to the pressure \( P_t \) is available in the pipe wall near the crack tip to drive the pipe rupture process.

Potential energy: The driving force for crack propagation is the pressure acting on the pipe wall behind the crack tip. The potential energy can be determined from the pressure acting on an increment of flap area over a displacement path.
\[ \Xi_p = \int_0^\beta \int_0^d P w dw d\beta \]  
(5.12)
\[ = \frac{P_t R^3}{6} \left[ 1 - \frac{3\beta}{4\beta_0} \right] \]  
(5.13)

Axial stretching: This is the energy dissipation associated with the relatively large in-plane strains observed adjacent to the crack path upon approach of the crack tip. A perfectly plastic material of yield strength, \( \sigma_y \), is assumed.
\[ \Xi_a = \int_0^d h \sigma_y \varepsilon_{zw} dw \]  
(5.14)
\[ = \frac{\beta R h}{6} \sigma_y \tan^2 \theta \tan^2 \beta \]  
(5.15)

Fracture energy: If the fracture energy absorbed in the pipe material during crack extension is denoted by \( F \) per unit area, then
\[ \Xi_f = \frac{Fn}{2} \]  
(5.16)
Kinetic energy: As the crack advances, the kinetic energy imparted to the flaps behind the walls is given by

$$\Xi_k = \frac{1}{2} \rho_s h \int_0^d V_w^2 dw$$

$$= \frac{\beta R h}{6} \rho_s V_t^2 \frac{\tan^2 \theta}{\sin^2 \beta}$$

Energy imparted to surrounding water: The flap motion is modeled by a flat plate length $d$ moving with velocity $\tilde{V}$ through the water. The kinetic energy, $\Xi_w$, imparted to the water (per unit thickness) is given by [76,77]:

$$\Xi_w = \frac{1}{8} \rho_w \pi d^2 \tilde{V}^2$$

The plate velocity used is an averaged value obtained as follows

$$\tilde{V} = \sqrt{\frac{1}{d} \int_0^d V_w^2 dw} = \frac{V_t \tan \theta}{\sqrt{3} \sin \beta}$$

Substituting in Equation (5.19) produces

$$\Xi_w = \frac{\pi \beta^2 R^2}{24} \rho_w V_t^2 \frac{\tan^2 \theta}{\sin^2 \beta}$$

The equations derived above are used to evaluate the magnitudes of the various energy terms (e.g. For Run A(24)A: $\Xi_a = 81$ J/m, $\Xi_e = 3.1$ J/m, $\Xi_f = 20.1$ J/m, $\Xi_k = 230$ J/m and $\Xi_p = 311$ J/m). Input data for the energy terms are given in Tables C.2 and C.4.
CHAPTER 5. DISCUSSION

5.3.1 Energy balance

Evaluation of the energy terms (see previous page) in Equation (5.5) indicates that the magnitudes of the elastic strain energy release and the fracture energy are smaller than the other energy terms and so can be neglected. Thus Equation (5.5) reduces to Equation (5.22).

\[ \Xi_p = \Xi_a + \Xi_k + \Xi_w \]  

(5.22)

For the axial rupture of pipes in air, \( \Xi_w = 0 \). A separate discussion of underwater pipe rupture follows in Section 5.4. Estimates of the relative magnitudes of \( \Xi_p, \Xi_a, \) and \( \Xi_k \) for a selection of test runs are given in Table C.3. These test runs are selected to represent the different pressurizing/surrounding fluids used. The crack speeds and opening angles used are given in Tables C.2 and C.4.

The breach opening profile assumed in the preceding analysis is a poor approximation of the experimental cross section shape (Figures D.60 to D.62). Emery et al. [22] performed a comparable analysis using a hinged ring opening shape. The energy estimates obtained were not significantly different from those obtained in the present study. More elaborate models [36,37] which consider the deformed regions upstream and downstream of the crack tip as separate regions produce essentially the same energy partition. It would seem unlikely that any further refinement to the energy balance analysis would significantly improve the present model.

For parameters appropriate to this study and listed in Tables C.2 and C.4, estimates of the relative magnitudes of the various energy components \( \Xi_p, \Xi_a \) and \( \Xi_k \) involved in the pipe rupture process were estimated (Table C.3). From these results, the relative importance of each energy component can be inferred. The energy imparted to the pipe wall as kinetic energy is a major dissipation mechanism in pipe
rupture performed in air. The outward motion of the pipe wall flap induced by the kinetic energy is evident in the high speed photographs of the rupture development process (Figures D.63 to D.66).

The identification of axial stretching as an important component of the deformation field accompanying pipe rupture is supported by the large axial strains experimentally measured in the wake of the propagating crack. Axial strain in excess of the material yield strain was measured in all the experimental runs (Figures D.48 through D.57). Similar observations have been reported in the literature for the air-pressurized pipe rupture case [7,10]. Axial stretching of the pipe wall acts as a major source of energy dissipation and must be taken into account in the development of theoretical models of the axial rupture process. In the pipe rupture experiments of Ives et al. [7], the axial strains measured on the outside and inside surfaces of the pipe were almost identical. This indicates that the measured axial strain is primarily a record of the stretching of the pipe material near the crack lips rather than surface strain caused by bending deformation of the pipe wall.

The presence of large axial strains preceding the propagating crack tip and the alignment of the principal strain direction (axial direction) is shown by the brittle coat cracking patterns in Figures D.58 and D.59. The crack patterns thus provide qualitative confirmation of the strain magnitude and direction as well as the axial stretching model of pipe wall deformation.

The stress at the crack tip required for crack extension is a combination of the hoop stress imposed by the internal pipe pressure and the load transmitted to the crack tip by the displacement of the free edges of the breach. The detailed manner in which the crack tip propagation is coupled with the plastic deformation of the pipe walls away from the crack tip is however not well understood.
CHAPTER 5. DISCUSSION

5.3.2 Crack speed

Substitution of the expressions for $\varepsilon_p$, $\varepsilon_a$, $\varepsilon_k$ and $\varepsilon_w$ in Equation (5.22) produces a quadratic equation in terms of the crack tip speed, $V_t$. Thus, if experimental values for the geometric parameters, $\beta$, $\beta_0$ and $\theta$ are available, the crack tip speed can be obtained using the following expression.

$$V_t = \sqrt{\frac{P_t R^2 \beta^2}{6} \left[ 1 - \frac{3\beta}{4\beta_0} \right] - \frac{\beta R h \sigma_y \tan^2 \theta}{6 \sin^2 \beta}}$$

(5.23)

From the above expression, the general parameters of importance in obtaining the crack speed depend on the pipe geometry ($R, h$), the pipe material properties ($\sigma_y, \rho_s$), the internal pipe pressure ($P_t$), the breach area configuration ($\beta, \beta_0, \theta$) and the external environment ($\rho_w$). One drawback in using Equation (5.23) to determine the crack speed is the assumed rupture geometry. As previously indicated, the deformed pipe geometry assumed in the energy balance analysis is a poor approximation of the observed geometry (Figures D.60 to D.62) which means the geometric parameters cannot be determined very accurately.

The crack speed predictions obtained using Equation 5.23 agree with the experimental measurements obtained in the present study and those of Emery et al. [22] to within $\pm 5\%$. However comparison with other published data was not possible because of a lack of data on the material and breach opening area parameters.
5.4 Surrounding Water

If the outward motion of the pipe walls is due to the pressure acting on the flaps behind the crack tip; increased inertia of the flaps should result in limited pipe wall motion. Experiments were performed in air and water to investigate the add-on inertial mass effect of the surrounding water on pipe rupture. The crack speeds (see Table C.2), crack opening area (Figures D.79 to D.84) measured for the underwater case were found to be lower than for the air case. Similarly, the measured peak strains for the underwater case were lower than for the air case (Figures D.48 to D.54).

Comparisons of the internal depressurization transients (Figures D.35 through D.39) for the exposed and underwater pipe rupture cases agree to within ±4% for each of the pressurizing fluids used. This observation is in agreement with other experimental work on the effect of surrounding water on gas depressurization. In these experiments which involved a submerged expansion tube, the gas depressurization within the tube was found to be unaffected by the external water pressure until the decompressed pressure level in the pipe drops to the external pressure [43,46]. From the almost identical depressurization histories measured in the exposed and underwater pipe rupture tests performed in the present study, it can be inferred that minimal overpressure was attained in the surrounding water during the measurement time period. Overpressure in the water surrounding the pipe results from the release of high pressure fluid contained in the pipe. This means the different rupture characteristics observed in underwater pipe rupture is mainly an add-on inertial mass effect of the surrounding water on the pipe flaps. This explanation is supported by an energy balance analysis which was performed to determine the
relative importance of various energy dissipation mechanisms.

The energy balance equation for underwater pipe rupture is given by Equation (5.22). The detailed evaluation of these energy ($E_p$, $E_a$, and $E_k$) terms is outlined in Section 5.3. The contribution in this work was the evaluation of the energy imparted to the surrounding water. The energy imparted to the surrounding water was assumed to be the kinetic energy absorbed by the surrounding water due to the motion of a flat plate through the water. The evaluation of the relative energy magnitudes are set out in Table C.3. As evidenced in Table C.3, the energy imparted to the surrounding water causes a reduction in the proportion of energy available for pipe wall motion (kinetic energy). This would account for the reduced deformation and lower crack opening areas measured. It is quite possible that the magnitude of the energy imparted to the surrounding water has been overestimated through the various simplifying assumptions which have been made. However, the effect is so large that it can be concluded that the energy absorbed by the surrounding water must be taken into account in any theoretical model of the underwater pipe rupture process.

The analysis carried out so far is suitable for the shallow water conditions obtained in the present experimental work. For deeper water, an alternative mechanism for the excess energy dissipation during underwater pipe rupture is the reduction in the differential pressure acting on the pipe wall flaps due to the external hydrostatic pressure. This would reduce the driving force on the flaps. The hydrostatic head available in the present study (0.05 MPa) is negligible.
5.5 Initial Freon Temperature

The measured crack tip speeds, crack opening rates and axial strain for the Freon-pressurized tests show a dependence on the initial Freon temperature. The values of crack tip speeds given in Table C.2 show an increasing trend with increase in fluid temperature. Comparison of the breach opening rate for various Freon temperatures (Figures D.87 and D.88) demonstrates a similar dependence on fluid temperature. This temperature dependency can be rationalized by a flap pressure driving force for breach growth. The acoustic speed in Freon decreases with temperature as shown in Table C.1. This in conjunction with the crack speed dependency on Freon temperature (Table C.2) means an increased pressure decay length with increase in temperature. The increased pressure decay length results in an increased flap area over which the pipe pressure acts resulting in an increased crack driving force. This would account for the increase in breach opening area.

The transient pressure records for the Freon pressurized tests (Figures D.20 through D.27) exhibit several interesting features. These features are discussed in light of the extensive literature available on hot liquid depressurization. These features occur beyond $\tau = 20$ so have no effect on the short term pressure history which controls the pipe rupture process. The study of the short term pressure history is one of the main purposes of this study.

When pressurized hot Freon is suddenly released from high pressure, its pressure drops rapidly with time. This pressure drop is arrested near the saturation pressure corresponding to the initial Freon temperature (see Figures D.20 to D.27). The pressure dip below the saturation pressure is termed the undershoot and plays an important role in the development of the subsequent two phase flow. This is because
the pressure drop determines the magnitude of the liquid superheat available for nucleation and growth of vapor bubbles. The pressure undershoot behavior has been observed in other studies [48–50]. However, the depressurization rates achieved in the present study are much larger than that obtained by Lienhard et al. [50,54] who used a quick opening release mechanism\(^1\) to provide a guillotine type of failure (The maximum dimensionless depressurization rate, \(\Sigma\), equals 0.078 compared to \(\Sigma=0.247\) in this study). Following the pressure undershoot, the system pressure recovers to a level close to the saturation pressure. This increase in pressure is a result of the nucleation and growth of vapor bubbles. The ambient liquid cannot accommodate the volume increase due to bubble growth without an increase in pressure, mainly because of its low compressibility. The pressure recovery behavior after the undershoot is complicated by a superposed oscillatory behavior.

5.5.1 Pressure trace oscillation

The pressure traces measured at the two transducer locations for the Freon tests (Figures D.20–D.27) exhibit oscillatory behavior just after the initial pressure dip. This behavior was determined not to be apparatus generated since the oscillations were not present in the water and air pressurized tests. The latter tests had been made under identical conditions as the Freon tests. The presence of the oscillatory behavior at both pressure transducer locations indicates the phenomenon is not a result of wave reflection effects.

Two possible causes are considered here; one is a bubble growth-collapse mechanism and the other is a reflection effect at the phase change boundary. Similar

\(^1\)called POP the QORC (Pull Out the Plug in the Quick Opening Release Configuration) which the authors justifiably claim is the ultimate nuclear acronym.
pressure oscillations were observed by Höppner [49]. He photographed bubbles resulting from the depressurization of water at 0.5 MPa and 120 °C in a vertical glass tube. The oscillations in the pressure trace were correlated with the vapor bubble growth-collapse sequence observed in the high speed photographs and good agreement was found. As mentioned earlier bubble growth results in pressure increase, similarly bubble collapse results in pressure decrease which would explain the pressure oscillations.

When a hot liquid is depressurized, there is flashing of the liquid into vapor. Flashing occurs in the liquid immediate to the rupture area. Consequently, there is a phase discontinuity at the boundary between the flashing liquid and the single phase liquid with an attendant discontinuity in acoustic speed. Such changes in acoustic speed could produce complicated reflections and refractions of the acoustic waves at the boundary and may well result in an oscillatory pressure behavior. The evolution of different flow regimes in the pipe has been observed photographically in a blowdown test by Necmi and Hancox [52].
5.6 Pipe Rupture Mechanism

The rupture of a pressurized pipe is an extremely complex process, involving interaction between the rupturing pipe, the escaping fluid and the surrounding fluid, if any is present.

A simple pipe rupture mechanism is presented here to provide a framework for summarizing the results of this investigation. The mechanism is based on results of the present work as well as suggestions and insights provided by various authors [7,22,40].

Pipe rupture is initiated by the ductile fracture of the ligament at the bottom of the machined starter groove. The snap-through of the ligament generates two crack lips. The resulting crack then propagates axially along the pipe. The initial stage of breach growth is accompanied by limited pipe wall motion. This is due to the constraint effect of the pipe wall (the inertia of the separating pipe wall). Subsequently, the breach growth is dictated by the rate of plastic deformation of the flaps formed behind the propagating crack tip. The tensile straining of the free edges of the crack tip is caused by the pressure induced opening of the pipe flaps. Thus the residual fluid pressure and corresponding rapid acceleration of the flaps behind the crack tip provide the driving force for the pipe rupture process. The internal pressure acting on the pipe wall decays rapidly from the crack tip pressure to zero due to the fluid escape through the crack opening. The pressure just ahead of the crack tip depends on the crack tip velocity. The decay profile of the pressure has a significant effect on the resultant driving force. The stress at the crack tip required to extend the crack is provided by the load transmitted to the crack tip by the displacement of the flaps and the residual wall hoop stress.
CHAPTER 5. DISCUSSION

5.7 Comments on Previous Investigations

The split ring model proposed by Emery et al. [22,24] and described in Chapter 2, is at present the only published analytical model capable of predicting some of the opening characteristics of axial rupture in pressurized pipes. An earlier version of the model which neglected the axial stretching of the pipe wall overpredicted the crack speed. In a newer version of the model, the axial strain energy dissipation mode was incorporated by the partition of input energy on the basis of a separate energy balance analysis. Full details of the energy partition scheme were not available at this time since work on the split ring model of pipe rupture is ongoing.

Given a crack extension criterion, namely the opening shape of the breach, the split ring model in conjunction with the one-dimensional transient fluid flow code (UW-BURST), correctly predicted the crack speed and depressurization transients measured by Emery et al. [22].

The transient fluid flow code (UW-BURST) was used in the present study to predict the depressurization transients for the water and gas-pressurized experimental runs. Good agreement between the measured and predicted pressure transients was obtained (Figures D.103 and D.104).

The energy partition technique offers a means of modeling the presence of surrounding fluids and soil backfill. No predictive model has this capability at present. Energy balance analyses which include the effect of soil backfill has been proposed in the literature [36–38]. This study presents the treatment for the underwater pipe rupture case in Section 5.3. These analyses could be used in the split ring model (when completed) to provide a parametric analysis for the effect of different types of backfill.
Chapter 6

Summary and Conclusions

A series of experiments has been performed to measure the characteristics of axial pipe rupture in pressurized pipes. The test runs were performed with different pressurizing (water, Freon and air) and surrounding (water and air) fluids. In the Freon tests, the initial Freon temperature was varied over a range of 24 to 55 °C. Standard test pipes were used and pipe rupture was initiated by the pressurization to failure of the wall material at the bottom of a groove machined in the outer surface of the pipe wall. The test pipes were instrumented with fast response pressure transducers and single element strain gages oriented in the axial direction.

In order to gain some information on the physical processes associated with pipe rupture, the immediate rupture zone was observed using high speed photography. These photographs provided information on the crack tip speed and the rate and extent of breach opening. In the liquid-pressurized pipe rupture case, the breach area is soon obscured by the liquid jet produced resulting in limited experimental data. Additional information about the rupture process was obtained by measuring the strain field along the crack propagation path and by monitoring the internal fluid depressurization history in the breach zone.

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The experimental results indicate that the rupture characteristics of pressure history, crack speed and breach opening area depend on the type of pressurizing and external fluids used. For Freon-pressurized pipe rupture, a dependence of the breach opening characteristics on the initial Freon temperature was observed.

Under identical experimental conditions, tests performed underwater resulted in lower crack tip speeds (up to 26%) and crack opening areas (up to 33%) than the in-air case. The observed depressurization transients measured were almost identical except for a repressurization effect due to a reflected compression wave in the liquid-pressurized underwater case. The reflected wave was a result of the spatial limitation of the containment vessel. The crack speeds and opening areas measured in the gas pressurized tests were much larger (order of magnitude) than for the liquid-pressurized case. The pressure decay profiles measured for all pressurizing fluids were found to collapse to a single curve when dimensionless time and pressure variables were used. However, because of the difference in acoustic speeds, the pressure decay length in the gas case was much longer than in the liquid case.

Test runs were carried out for different initial Freon temperatures. The data obtained show several common features; when hot Freon is suddenly released from high pressure, its pressure drops very rapidly with time and dips below the saturation pressure. This is followed by pressure oscillations about the saturation pressure (The oscillations occur after the short term pressure response which was of primary interest in this study). The breach opening area and crack speed show an increasing trend with increase in initial Freon temperature.
The objective of this study was to determine the effect of different types of pressurizing and surrounding fluids on the physical processes associated with pipe rupture in order to gain insight into the mechanism responsible for the axial rupture of pressurized pipes. The following conclusions can be made based on the results of the investigation.

1. The pipe rupture facility constructed for the experimental work provides a convenient, safe and repeatable means of studying axial pipe rupture. The apparatus is particularly well suited to the investigation of the effect of various pressurizing and surrounding fluid combinations.

2. High speed photography provided the most useful experimental technique for observing the development of an axial breach in the present study. Information on the crack tip propagation and breach opening rate are obtained. For liquid pressurized pipes, however, the breach area is soon obscured by the exiting liquid jet resulting in limited experimental data.

3. For the pipe wall material and defect geometry used in this investigation, the opening characteristics (crack tip speed, breach opening rate and extent and pipe wall deformation) of pipe rupture are determined by the type of pressure medium used and on whether the rupturing pipe is surrounded by a liquid or a gas. The presence of a surrounding water results in smaller opening areas (up to 33%) and lower crack tip speeds (up to 26%) compared to the exposed case. This is due to the add-on mass effect of the surrounding water. The energy imparted to the surrounding fluid reduces the energy available for breach growth.

4. The pressure acting on the pipe flaps formed behind the propagating crack tip
appears to be the driving force for the axial rupture of pressurized pipes. An energy balance analysis proved useful in determining and assessing the relative importance of the major energy dissipation modes. The energy provided by the fluid pressure acting on the pipe wall flaps is partitioned among the following processes:

- Kinetic energy imparted to the pipe walls.
- Plastic straining of the pipe walls.
- Energy imparted to the surrounding water (important only in underwater pipe rupture).

The magnitude of the driving force depends on the pressure acting on the flaps and the pressure decay length (an estimate of the area over which the pipe pressure acts).

The pressure-induced opening results in large scale axial straining of the free edges of the pipe wall. The development of the breach is in turn dependent on the pressure decay profile. Thus, the effect of surrounding water is to augment the inertial mass to be accelerated by the pressure acting on the flaps leading to reduced pipe deformation.

5. The depressurization transients for the different pressurizing fluids collapse to a single curve indicating an essentially universal relationship for the dimensionless pressure downstream of a crack tip propagating at constant speed. The pressure decay profile is also independent of the magnitude of the initial pipe pressure. The pressure decay length is thus an important length scale of the depressurization process. The magnitude of the decay length depends on
CHAPTER 6. SUMMARY AND CONCLUSIONS

the acoustic speed in the pressurizing fluid.

6. A one-dimensional transient fluid code (UW-BURST) for fluid depressurization during axial pipe rupture successfully predicts the depressurization history for both air-pressurized and water-pressurized pipe rupture. The code requires experimental data inputs.

Some Thoughts on Further Work

The present study indicates the need for further investigation of the axial rupture of pressurized pipes. A few suggested areas of further research and some recommendations follow.

1. More detailed experimental information to elucidate the deformation processes which occur during axial pipe rupture is required to guide future development of theoretical models. In this connection, the use of a high frequency stroboscopic flash and much higher camera framing rates would provide more detailed visual data. This data should be analyzed using an optical reader or image analysis software to provide more precise information on the breach opening development. Extensive strain gaging in the vicinity of the crack propagation path is also required to delineate the extent of the plastic deformation zone.

2. It would be desirable to establish scaling laws such that breach opening characteristics in practical applications (for example, pipelines) could be reproduced in smaller diameter pipes. This would provide savings in cost of materials and labor. A primary step in this direction would be the determination of general
criteria for crack advance.

3. A complete analysis of the axial rupture of pressurized pipes would involve the derivation of the equations governing pipe wall deformation, fluid depressurization and the motion of the surrounding fluid. This formulation would account for the interaction between fluid depressurization, pipe wall deformation and the surrounding water. A numerical solution of the governing equations would be required. The need to time step the solution in order to obtain the evolution of the system requires massive amounts of computational resources. However recent advances in the processing capability of digital computers make the above solution scheme possible. This approach would allow the inclusion of normally neglected effects such as the strain rate sensitivity of pipe wall material properties. This numerical approach is made necessary since improvements in analytical models, such as the energy balance analysis, result in increased computational difficulties without producing better solutions.
References


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**Appendix A**

**Fluid Depressurization Models**

**Basic Equations**

Specification of a problem in fluid dynamics requires a statement of the laws of conservation of mass, momentum and energy. Supplementary information describing the state property behavior of the fluid and a set of initial and boundary conditions are also required. In the most general form, the conservation laws can be stated in vector tensor notation\(^1\) [78].

Conservation of mass

\[
\frac{\partial \rho}{\partial t} = - (\nabla \cdot \rho u) \tag{A.1}
\]

Conservation of momentum

\[
\frac{\partial \rho u}{\partial t} = - [\nabla \cdot \rho uu] - \nabla P - [\nabla \cdot \mathbf{T}] + \rho g \tag{A.2}
\]

---

\(^1\)In this appendix, light face italic symbols are used for scalars, boldface symbols for vectors and boldface Greek symbols for tensors. In addition, dot product operators enclosed in ( ) are scalars and operations enclosed in [ ] are vectors.
Conservation of energy

\[
\frac{\partial}{\partial t} \rho (\hat{U} + \frac{1}{2} u^2) = - (\nabla \cdot \rho \dot{u} (\hat{U} + \frac{1}{2} u^2)) - (\nabla \cdot q) + \rho (u \cdot g) \\
- (\nabla \cdot P u) - (\nabla \cdot [\mathbf{T} \cdot u])
\]  

(A.3)

These equations were derived by applying conservation principles to stationary differential element through which a fluid is flowing.

For a single phase of a pure substance, only two thermodynamic properties are needed to define its thermodynamic state. All other properties can be defined as functions of two others. This function is called the equation of state and can be expressed mathematically with generalized variables \( \xi_i \):

\[
\xi_3 = f(\xi_1, \xi_2)
\]  

(A.4)

The variables \( q \), and \( \mathbf{T} \) in Equations (A.2) and (A.3) can be expressed as functions of velocity and temperature (or \( \hat{U} \) fields, using stress-strain (e.g. Newton's Law) and heat flow (e.g. Fourier's Law) relations. The Equations (A.1) to (A.4) and a set of side conditions uniquely define the following variables:

\( \rho(r,t), \ P(r,t), \ u(r,t) \) and \( \hat{U}(r,t) \)

**BURST code [26]**

In order to solve the set of equations, appropriate simplifying assumptions have to be made. If an average flow can be defined, the system of equations (A.1) to (A.4) can be applied in one-dimensional form. Meyer [25] proposed various one-dimensional models for the treatment of transient fluid flow. The sectionalized
compressible model is the most rigorous of these and was used by Rose et al. [26] in the development of the BURST (Blowdown Under Rapid Sonic Transient) code. The model is based on a direct numerical solution to multiple point (or sectionalized) difference equation approximations to the conservation laws. The following one dimensional conservation equations are the starting point of the sectionalized compressible model:

Conservation of mass

\[ A \frac{\partial p}{\partial t} + \frac{\partial}{\partial z}(GA) = 0 \quad (A.5) \]

Conservation of momentum

\[ A \frac{\partial G}{\partial t} + \frac{\partial}{\partial z} \left( \frac{G^2 A}{\rho} \right) = -A \frac{\partial P}{\partial z} - \frac{A(f/\rho)|G|G}{2D_h} - A \rho g \quad (A.6) \]

Conservation of energy

\[ A \frac{\partial}{\partial t}(\rho H) + \frac{\partial}{\partial z}(GHA) = \frac{A^q}{l} + AQ + A \frac{\partial P}{\partial t} - \frac{A}{2} \frac{\partial}{\partial t} \left( \frac{G^2}{\rho} \right) - \frac{\partial}{\partial z} \left( \frac{AG^3}{2\rho^2} \right) - AGg \quad (A.7) \]

In order to make the system of equations (A.5) to (A.7) explicit in the variables \( G, P, \) and \( H, \) the density was expressed as a function of enthalpy and pressure \([\rho = \rho(H, P)].\)

The time derivative of density was then expressed as follows.

\[ \frac{\partial \rho}{\partial t} = \left( \frac{\partial \rho}{\partial H} \right)_P \frac{\partial H}{\partial t} + \left( \frac{\partial \rho}{\partial P} \right)_H \frac{\partial P}{\partial t} \]

\[ = R_H \frac{\partial H}{\partial t} + R_P \frac{\partial \rho}{\partial t} \quad (A.8) \]
where the partial derivatives of density can be defined as

\[ R_H = \left( \frac{\partial \rho}{\partial H} \right)_P \quad R_P = \left( \frac{\partial \rho}{\partial P} \right)_H \]  

Equation (A.8) was then introduced into Equation (A.5). To relate the above expressions to the acoustic speed, \( a \), in the fluid, the specific volume \( v \) was considered as a function of enthalpy and pressure \( v = v(H, P) \).

The total differential of \( v \) was then expressed as follows:

\[ dv = \left( \frac{\partial v}{\partial H} \right)_P dH + \left( \frac{\partial v}{\partial P} \right)_H dP \]  

The change in \( v \) was constrained to apply to only isentropic conditions (ie. \( ds = 0 \)).

From the first law of thermodynamics \( (Tds = dU + Pdv) \) and the definition of enthalpy \( (H = U + Pv) \),

\[ dH = Tds + Pdv \]  

Hence for \( ds = 0 \)

\[ dH = vdP \]  

substituting Equations (A.12) to (A.10)

\[ (dv)_s = \left( \frac{\partial v}{\partial H} \right)_P vdP + \left( \frac{\partial v}{\partial P} \right)_H dP \]  

or in more familiar notation

\[ \left( \frac{\partial v}{\partial P} \right)_s = v \left( \frac{\partial v}{\partial H} \right)_P + \left( \frac{\partial v}{\partial P} \right)_H \]
The desired expression for $a$ can then be written as

$$a^2 = \left( \frac{\partial P}{\partial \rho} \right)_s - v^2 \left( \frac{\partial P}{\partial v} \right)_s = \frac{-v^2}{v \left( \frac{\partial v}{\partial H} \right)_P + \left( \frac{\partial v}{\partial P} \right)_H}$$  \hspace{1cm} (A.15)

$$= \frac{\rho}{\left( \frac{\partial P}{\partial H} \right)_P + \rho \left( \frac{\partial P}{\partial P} \right)_H} = \frac{\rho}{R_H + \rho R_P}$$  \hspace{1cm} (A.16)

Hence, the propagation of density (pressure) perturbations was assumed to occur isentropically, but the fluid was otherwise permitted in the model to undergo entropy changes as implied in the heat addition and friction terms. The authors then eliminated density-time changes from Equations (A.5) to (A.7) and after some manipulation produced three differential equations explicit in $G$, $P$ and $H$.

$$-\frac{\partial G}{\partial t} = \frac{\partial}{\partial z} \left( \frac{G^2}{\rho} \right) + \frac{\partial P}{\partial z} + \frac{f|G|G}{2\rho D_h} + \frac{1}{A} \frac{G^2}{\rho} \frac{\partial A}{\partial z} + \rho g$$  \hspace{1cm} (A.17)

$$-\frac{\partial P}{\partial t} = \frac{a^2}{\rho} \left\{ R_H \left[ \frac{G \partial P}{\rho \partial z} - \frac{G \partial H}{\partial z} \right] + \frac{q}{l} + Q + \frac{f|G|G^2}{2\rho^2 D_h} - \frac{\partial G}{\partial z} + \frac{G \partial A}{A \partial z} \right\}$$  \hspace{1cm} (A.18)

$$-\frac{\partial H}{\partial t} = -\frac{a^2}{\rho} \left\{ R_P \left[ \frac{G \partial P}{\rho \partial z} - \frac{G \partial H}{\partial z} \right] + \frac{q}{l} + Q + \frac{f|G|G^2}{2\rho^2 D_h} - \frac{\partial G}{\partial z} - \frac{G \partial A}{A \partial z} \right\}$$  \hspace{1cm} (A.19)

where $a$ is given by Equation (A.16).

For blowdown of pressurized liquid from a pipe, the following side conditions were given for a region $0 < z < L$:

$A(z)$, $P(t, L)$, $G(t, 0)$, $P(0, z)$, $G(0, z)$ and $H(0, z)$

The quantities $\rho$, $a$, $R_P$ and $R_H$ were treated as state equations with quite general dependence on the spatial coordinate, pressure and enthalpy. Constant average values of $R_P$ and $R_H$ were used for the blowdown of high pressure water; the actual variation of $R_H$ and $R_P$ during blowdown transient with water at ambient temperature was determined to be less than 10%. The variation of water density with
pressure was obtained using Equation (A.20).

\[ \rho(P, H) = \rho_0 + R_P(P - P_0) + R_H(H - H_0) \]  \hspace{1cm} (A.20)

The quantities with subscript zero are initial conditions of the system. The partial differential equations for the unknowns \( G(t, z) \), \( P(t, z) \) and \( H(t, z) \) were written in a difference form and solved numerically for subcooled decompression problems. The predicted pressure histories obtained for the blowdown of pressurized water using the BURST code were found to agree fairly well with experimental data [26].

**UW-BURST [23]**

The BURST code is limited to fixed geometries or spatially varying geometries. Depressurization in a rupturing pipe must consider in addition the effects of leakage from the crack as well the dilation of the cross sectional flow area downstream of the crack tip. Emery et al. [23] have modified the analysis by Rose to handle these effects. The channel flow equations are similar to conservation laws presented earlier except for the wall leakage and flow area change terms.

Conservation of mass

\[ A \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z} (GA) = -G_iW - \rho \frac{\partial A}{\partial t} \]  \hspace{1cm} (A.21)

where the terms on the right hand side represent leakage flow and the effect of flow area change due to the opening of the pipe behind the crack tip.

Conservation of momentum

\[ A \frac{\partial G}{\partial t} + \frac{\partial}{\partial z} \left( \frac{G^2A}{\rho} \right) = -G_iW u - \frac{G^2}{\rho} \frac{\partial A}{\partial z} - A \frac{\partial P}{\partial z} - \frac{A(f/\rho)|G|G}{2D_h} - A\rho g \]  \hspace{1cm} (A.22)
APPENDIX A. FLUID DEPRESSURIZATION MODELS

The expression for momentum is unchanged by the effect or rate of flow area change but includes the axial momentum of the leakage flow where

\[ u = \begin{cases} \frac{G}{\rho} & \text{for } G_i \geq 0 \\ 0 & \text{for } G_i < 0 \end{cases} \]

Conservation of energy

\[ A\frac{\partial}{\partial t}(\rho H) + \frac{\partial}{\partial z}(GHA) + \left( e + \frac{P}{\rho} \right) G_i W = A\frac{q}{l} + A Q + A\frac{\partial p}{\partial t} - A\frac{\partial}{\partial t}\left( \frac{G^2}{\rho} \right) - \frac{\partial}{\partial z}\left( \frac{AG^3}{2\rho^2} \right) - AG\rho \quad (A.23) \]

where \( e \equiv H - P/\rho + u^2/2 \) is the intrinsic energy of the flow. Using the same treatment as Rose et al. [26], the conservation equations were reduced to equations explicit in \( G, P \) and \( H \).

\[ -\frac{\partial G}{\partial t} = \frac{\partial}{\partial z}\left( \frac{G^2}{\rho} \right) + \frac{\partial P}{\partial z} + \frac{f|G|G}{2\rho D_h} + \frac{G_i W}{A} + \frac{1}{A} \frac{G^2 \partial A}{\rho \partial z} + \rho g \quad (A.24) \]

\[ -\frac{\partial P}{\partial t} = -\frac{a^2}{\rho} \left\{ R_H \left[ \frac{G \partial P}{\rho \partial z} - G \frac{\partial H}{\partial z} \right] + \frac{q}{l} + Q + \frac{f|G|^2}{2\rho^2 D_h} + \frac{\partial G}{\partial z} + \frac{G \partial A}{A \partial z} \right\} + \left[ a^2 + \frac{a^2 R_H}{\rho} \right] \frac{P}{\rho} \frac{\partial A}{\rho} \frac{\partial A}{\partial t} \quad (A.25) \]

\[ -\frac{\partial H}{\partial t} = \frac{a^2}{\rho} \left\{ R_P \left[ \frac{G \partial P}{\rho \partial z} - G \frac{\partial H}{\partial z} \right] + \frac{q}{l} + Q + \frac{f|G|^2}{2\rho^2 D_h} - \frac{\partial G}{\partial z} - \frac{G \partial A}{A \partial z} \right\} + \frac{a^2}{\rho} - \frac{a^2 R_P}{\rho} \left[ \frac{H - \frac{G^2}{2\rho^2} - \frac{G u}{\rho}}{A} \right] \frac{G_i W}{A} + \left[ \frac{a^2}{\rho} + \frac{a^2 R_H}{\rho} \frac{P}{\rho} \right] \frac{\rho \partial A}{A \partial t} \quad (A.26) \]

where \( e' \equiv H + G^2/2\rho^2 \).

The important coupling between the structural response of the rupturing pipe and fluid depressurization are manifested in the leakage term \( G_i \), the rate of cross sectional area change \( \partial A/\partial t \) and to a lesser extent by the spatial area change \( \partial A/\partial z \).

If the preceding equations are used with a gas of specific heat ratio \( \gamma \), the state property terms may be identified as;
APPENDIX A. FLUID DEPRESSURIZATION MODELS

\[ a^2 = (\gamma - 1)H, \quad \frac{a^2 R_H}{\rho} = - (\gamma - 1) \quad \text{and} \quad a^2 R_P = \gamma \]

The system of equations (A.24) to (A.26) were solved by expressing the equations in terms of finite differences on a mesh where the pressure and enthalpy nodes \( P_j \) and \( H_j \) were located midway between the mass flow nodes \( G_j \) in order to ensure the conservation of the physical variables. Since the fluid depressurization can be considered as adiabatic, the values of the surface heat flux \( q \) and the volumetric heat generation \( Q \) in Equations (A.24) to (A.26) are zero.

Because the advection terms of fluid through the control volumes, the finite difference algorithm is sensitive to the particular differencing form used and manifests considerable phase shift and dissipation unless special care is taken. Although upwind differencing damps the solution, the errors are not likely to exceed those associated with the one-dimensional treatment of the flow.

The spatial derivatives were represented by;

\[
\frac{\partial f}{\partial z} = \frac{f(i+1) - f(i-1)}{2\Delta z}
\]  

(A.27)

where \( f \) is \( H, P, A \).

The terms in \( G \) are given in upwind differencing form.

\[
\frac{\partial G}{\partial z} = \begin{cases} 
\frac{G(i) - G(i-1)}{\Delta z} & G(i), G(i - 1) \geq 0 \\
\frac{G(i+1) - G(i)}{\Delta z} & G(i + 1), G(i) \leq 0 \\
\frac{G(i+1) - G(i-1)}{\Delta z} & G(i + 1) < 0, G(i + 1) > 0 \\
0 & \text{otherwise}
\end{cases}
\]

These special difference forms preserve the correct advection nature and assure the conservation of mass and momentum.
The time derivative is given by:

\[ \frac{\partial f}{\partial t} = \frac{f(t + \Delta t) - f(t)}{\Delta t} = \eta(\rho, H, G, e', z, t) \]  

where the right hand side of Equations (A.24) to (A.26) is represented schematically by a function of which \( \eta \) which is evaluated at the present time \( t \).

To ensure numerical stability of the explicit finite difference equation, a program time-step size of the order of the time for a pressure wave to traverse the mesh point at the maximum wave speed in the system was used.

\[ \Delta t \leq \frac{\Delta z}{(\rho + a)} \]  

The experimental inputs required for the code are the crack tip speed and the crack opening shape. Satisfactory agreement between the predictions of the code and experimental data for gas-pressurized pipe rupture has been reported (Figure D.6). The numerical computation was performed without including the area-time rate of change terms which had been found to be negligible. The UW-BURST code was used to predict the depressurization transients for water and air-pressurized pipe rupture cases in the present study. Only minor modifications were made to the source code.
Appendix B

Error Analysis

The following sections describe the evaluation of experimental error in reduced data such as crack tip speed, crack lip speed and internal pressure.

Rupture pressure

Statistical methods can be used to define the experimental error tolerances when several repetitions of an experiment give a range of values of data. Replication of individual observations allow the mean and standard deviation to be calculated for the data and confidence limits established. The sample mean and standard deviation of that mean are given by the following equations [79]:

\[
\bar{X} = \frac{1}{N} \sum_{i=1}^{N} X_i \quad \text{(B.1)}
\]

\[
sd = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (X_i - \bar{X})^2} \quad \text{(B.2)}
\]
If the data form a random sequence, a Gaussian or normal error distribution can be assumed. For a perfect Gaussian distribution, 68% of the readings lie within ±1sd of \( \bar{X} \) and 95% of the readings lie within ±2sd of \( \bar{X} \). Since the pipe rupture tests were performed using a standard test pipe, the measured rupture pressures can be treated as a random sequence and the above analysis applied. The pipe rupture pressure quoted in Chapter 4 give the mean value ± two standard deviations.

**Uncertainty analysis**

In experimental work, the measurements from several different instruments are used to compute certain quantities. If the uncertainty of each instrument is known, the overall uncertainty in the computed result can be estimated. The following analysis provides relative weighting for individual errors. For a dependent variable, \( Y \), related to some independent variables, \( m_1, m_2, \ldots, m_n \) by the function

\[
Y = f(m_1, m_2, \ldots, m_n)
\]  

the uncertainty in the result is

\[
\epsilon_Y = \sqrt{\left( \epsilon_{m_1} \frac{\partial f}{\partial m_1} \right)^2 + \cdots + \left( \epsilon_{m_n} \frac{\partial f}{\partial m_n} \right)^2}
\]

where \( \epsilon_{m_1}, \epsilon_{m_2}, \ldots, \epsilon_{m_n} \) are the uncertainties or probable errors of the variables \( m_1, m_2, \ldots, m_n \) respectively. Use of Equation (B.4) requires the uncertainty of each independent variable. These uncertainties are usually determined from the precision of the instruments used, but more often from the experience of the experimenter.

The procedure outlined above was applied to other measured variables and the results are compiled in Table B.1.
Table B.1 Measurement uncertainties

<table>
<thead>
<tr>
<th>Measured quantity</th>
<th>Uncertainty estimate</th>
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<td>$P/P_0$</td>
<td>±1.5%</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>±1.9%</td>
</tr>
<tr>
<td>$\Sigma$</td>
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</tr>
<tr>
<td>$V_i$</td>
<td>±2.5%</td>
</tr>
<tr>
<td>$V_i$</td>
<td>±3.1%</td>
</tr>
<tr>
<td>$\alpha/A$</td>
<td>±4.9%</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>±3.5%</td>
</tr>
</tbody>
</table>
# Table C.1 Test matrix and calculated results

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<tr>
<th>Run Number</th>
<th>Initial Pressure (MPa)</th>
<th>Rarefaction wave speed (m/s)</th>
<th>Dimensionless depressurization rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Sigma_{PT-1}$</td>
</tr>
<tr>
<td>W(24)A</td>
<td>8.59</td>
<td>1303</td>
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</tr>
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<td>1414</td>
<td>0.171</td>
</tr>
<tr>
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<td>8.53</td>
<td>1427</td>
<td>0.160</td>
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<td>1338</td>
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<td>0.151</td>
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Table C.2 Results from photographic data

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<tr>
<th>Run Number</th>
<th>Crack tip speed (m/s)</th>
<th>Crack lip speed (m/s)</th>
<th>Opening Area (α/A)</th>
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<td>50.8</td>
<td>5.1</td>
<td>0.33</td>
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<td>0.53</td>
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Table C.3 Relative magnitudes of energy terms

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<td>F(35)A</td>
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<td>0.15</td>
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<td>0.17</td>
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<td>F(45)W</td>
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<td>-</td>
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<td>0.65</td>
<td>0.10</td>
<td>0.25</td>
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<tr>
<td>A(24)A</td>
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<td>0.74</td>
<td>-</td>
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<tr>
<td>A(24)W</td>
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Table C.4 Input data for energy terms

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<th>$P_t$ (MPa)</th>
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<td>A(24)W</td>
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<td>8°</td>
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<table>
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<th>$h$ (mm)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\rho_s$ (kg/m$^3$)</th>
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<table>
<thead>
<tr>
<th>$F$ (kJ/m$^2$)</th>
<th>$\varepsilon$ (GPa)</th>
<th>$\rho_w$ (kg/m$^3$)</th>
<th>$n$ (mm)</th>
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<tbody>
<tr>
<td>225</td>
<td>200</td>
<td>1000</td>
<td>0.18</td>
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LEGEND:

A  Accumulator          R  Pressure regulator
B  Bridge amplifier     S  Regulated power supply
C  Charge amplifier     T  Trigger circuit
M  Microcomputer        U  On/Off switch for pump
O  Oscilloscope         V  Manual control for solenoid valve
P  Pressure gage        Z  Pressurizer

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