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LOFT MEASUREMENT REQUIREMENTS DOCUMENT

JOHN D. BURTT

July 1978

EG&G Idaho, Inc.

ENERGY SAFETY ENVIRONMENT

IDAHO NATIONAL ENGINEERING LABORATORY

DEPARTMENT OF ENERGY

IDAHO OPERATIONS OFFICE UNDER CONTRACT EY-76-C-07-1570

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NUREG/CR-0246

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July 1978

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Operated by
EG&G Idaho, Inc.
for the
Department of Energy

Prepared for the
U.S. Nuclear Regulatory Commission
and
Department of Energy
Idaho Operations Office
Under Contract No. EY-76-C-07-1570

ABSTRACT

The LOFT Measurement Requirements Document (MRD) establishes measurement criteria for the experimental measurements desired in the Loss-of-Fluid Test (LOFT) facility. The MRD specifies (a) the measurements necessary to attain the objectives of the LOFT Integral Test Program and (b) the range, accuracy, response, and priority requirements for the experimental measurements to insure that all LOFT experiment transients can be followed by the instrumentation.

SUMMARY

Specific measurement criteria are required to fulfill the objectives of the Loss-of-Fluid Test (LOFT) Integral Test Program with emphasis placed upon those measurements required for verification of large pressurized water reactor safety related computer codes. Range requirements are determined by examination of maximum and minimum values of a given parameter. Accuracies are established to represent the cumulative allowable error of all measurement system components. Response criteria are calculated in one of several ways to insure all transients will be followed. Priorities are assigned to indicate the relative importance of each measurement to the LOFT Program.

The basis for the measurement criteria is a RELAP4/MOD5 computer code analysis of LOFT nuclear Test L2-4, considered to be the "worst-case" transient of the L2 test series due to the high power level (52.5 kW/m). Using the LOFT facility RELAP4/MOD5 model, developed for LOFT experiment prediction calculations, parameter plots for temperature, pressure, velocity, and density are obtained. The study of these parametric transients results in the establishment of measurement criteria for each LOFT system. The five major systems are the reactor, primary coolant, secondary coolant, emergency core coolant, and blowdown suppression tank systems. The measurement criteria are summarized by system in tabular form.

ACRONYMS

BST	Blowdown Suppression Tank
DNB	Departure from Nucleate Boiling
ECC	Emergency Core Coolant
ECCS	Emergency Core Cooling System
EOS	Experiment Operating Specification
ESF	Engineered Safety Features
FCF	Facility Change Form
HPIS	High-Pressure Injection System
LPIS	Low-Pressure Injection System
LOCA	Loss-of-Coolant Accident
LOCE	Loss-of-Coolant Experiment
LOFT	Loss-of-Fluid Test
LPWR	Large Pressurized Water Reactor
MRD	Measurement Requirements Document
NPSH	Net Positive Suction Head
PCS	Primary Coolant System
PCT	Peak Cladding Temperature
RD	Reading
RELAP	Transient Thermal-Hydraulic Computer Code
SCS	Secondary Coolant System

CONTENTS

FIGURES

TABLES

LOFT MEASUREMENT REQUIREMENTS DOCUMENT

I. INTRODUCTION

The Loss-of-Fluid Test (LOFT) facility is comprised of components and component simulators designed to represent the behavior of an entire large pressurized water reactor (LPWR) during a postulated loss-of-coolant accident (LOCA). The LOFT Program is expected to contribute significantly to the general understanding of LOCA behavior in LPWRs through carefully controlled loss-of-coolant experiments (LOCE). The LOFT Program is part of the Water Reactor Safety Research Program sponsored by the Nuclear Regulatory Commission and is administered by the Department of Energy. The LOFT facility is operated by EG&G Idaho, Inc., at the Idaho National Engineering Laboratory (INEL).

The LOFT system is a nuclear facility designed to provide LOCE data for the study of:

(1) The interaction between core thermal response and blowdown

(2) The interaction between blowdown and emergency core cooling

(3) The interaction between core thermal response and the delivery of emergency core coolant (ECC)

(4) The ECC performance in regions of fuel damage.

LOFT will provide data on LPWR systems effects, heat sources, and fluid envelopes that are different from those of other experiments used as data sources in component model development. As a consequence, it is imperative that LOFT measurements provide for the acquisition of experimental data that are representative of the interactive events and processes that occur during the LOFT LOCEs. Moreover, these data must be of the form and quality that will allow their use in component analytical model evaluation to provide positive identification of the source of any observed deviation from predicted behavior.

1. LOFT FACILITY DESCRIPTION

The LOFT facility is a 55 MW(t) pressurized water reactor intended to simulate the major behavioral aspects of generic 1000 MW(e) LPWRs in a carefully conducted LOCE. The current nuclear core is approximately 5.5 ft (168 cm) long and 2 ft (61 cm) in diameter and contains 1300 fuel rods and four control assemblies of typical LPWR design. The primary coolant system is designed with a similar primary system volume-to-core power ratio as exists in typical LPWRs. Primary system subvolumes, for example, inlet plenum, core region, outlet plenum, outlet piping, steam generator, and inlet piping, also are designed with relative volumes similar to LPWRs. The unbroken LPWR reactor coolant pump loops (three) are simulated by the single unbroken circulating (intact) loop in the LOFT primary system, and the postulated broken LPWR Loop is simulated by the LOFT blowdown (broken) loop (see Figure 1).

The LOFT broken loop is orificed to simulate various break sizes and contains steam generator and pump simulators to model the effects of these components in the broken LPWR loop. The capability exists to simulate either hot leg (reactor vessel outlet piping) or cold leg (reactor vessel inlet piping) breaks by relocating the steam generator and pump simulators. Quick-opening valves (with opening times adjustable from approximately 10 to 50 ms) simulate the initiation of primary coolant piping ruptures.

During the LOCEs, primary coolant blowdown effluent is collected in a blowdown suppression tank which can model the significant portions of the various LPWR containment back pressure transients. The capability also exists to blowdown directly to the containment, if program requirements so dictate. Pressure reduction and decontamination spray systems are included in the containment to simulate similar systems in a LPWR containment.

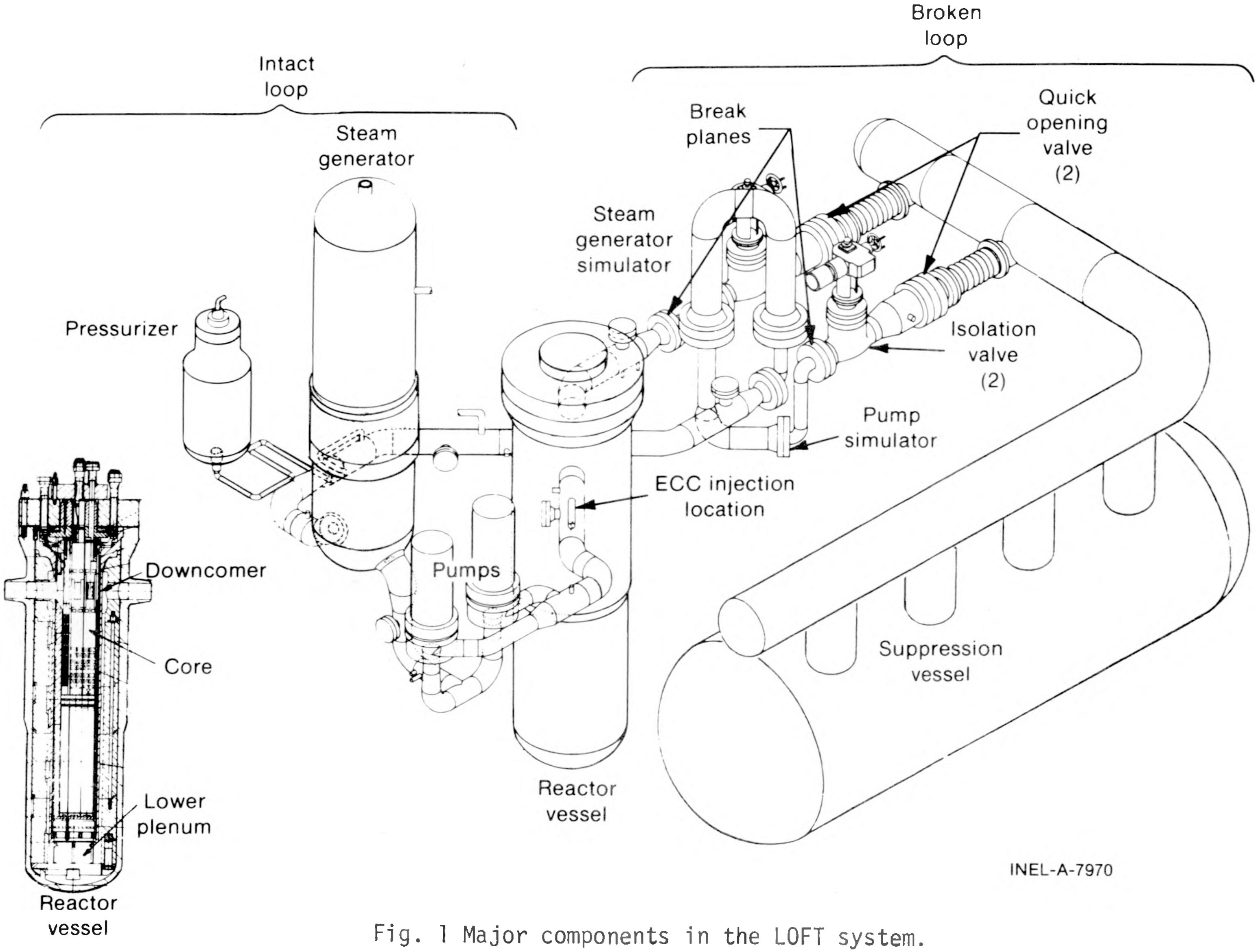


Fig. 1 Major components in the LOFT system.

Emergency core cooling systems (ECCS) are provided to model the loss-of-coolant engineered safety features (ESF) in LPWRs. The ECC is supplied by either of two high-pressure injection system (HPIS) positive displacement pumps, either of two low-pressure injection system (LPIS) centrifugal pumps, and by either of two nitrogen driven accumulators. Each HPIS pump has a capacity which can be preset between 2.7 and 27 gpm (0.17 and 1.7 l/s) at up to 2500 psig (17.2 MPa) discharge pressure. Each LPIS pump has a capacity of up to 300 gpm (18.9 l/s) at a 325 ft (99 m) head, and each accumulator injects approximately 60.8 ft^3 (1.72 m^3) of coolant and 34.2 ft^3 (0.97 m^3) of pressurizing nitrogen presentable at pressures from 0 to 1000 psig (0 to 6.9 MPa). LPIS and accumulator discharge lines are orificed as required to simulate various LPWR emergency coolant injection systems. The accumulators are equipped with an adjustable height "standpipe" which allows the effective accumulator volume to be varied.

During power operation, the heat is transferred from the primary coolant system to the secondary side of a vertical, U-tube steam generator. Steam generated at approximately 920 to 1020 psig (6.3 to 7.0 MPa) is fed to an air-cooled condenser and is condensed at approximately 300 psia (2 MPa). A condensate subcooler further reduces condensate temperature by 10°F (260 K) to provide sufficient feedwater pump net positive suction head (NPSH), and feedwater is returned to the steam generator at a nominal temperature of 407°F (480 K). A modulating steam flow control valve is provided to maintain steam generator pressure between 920 and 1020 psia (6.3 and 7.0 MPa) following a reactor trip, as long as the primary coolant temperature is at or above the saturation temperature corresponding to 920 psia (6.3 MPa). Fluid pressure, temperature, velocity, and density are monitored by extensive instrumentation at key points in the primary coolant, emergency core coolant, blowdown, and secondary coolant systems. Core thermocouples are provided to monitor fuel rod cladding temperatures and support tube temperatures at 196 incore locations. Four fixed nuclear detectors and the traversing incore nuclear detector system determine core nuclear response and neutron flux shapes.

2. PURPOSE AND SCOPE

The purpose of the Measurement Requirements Document (MRD) is to specify the measurements necessary to attain the objectives of the LOFT integral Test Program. These objectives are:

(1) To provide data required to evaluate and improve the analytical methods currently used to predict the LOCA response of LPWRs. The performance of ESFs with particular emphasis on ECCSs and the quantitative margins of safety inherent in the performance of the ESFs, are of primary interest.

(2) To identify and investigate any unexpected event(s) or threshold(s) in the response of either the plant or the ESFs and develop analytical techniques that adequately describe and account for the unexpected behavior(s).

It is therefore mandatory that the measurement plan be defined by analyses, thus insuring that information essential for the evaluation and refinement of analytical techniques will be obtained from the LOFT experiments.

The scope of the MRD is limited to the delineation of the measurements that are required to obtain information vital to the analysis, development, and verification of computer codes dealing with loss-of-coolant-type nuclear accidents. No measurements are specified in the MRD for redundancy or for requalification or operation of the LOFT facility. Also there is no intent to tailor measurement requirements to existing instrumentation capability, although technically unreasonable requirements are avoided wherever possible. The MRD does not preclude the installation of additional measurements in LOFT not required herein. However, addition of any measurement in LOFT does require a change to the facility initiated by a facility change form (FCF).

Section II of the MRD describes the range, accuracy, response, and priority requirements established for the LOFT experimental measurements. Clarifications and general comments on measurement requirements for the five major LOFT systems are compiled in Section III. Calculations and figures to support the measurement criteria analysis are presented in Appendix A. Detailed measurement types and locations are specified in the LOFT System and Test Description[1]. Measurements required for each LOFT test, including range and data acquisition rate, are specified in the experiment operating specification (EOS) for each LOFT test.

II. DESCRIPTION AND IDENTIFICATION OF MEASUREMENT CRITERIA

Measurement criteria define the quantitative requirements associated with measurement identification and catagory. They are both pertinent and necessary to full specification of measurement requirements and are accordingly included in the tables provided in this document. The criteria necessary are range, accuracy, response, and priority. These criteria are discussed in the following sections.

1. RANGE REQUIREMENTS

Range requirements were determined by the cumulative examination of maximum and minimum values of a given parameter. The primary source of data for determining range requirements was taken from the RELAP4/MOD5 computer code[2] analysis for LOFT nuclear LOCE L2-4. Backup information to insure adequate ranging was taken from the LOFT nonnuclear LOCE L1-4[3] and Semiscale Test S-06-4[4] experimental data.

Two basic rules were followed in specifying range requirements:

(1) The range requirements for all measurements shall encompass the full range anticipated in all experiments considered. Therefore, the ranges are quite broad. The ranges used in a particular experiment do not necessarily have to conform exactly to the ranges herein, especially if analysis shows a smaller range will suffice or is desired.

(2) The range specified shall be for the entire channel and shall cover the detector, interface equipment, readout, and data processing necessary to obtain useable output.

2. ACCURACY REQUIREMENTS

The accuracy requirements, as listed for each measurement, represent the cumulative allowable error of all measurement system component errors such as, but not limited to, detection, transmittal, digitizing, and recording.

The accuracies included in this document are dictated by an analysis of the required application of the measurement in the analytical model. Thus, the accuracy requirement criteria are governed primarily by actual needs of model verification, rather than existing hardware or facility limitations.

Detailed studies of measurement accuracy requirements are currently underway. These studies use an abbreviated model of the LOFT system with the RELAP4/MOD5 computer code and involve statistically varying principal variables from base values. The results of this study will then predict the maximum error of any variable that will allow the peak cladding temperature (PCT) to fall within the established error band of ±20°F (11 K)[5].

Five basic criteria were used regarding accuracy requirements as follows:

(1) Values listed are 2σ limits, which means a 95.4% probability or confidence limit exists that the total error in the measurements will fall within the stated limits.

(2) Accuracies are listed to one significant figure because of the assumed statistical nature of the cumulative error.

(3) Unless otherwise specified, the stated accuracy covers the entire range. Range staggering for satisfying the requirements of a specific experiment is considered permissible.

(4) The specified accuracy applies to the entire channel and covers the detector, interface equipment, readout, and recording system.

(5) Accuracies are specified as an absolute variance [for example ±20°F (11 K)] plus a percent of reading. The total accuracy is the arithematic sum of the two values.

3. RESPONSE REQUIREMENTS

This document specifies limits on time response characteristics of the various measurement systems to insure that all LOCE transients can be followed by the instrumentation. The assumption in this section is that the worst (maximum error) case of a transient signal can be represented by a simple linear ramp with slope "M". The value of M is the given maximum rate of change of a measured quantity.

The response time criteria for a measurement are specified in terms of maximum allowable (upper limit) rise time. Rise time (τ_R) is defined as the time required for the system to go from 10 to 90% of the value of an impressed step function. It is equal to 2.2 times the time constant (τ) for first-order systems:

$$\tau_R = 2.2\tau.$$

The rise time specified is for the entire channel and covers the detector, interface equipment, readout, and data processing necessary to obtain useable output. The time specified is the maximum response time allowed for a particular measurement system. In any case for which the measurement is considered to be a steady-state rather than a transient measurement, the rise time is chosen arbitrarily to be 1 second.

The relationship between the given quantities and the time response variables depend upon the type of measurement system; in fact, the number and nature of the variables necessary to describe a system depend upon the type of system. Four types of system responses are discussed: first-order, second-order, delay line, and electronic filter.

3.1 First Order

The first-order system response is the response of a simple, single-stage, resistance-capacitance filter. This response is a reasonable approximation to the response of thermocouples and turbine flowmeters under certain conditions. For first-order systems, the maximum measurement error for a ramp input is τM, where τ is the time constant of the measurement system. (The measurement error is less at the beginning of the ramp.) Therefore, to make the measurement error less than the given allowable error (E), the time constant is restricted as follows:

$$\tau < E/M.$$

3.2 Second Order

Second-order models are generally necessary to describe systems with inertial effects, such as drag discs. Second-order systems can be described by two parameters: an undamped natural frequency (ω_n) (expressed in radians per second) and a damping factor (ζ). The system is classified underdamped, critically damped, or overdamped according to whether ζ is less than, equal to, or greater than unity. The asymtotic measurement error for a ramp input is $2M\zeta/\omega_n$. At the beginning of the ramp, the error is smaller for overdamped and critically damped systems. The error may be larger at the beginning of the ramp for underdamped systems, but it is never more than twice as large as the asymtotic error; therefore, for overdamped and critically damped systems, the following is specified:

$$\frac{\zeta}{\omega_n} < \frac{E}{2M} .$$

A conservative requirement for underdamped systems is

$$\frac{\zeta}{\omega_n} < \frac{E}{4M} .$$

3.3 Delay Lines

Long electronic transmission lines and, perhaps, long fluid lines for stand-off pressure transducers, introduce a time delay in the signals. Ideally, this time delay is the same for all frequency components, so that the signals are not distorted or changed in any way except for the simple time delay. The error in the delay line response to a ramp input is MT, where T is the delay time of the line. The requirement then is

$$T < E/M$$

to keep the error below the maximum allowable error E.

3.4 Electronic Filters

In some measurement systems, such as densitometers, the system time response characteristics are determined by electronic filters. When well designed, the filter cut-off frequency is significantly above the highest interesting signal frequency, and the filter can be treated as a delay line. Filter delay times should be easilty determined from the manufacturers specifications or from filter design reference books.

4. PRIORITY REQUIREMENTS

The priority rating of each measurement consists of a single number and is based upon the importance of the particular measurement in providing information necessary to achieving the LOFT program objectives. Three possible ratings are used:

(1) A Class 1 measurement is considered essential to achieving the LOFT objectives

(2) A Class 2 measurement is considered beneficial to achieving the LOFT objectives and provides some redundancy for the Class 1 measurements

(3) A Class 3 measurement provides data of interest which are not necessarily related to the LOFT objectives.

This priority system is designed to aid (a) in evaluating the impact that loss of instrumentation during a LOCE would have upon subsequent experiments and (b) in advanced instrumentation design.

III. SYSTEM MEASUREMENT REQUIREMENTS

Clarifications and general comments on measurement requirements for the five major LOFT systems (reactor, primary coolant, secondary coolant, emergency core coolant, and blowdown suppression tank systems) are compiled in this section. No attempt has been made to describe in detail the criteria analysis for each measurement; sample calculations have been fully worked out in Appendix A of this document.

The primary source of data used in the analysis to establish measurement requirements for the LOFT system is the RELAP4/MOD5 computer code. This code is emphasized because of its current status in nuclear safety analysis throughout the nuclear industry and because of its position as a primary code used in the LOFT experiment prediction analyses. This emphasis was not meant to indicate that other codes are less important to the LOFT code verification objective.

The model used in this analysis and shown in Figure 2 is the current model of the LOFT facility with the nuclear core installed. Initial conditions used in the analysis were set at expected conditions for nuclear LOCE L2-4, a 200% offset shear cold leg break at 52.5 kW/m maximum linear heat generation rate. LOCE L2-4 was selected for the criteria analysis because it is considered to be the "worst-case" transient of the initial nuclear test series due to its high power level.

The measurement requirements for each of the five major LOFT systems are discussed in the following sections:

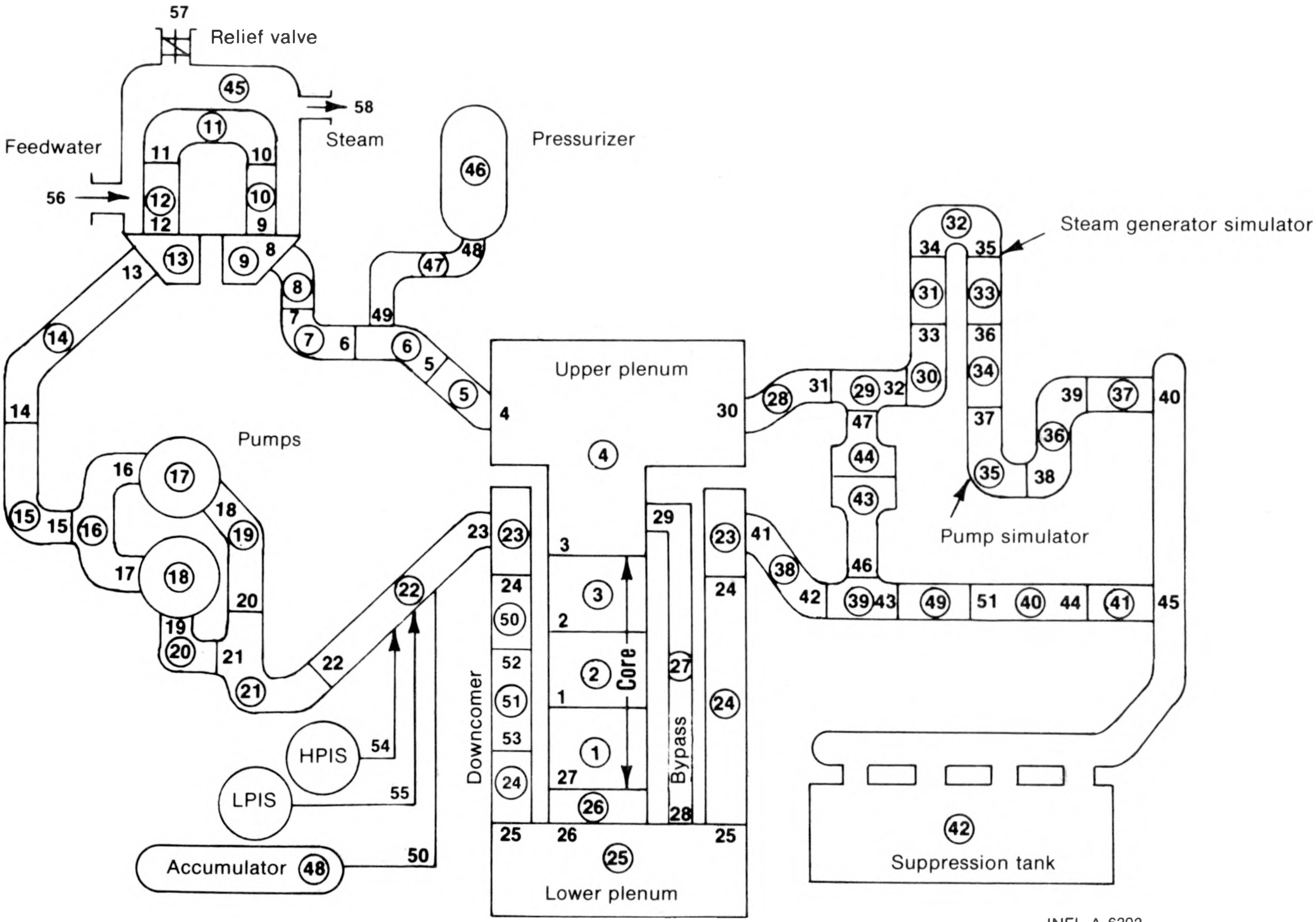


Fig. 2 RELAP4/MOD5 computer code model of the LOFT system.

1. REACTOR SYSTEM

Measurements taken in the reactor system are the most important of the measurements required for the LOFT experimental program, particularly those measuring the fuel rod cladding temperatures. Included in this system are the reactor vessel upper plenum, lower plenum, downcomer, and core measurements. The purpose of these measurements is to obtain the reactor system's thermal-hydraulic response to a blowdown transient.

1.1 Measurement Categories

The six main categories of reactor system measurements are temperature, pressure, velocity, density, mass flow, and liquid level.

1.1.1 Temperature. Temperature measurements are required (a) to evaluate the steady-state and transient predictive capabilities of appropriate computer codes, (b) to assess the effectiveness of the ECC, and (c) to determine whether any unexpected phenomena occur during the LOCE.

The fuel rod cladding temperatures are the most important data to be obtained during a nuclear LOCE. They reflect coolant conditions such as preferential flow, cross flow, ECC reflood, time and location of metal-water reactions, departure from nucleate boiling (DNB), and the effects of processes occurring within the core that indicate the potential for cladding damage and possible release of radioactive fission products.

1.1.2 Pressure. Pressure data are needed from LOFT to evaluate the capabilities of computer codes in calculating LOCA effects in LPWRs. Data will be obtained from both absolute and differential pressure measurements.

1.1.3 Velocity. Velocity measurements are required (a) to define mass flow variables (that is, direction, magnitude, and distribution of flow through the core) and (b) to interpret pressure and heat transfer measurements.

1.1.4 Density. Density measurements are used (a) to support the mass flow measurements, (b) to act as a major source of data on two-phase flow through the core, and (c) to provide information on ECC distribution to the core.

1.1.5 Mass Flow. Mass flow measurements are taken at the core inlet and outlet to insure an adequate understanding of core flow phenomena during a LOCE. While current instrumentation is incapable of directly measuring core mass flow, this requirement should be a primary goal of advanced instrument designs.

1.1.6 Liquid Level. Liquid level measurements are required to insure a comprehensive understanding of core reflood phenomena following the end of blowdown. These measurements, in conjunction with those of density will allow the rate of core reflooding to be calculated.

1.2 Measurement Criteria

Measurement criteria applicable to reactor system measurements for each of the measurement categories are discussed in the following sections and are summarized in Table I.

1.2.1 Temperature. Reactor system temperature measurements have the following ranges:

(1) Fuel rod cladding - 300 to 2300°F (422 to 1533 K)

(2) Upper plenum - 70 to 1300°F (294 to 978 K)

TABLE I

REACTOR SYSTEM MEASUREMENT CRITERIA

Measurement	Priority	Range	Accuracy	Response
Temperature:				
Fuel rod cladding	1	300 - 2300°F (422 - 1533 K)	±20°F (±11 K)	120 ms
Upper plenum	1	70 - 1300°F (294 - 978 K)	±(1.2°F + 1% RD) (0.7 K)	900 ms
Lower plenum	1	70 - 700°F (294 - 648 K)	±(0.6°F + 1% RD) (0.4 K)	900 ms
Downcomer	1	70 - 700°F (294 - 648 K)	±(0.6°F + 1% RD) (0.4 K)	900 ms
Pressure:				
Absolute	1	0 - 2500 psig (0 - 17.5 MPa)	±(12.5 psi + 5% RD) (90 kPa)	30 ms/850 ms
Differential	1	0 - 75 psid (0 - 500 kPa)	±(0.4 psi + 5% RD) (2.5 kPa)	110 ms
Velocity	1	0 - 135 ft/sec (0 - 40 m/s	±(0.7 ft/sec + 5% RD) (0.2 m/s)	30 ms
Density	1	0 - 62.4 lb/ft^3 (0 - 1000 kgm^3	±(0.03 lb/ft^3 + 0.5% RD) (0.5 kg/m^3)	1 ms
Mass flow	1	0 - 5 mlb/hr (0 - 3100 kg/s)	±50,000 lb/hr (±30 kg/s)	200 ms
Liquid level:				
Core	1	0 - 66 in. (0 - 167 cm)	±1 in. (2.5 cm)	1 s
Downcomer	1	0 - 162 in. (0 - 411.5 cm)	±1 in. (2.5 cm)	1 s
Lower plenum	1	0 - 36 in. (0 - 91 cm)	±1 in. (2.5 cm)	1 s

(3) Lower plenum - 70 to 700°F (294 to 648 K)

(4) Downcomer - 70 to 700°F (294 to 648 K).

Margins have been added (a) to the fuel cladding range to insure that the peak cladding temperature is measured and (b) to the upper plenum range to include the potential of superheated steam passing the thermocouples.

Accuracy for fuel cladding temperatures is set at ±20°F (11 K) as per Appendix K of 10 CFR 50[5]. The other temperature accuracies are established at 1% reading (RD). Response times are calculated using first-order system criteria. Attempts should be made to design and install thermocouples capable of measuring vapor as well as fluid temperatures.

Location and number of temperature measurements should follow the following nonexclusive guidelines:

(1) Measurements of cladding temperatures representative of the hot spot, average, and cooler regions of the core should be obtained.

(2) Measurements should be taken in the one-half of core nearest the broken loop.

(3) Measurements should be located such that number of variations caused by instrumentation will be minimized.

(4) Measurements should be located in order to investigate the effect of incore instrumentation on core thermal response.

(5) Measurements should exhibit regional symmetry to facilitate comparison of temperatures in the various regions.

(6) Measurements should be taken on at least three different core radii to determine symmetry in core thermal behavior.

(7) Measurements should be taken to allow determination of radial and axial temperature profiles.

(8) Measurements should be taken to provide a detailed axial temperature profile for selected fuel rods.

(9) Measurements should be taken with close axial spacing in the region of predicted maximum temperature and in the region where delayed DNB and rewet are expected to occur.

(10) Sufficient measurements should be taken to provide complete axial and radial temperature profiles with the greatest number concentrated near the expected core hot spot.

(11) Sufficient measurements should be taken at selected elevations to provide for measurement redundancy.

1.2.2 Pressure. Absolute pressure measurements range from 0 to 2500 psig (0 to 17.5 MPa), with an accuracy of ±12.5 psia (90 kPa) +5% RD. Response is a first-order phenomenon and is calculated for both subcooled blowdown (30 ms) and for saturated blowdown (850 ms). Exact response criteria should be selected with the specific experiment requirements in mind.

Differential pressure measurements range from 0 to 75 psig (0 to 0.5 MPa) with an accuracy of ±0.4 psi (2.5 kPa) +5% RD. Response time is 110 ms.

Pressure measurements should be taken at the following locations:

(1) In upper plenum outside end boxes

(2) On downcomer instrument stalks in lower plenum

(3) At the top of the instrument stalks in downcomer

(4) At locations that will support other measurements.

1.2.3 Velocity. Range requirements for fluid velocity measurements in the reactor vessel is 0 to 135 ft/sec (0 to 40 m/s) and are directionally independent. This wide range encompasses the high-flow deviations that begin at about 25 seconds after rupture initation. Similar behavior has been noted in past experiments in LOFT, so response criteria has been set to follow these transients as closely as possible. Accuracy for these measurements is set at 0.7 ft/sec (0.2 m/s) +5% RD.

1.2.4 Density. Because RELAP4/MOD5 handles density homogeneously in each model volume, establishing fixed measurement variables is difficult. Range is set at a standard 0 to 62.4 lb/ft^3 (0 to 1000 kg/m^3). Accuracy requirements for density measurements are quite strict [0.03 lb/ft^3 (0.5 kg/m^3) +0.5% RD] in order that vapor densities can be measurable with some certainty. Response is arbitrarily established at 1 ms to follow any density transient.

1.2.5 Mass Flow. The reactor vessel mass flow measurement range is set at from 0 to 5×10^6 lb/hr ±50,000 lb/hr (0 to 3100 kg/s ± 30 kg/s). Response time is established at 200 ms.

1.2.6 Liquid Level. Ranges for liquid level measurements in the reactor vessel are set at the height of the section being monitored:

(1) Core - 66 in. (167 cm)

(2) Downcomer - 162 in. (411.5 cm)

(3) Lower plenum - 36 in. (91 cm).

Accuracy for liquid level measurements in the reactor vessel is set within ±1 in. (2.54 cm); response time is set at 1 second.

Priorities depend upon the exact location of the measurement device; therefore, priorities assigned to the measurements herein give a general overall value. For example, cladding temperatures in peripheral fuel assemblies are priority Class 2; those nearer the center (hottest) portion of the reactor are priority Class 1.

2. PRIMARY COOLANT SYSTEM

The purpose of the primary coolant system (PCS) measurements is to obtain information about system behavior under transient conditions and to obtain adequate initial condition data prior to each experiment. Of primary importance to PCS evaluation are measurements in areas of the system expected to experience critical flow, that is, upstream of breaks. Measurements should also be taken to evaluate performance of specific components such as the pressurizer.

2.1 Measurement Categories

The main measurements taken in the PCS are temperature, pressure, velocity, density, momentum flux, and mass flow.

2.1.1 Temperature. Temperature measurements in the PCS are necessary for determining fluid properties for use in interpreting mass flow, differential pressure, and heat transfer predictions. During the transient, temperature measurements will be taken up and downstream of the ECC injection point to define the distribution of liquid and vapor near the vessel inlet and define the dynamics of the injected coolant. Pre-LOCE readings are important to the subcooled and saturated decompression processes.

2.1.2 Pressure. Absolute and differential pressure measurements in the PCS are required to define fluid properties both before and during the transient. During the LOCE, pressure must be known to determine the overall depressurization process and to assess the effect of pipe area changes on system performance and modeling.

Differential pressure measurements provide basic data on two-phase pressure losses, the region of ECC injection, and ΔP head rise due to mixing and condensation. They are also used to detail the transient across the steam generator and primary coolant pumps.

2.1.3 Velocity. Velocity measurements in the PCS are used to indirectly determine the mass flow in the primary system. These measurements are needed to assess the total system performance, especially the effectiveness of the ECCS.

2.1.4 Density. Density measurements are used to complement velocity measurements for mass flow calculations and to define the liquid-vapor distribution of injected ECC.

2.1.5 Momentum Flux. Momentum flux (ρv^2) measurements are required to complete a system of cross checks for velocity and density measurements. These three measurements are used to confirm each other at any given time.

2.1.6 Mass Flow. Mass flow measurements provide the analytical base for a variety of system parameters, such as thermal power. Mass flow has a tremendous effect upon system transient behavior, and maximum effort should be placed on development of highly accurate instrumentation for these measurements.

2.2 Measurement Criteria

Measurement criteria for the PCS measurements are tabulated in Table II and discussed in the following sections.

2.2.1 Temperature. Temperature measurements for the PCS range from the nominal ECCS temperatures of 70°F (294 K) to a peak of 650°F (620 K). Although some locations in the PCS will display a smaller range, for simplicity, one standard temperature range was established. First-order response time is established at 400 ms. Again, advanced thermocouple designs to accurately measure vapor temperatures should be considered.

2.2.2 Pressure. The range for absolute pressure measurements is based upon the reactor system criteria of 0 to 2500 psi (0 to 17.3 MPa). As with the reactor system measurements, the response time should be set for subcooled blowdown (30 ms) or saturated blowdown (850 ms), depending upon the emphasis required by the specific experiment.

Differential pressure measurement requirements depend upon the actual location of the measurement, thus no uniform range can be specified. Ranges vary from a low of -50 psid (-0.35 MPa) to a maximum of 900 psid (6.2 MPa). Accuracy is standard 5% RD. response times are first-order calculations.

2.2.3 Velocity. As with the ΔP requirements, velocity measurement depend a great deal on location and, as such, range criteria are not standard values.

The range for velocity measurements varies from 0 ft/sec to a maximum of 825 ft/sec (250 m/s). The ranges are large to encompass all calculated spikes and, at users discretion, may be reduced. Accuracy for these measurements is set at 5% RD to conform with other system velocity measurements, and response is calculated to be 100 ms.

TABLE II

PRIMARY COOLANT SYSTEM MEASUREMENT CRITERIA

Measurement	Priority	Range	Accuracy	Response
Temperature	1	70 - 650°F (294 - 620 K)	±(1°F + 1% RD) (0.4 K)	400 ms
Pressure:				
Absolute	1	0 - 2500 psig (0 - 17.5 MPa)	±(12.5 psi + 5% RD) (90 kPa)	30 ms/850 ms
Differential:				
Intact loop	1	-50 ± 50 psid (-35 ± 0.35 MPa)	±(0.5 psi + 5% RD) (3.5 kPa)	100 ms
Broken loop hot leg 14-to-5-in. contraction	1	0 - 90 psid (0 - 0.6 MPa)	±(0.5 psi + 5% RD) (3.0 kPa)	200 ms
Broken loop break plane		0 - 900 psid (0 - 6.2 MPa)	±(4.5 psi + 5% RD) (31 kPa)	600 ms
Broken loop pump simulator		0 - 500 psid (0 - 3.5 MPa)	±(2.5 psi + 5% RD) (18 kPa)	800 ms
Broken loop steam generator simulator		0 - 200 psid (0 - 1.5 MPa)	±(1.0 psi + 5% RD) (7.5 kPa)	150 ms
Velocity:				
Broken loop cold leg		0 - 150 ft/sec (0 - 46 m/s)	±(0.75 ft/sec + 5% RD) (0.3 m/s)	100 ms
Broken loop hot leg	1	0 - 60 ft/sec (0 - 19 m/s)	±(0.3 ft/sec + 5% RD) (0.1 m/s)	100 ms
Intact loop cold leg	1	0 - 825 ft/sec (0 - 250 m/s)	±(4 ft/sec + 5% RD) (1.3 m/s)	100 ms

TABLE II (continued)

Measurement	Priority	Range	Accuracy	Response
Intact loop hot leg	1	0 - 140 ft/sec (0 - 40 m/s)	±(0.7 ft/sec + 5% RD) (0.2 m/s)	100 ms
Intact loop steam generator		0 - 575 ft/sec (0 - 175 m/s)	±(3 ft/sec + 5% RD) (0.9 m/s)	100 ms
Flow Rate:				
Intact loop hot leg		0 - 5 Mlb/hr (0 - 3100 kg/s)	±50,000 lb/hr (±30 kg/s)	200 ms
Momentum flux (nominal)		-20 ±50 klb/ft-sec^2 (-29 ±75 mg/m-s^2)	±(350 lb/ft-sec^2 + 5% RD) (520 kg/m-s^2)	1 ms
Density (nominal, average)		0 - 62.4 lb/ft^3 (0 - 1000 kg/m^3)	±(0.03 lb/ft^3 + 0.5% RD) (0.5 kg/m)	1 ms

2.2.4 Density. Density measurements are limited by the calculational techniques of RELAP4/MOD5 and, therefore, are assigned nominal values. Range for these measurements is set at 0 to 62.4 lb/ft^3 (0 to 1000 kg/m^3). Accuracy and response criteria correspond to reactor system requirements, 0.5% RD and 1 ms.

2.2.5 Momentum Flux. Criteria for these measurements are difficult to determine, particularly response, which is a second-order calculation. A range was calculated using data from RELAP4/MOD5 and set at -20 to +50 $klb/ft\text{-}sec^2$ (-29 to +75 $Mg/m\text{-}s^2$). For these measurements, accuracy is set at 5% RD to match velocity measurements and response time is arbitrarily set at 1 ms. Momentum flux measurements should be directionally dependant.

2.2.6 Mass Flow. Mass flow measurements in the PCS conform exactly to their counterparts in the reactor system: range 0 to 5×10^6 lb/hr (0 to 3100 kg/s), accuracy ±50,000 lb/hr (30 kg/s), and response time 200 ms.

Measurements should be taken at the following locations in the PCS:

(1) Broken loop near reactor vessel inlet

(2) Broken loop near reactor vessel outlet

(3) Intact loop near reactor vessel outlet

(4) Intact loop near reactor vessel inlet

(5) Across all major components (that is, pressurizer, primary coolant pumps, etc.)

(6) Across either side of the PCS ECC injection points

(7) All other locations required to complete loop analysis such as the pressurizer spray bypass line.

3. SECONDARY COOLANT SYSTEM

The principal purpose of the secondary coolant system (SCS) measurements is to obtain information for use in determining the direction of energy exchange between the primary to secondary systems. These measurements are also required to support the determination of plant thermal power as and initial LOCE condition. The measurement goal of the secondary coolant system is the capability of plotting the energy content as a function of time. This will require measurements of all portions, such as the steam dome.

3.1 Measurement Categories

The RELAP4/MOD5 model of the SCS is minimal, with only the average values within the steam generator being calculated. Thus the measurement requirements are established for near steady-state conditions. The SCS categories are temperature, pressure, and flow rate. These three categories of measurements are used to determine core thermal power by means of secondary calorimetrics.

3.2 Measurement Criteria

Measurement criteria for the SCS are summarized in Table III.

All SCS measurement requirements are based upon system technical requirements. The ranges for these measurements are:

(1) Temperature - 250 to 650°F (393 to 618 K)

TABLE III

SECONDARY COOLANT SYSTEM MEASUREMENT CRITERIA

Measurement	Priority	Range	Accuracy	Response
Temperature:				
Feed and steam	1	250 - 650°F (393 - 618 K)	±(0.5% + 1% RD) (0.2 K)	1 s
Pressure		0 - 1100 psig (0 - 7.6 MPa)	±(1.1 psi + 1% RD) (7.6 kPa)	600 ms
Flow rate:				
Feedwater		0 - 730 gpm (0 - 46 l/s)	±(1 gpm + 1% RD) (0.05 l/s)	1 s

(2) Pressure - 0 to 1100 psig (0 to 7.6 MPa)

(3) Flow rate (feedwater) - 0 to 730 gpm (0 to 46 l/s).

With the goal of calculating reactor power to within 1% RD, response of temperature and flow rate measurements for the SCS is considered steady-state and set to 1 second. Pressure response is calculated at 600 ms.

4. EMERGENCY CORE COOLANT SYSTEM

Evaluation of ECCS performance during a LOCE requires that sufficient instrumentation shall be provided to determine the following:

(1) System initial conditions including boric acid concentration and temperature of the stored ECC

(2) The quantity of coolant delivered

(3) The rate of delivery of coolant to each injection point

(4) The locations at which the coolant is delivered

(5) Temperature of the injected water

(6) The times in the LOCE after the break opening at which coolant delivery is initiated and ECC actually reaches the PCS.

4.1 Measurement Categories

With the exception of the accumulators, the ECCS is modeled as a fill system and only flow rates are calculated. The other required measurements, temperature and pressure, are steady-state quantities and are treated as such.

4.2 Measurement Criteria

Measurement criteria for the ECCS are summarized in Table IV.

Temperature and absolute pressure ranges for the ECCS are based upon expected initial conditions, since RELAP4/MOD5 calculations require these values as input and are not calculated. The criteria for these measurements are as follows:

(1) Temperature - 0 to 200°F (255 to 367 K) for the accumulators
  - 0 to 400°F (255 to 478 K) for the LPIS and HPIS

(2) Pressure - 0 to 1000 psi (0 to 6.9 MPa).

Accuracies are the same as all other temperature and pressure measurements, 1 and 5% RD, respectively. Both of these measurements are considered steady-state with a response time of 1 second.

Flow rates are calculated using RELAP4/MOD5. Calculated flow rate ranges are:

(1) Accumulator - 0 to 150 lb/s (0 to 70 kg/s)

(2) LPIS - 0 to 25 lb/s (0 to 10 kg/s)

(3) HPIS - 0 to 5 lb/s (0 to 2 kg/s).

Flow rate accuracy is set at 5% RD, and response is determined using first-order techniques.

ECCS measurements should be located at all possible injection points and at locations which will give a complete understanding of the system (that is, across LPIS heat exchangers, etc.).

TABLE IV

EMERGENCY CORE COOLANT SYSTEM MEASUREMENT CRITERIA

Measurement	Priority	Range	Accuracy	Response
Temperature:				
Accumulators	1	0 - 200°F (255 - 367 K)	±(0.2°F + 1% RD) (0.1 K)	1 s
LPIS	2	0 - 400°F (255 - 478 K)	±(0.4 °F + 1% RD) (0.2 K)	1 s
HPIS	2	0 - 400°F (255 - 478 K)	±(0.4 °F + 1% RD) (0.2 K)	1 s
Pressure:				
Accumulator	2	0 - 1000 psi (0 - 6.9 MPa)	±(5 psi + 5% RD) (34.5 kPa)	1 s
Flow rate:				
Accumulator	1	0 - 150 lb/sec (0 - 70 kg/s)	±(0.8 lb/sec + 5% RD) (0.4 kg/s)	500 ms
LPIS	1	0 - 25 lb/sec (0 - 10 kg/s)	±(0.1 lb/sec + 5% RD) (0.05 kg/s)	100 ms
HPIS	1	0 - 5 lb/sec (0 - 2 kg/s)	±(0.1 lb/sec + 5% RD) (0.05 kg/s)	1 s

5. BLOWDOWN SUPPRESSION TANK SYSTEM

The blowdown suppression tank system does not affect the thermal and hydraulic behavior of the LOFT system until late in the blowdown, when the break flow becomes unchoked. During reflood, however, the blowdown suppression tank (BST) pressure does control both the break flow and the PCS vapor density by providing a pressure base. The difference between initial and final mass inventory in the BST is also used to calculate total break flow and to estimate the flow rate.

5.1 Measurement Categories

The model of the BST used in the RELAP4/MOD5 calculations is limited to one volume, and thus a detailed analysis for measurement requirements is not based entirely on the computer code. The main categories which can be studied are temperature and pressure. The average values of these categories are calculated using RELAP4/MOD5.

5.2 Measurement Criteria

Measurement criteria for the BST are summarized in Table V.

Ranges for average temperature and pressure are 70 to 300°F (294 to 423 K) and 0 to 50 psig (0 to 0.35 MPa), respectively. Accuracy of the pressure measurements has been established at within 5% RD by FLECHT test results[6]. The temperature accuracy is established at 1% RD to provide the capability of determining what portion of the tank pressure is caused by fluid vapor pressure. Response is calculated using first-order response equations.

TABLE V

BLOWDOWN SUPPRESSION TANK SYSTEM MEASUREMENT CRITERIA

Measurement	Priority	Range	Accuracy	Response
Temperature	1	70 - 300°F (294 - 423 K)	±(0.3 °F + 1% RD) (0.1 K)	400 ms
Pressure	1	0 - 50 psig (0 - 0.35 MPa)	±(0.3 psi + 5% RD) (1.8 kPa)	150 ms

IV. REFERENCES

1. D. L. Reeder, LOFT System and Test Description (5.5-foot Nuclear Core 1 LOCEs), TREE-NUREG-1208 (July 1978).

2. C. S. Bruch (ed.), RELAP4/MOD5 - A Computer Program for the Transient Thermal-Hydraulic Analysis of Nuclear Reactors and Related Systems - Users Manual, ANCR-NUREG-1335 (September 1976).

3. D. L. Batt, Experiment Data Report for LOFT Nonnuclear Test L1-4, TREE-NUREG-1084 (July 1977).

4. R. L. Gillins et al., Experiment Data Report for Semiscale Mod-1 Test S-06-4 (LOFT Counterpart Test), TREE-NUREG-1124 (December 1977).

5. U. S. Atomic Energy Commission, Code of Federal Regulations, Title 10 - Atomic Energy, Part 50, Licensing of Production and Utilization Facilities, Appendix K, "ECCS Evaluation Models", Docket No. RM-50-1 (January 1, 1976).

6. F. F. Cadek et al., PWR FLECHT Final Report Supplement, Westinghouse Electric Corporation Report WCAP-7931 (October 1972).

APPENDIX A

LOFT MEASUREMENT REQUIREMENTS DOCUMENT CALCULATIONS

APPENDIX A

LOFT MEASUREMENT REQUIREMENTS DOCUMENT CALCULATIONS

1. INTRODUCTION

The basis for the LOFT measurements criteria is detailed in this appendix to support the specific requirements tabulated in the main body of the Measurement Requirements Document (MRD). This support is primarily in the form of data plots showing measurement transients calculated using the RELAP4/MOD5 computer code[A-1].

The technique used to analyze the data plots for criteria requirements was essentially the same for each of the five major LOFT systems (reactor, primary coolant, secondary coolant, emergency core coolant, and blowdown suppression tank system). A complete compilation of the analyses would be undesirable due to both quantity and repetition; therefore, two sample calculations are fully worked in this appendix using specific measurements.

2. CALCULATIONS

The measurements selected for the two sample calculations are the fuel rod cladding temperature and the reactor vessel upper plenum pressure.

2.1 Fuel Rod Cladding Temperature

For the fuel cladding temperature measurement, the range, accuracy, and response criteria were selected as follows:

2.1.1 Range Criteria. The maximum temperature capability for the hot fuel rods should be 2300°F (1533 K) based upon the maximum predicted temperature of 1950°F (1340 K) (see Figure A-1) plus a margin of 20%. This margin has been included to insure that in the event the peak cladding temperature is underpredicted in the computer calculations, the peak temperature will still be within the range of the instrument.

2.1.2 Accuracy Criteria. Appendix K to 10 CFR Part 50[A-2] requires a peak cladding temperature predictability of $\pm 20°F$ (11 K). Therefore, this requirement is set as the accuracy required of fuel rod cladding temperature measurements. This corresponds to a 1% of range accuracy.

2.1.3 Response Criteria. Thermocouples will use first-order electronics systems and thus will use response equation

$$\tau_R < 2.2 \frac{E}{M} .$$

A study of Figure A-1 indicates the maximum slope (M) lies between 0.75 and 1.5 seconds, so

$$M = \frac{760 \text{ K} - 610 \text{ K}}{1.5 - 0.75 \text{ s}} = 200 \text{ K/s}$$

$$E = 11 \text{ K}$$

$$\tau_R < 2.2 \ \frac{(11 \text{ K})}{200 \text{ K/s}} = 0.121 \text{ s.}$$

For ease, the maximum allowable response is then set at 120 ms.

2.2 Upper Plenum Pressure

For the upper plenum pressure measurements, the range, accuracy, and response criteria were selected as follows:

2.2.1 Range Criteria. Range criteria for upper plenum pressure transducers is set at 0 to 2500 psig (0 to 17.5 MPa). Study of Figure A-2 shows this is high by test standards, but is adequate to handle any pretest system manipulation except hydrostatic testing.

2.2.2 Accuracy Criteria. No specific pressure accuracy requirement has been identified to date. Therefore the criteria is set at 5% of reading.

2.2.3 Response Criteria. Using first-order system equations to calculate response, there are two separate transients to consider.

(1) Subcooled Blowdown. Subcooled blowdown lasts approximately 0.08 seconds[A-3] following rupture initiation, during which time the system pressure falls from 15.7 MPa to 11.75 MPa (Figure A-5).

$$M = \frac{15.7 \text{ MPa} - 11.75 \text{ MPa}}{0.080 - 0.0 \text{ s}}$$

$$= 49.4 \text{ MPa/s}$$

$$E = \text{(\% accuracy) (mean value during time considered)}$$

$$= (0.05)\ \frac{(15.7 + 11.75)}{2}$$

$$= 0.686\ \text{MPa}$$

$$\tau_R < 2.2\ \frac{(0.686\ \text{MPa})}{49.4\ \text{MPa/s}} = 0.031\ \text{s}\ .$$

For ease, subcooled blowdown response criteria is then set at 30 ms.

(2) Saturated Blowdown. Saturated blowdown begins at 0.08 seconds and continues to nearly 50 seconds after rupture initiation[A-3]. The worst transient, shown on Figure A-5, is between 0.08 and 2 seconds.

$$M = \frac{11.75\ \text{MPa} - 9.2\ \text{MPa}}{2.0 - 0.08\ \text{s}}$$

$$= 1.33\ \text{MPa/s}$$

$$E = \text{(\% accuracy) (mean value during time considered)}$$

$$= (0.05)\ \frac{(11.75 + 9.2\ \text{MPa})}{2}$$

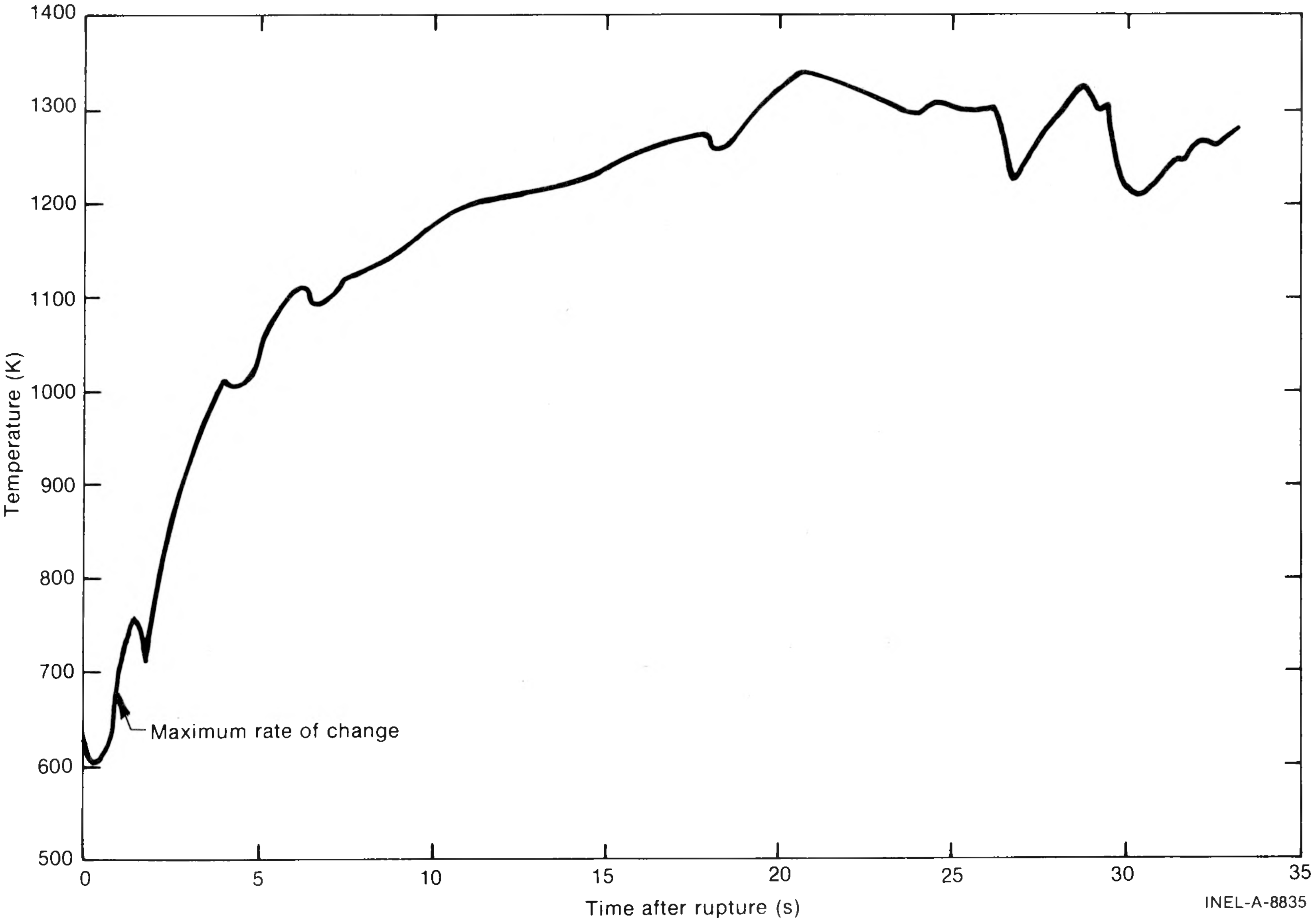
$$= 0.52\ \text{MPa}$$

$$\tau_R < 2.2\ \frac{(0.52\ \text{MPa})}{1.33\ \text{MPa/s}} = 0.868\ \text{s}\ .$$

For ease, the saturated blowdown response criteria is then set at 850 ms.

3. RELAP4/MOD5 COMPUTED DATA

This section contains figures of computed data showing measurement transients calculated using the RELAP4/MOD5 computer code[A-1].



INEL-A-8835

Fig. A-1 Peak temperature of fuel rod cladding.

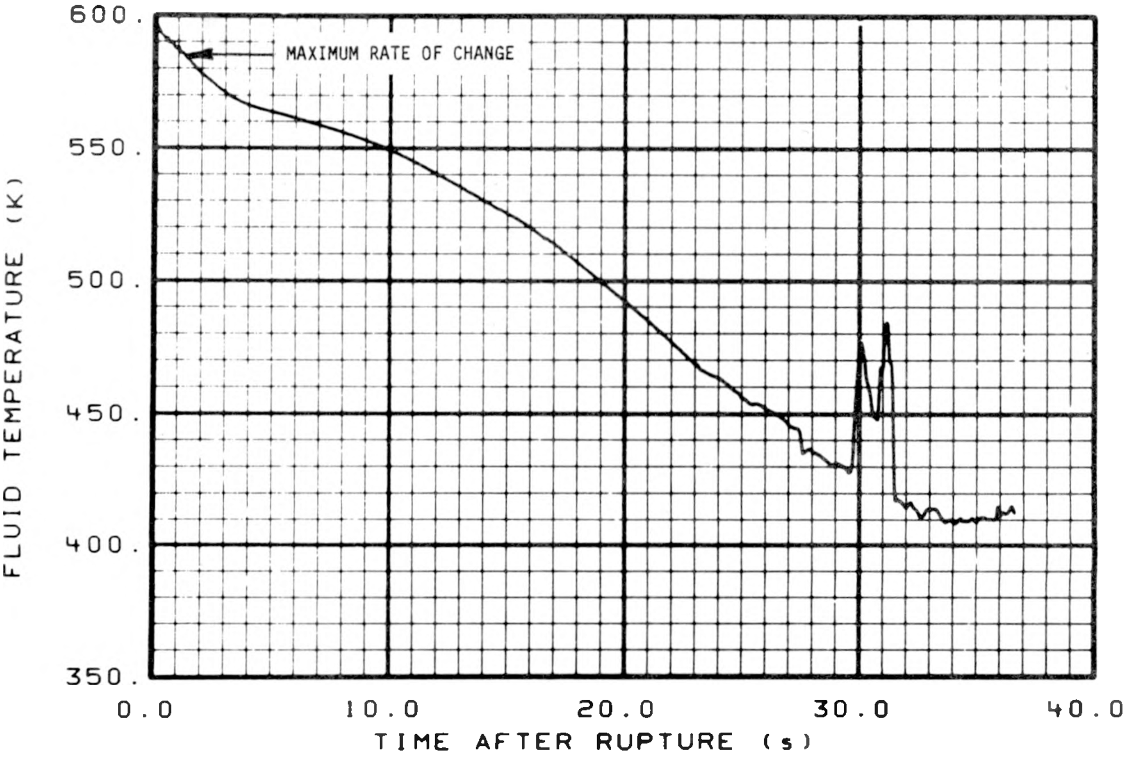


Fig. A-2 Temperature in reactor vessel upper plenum.

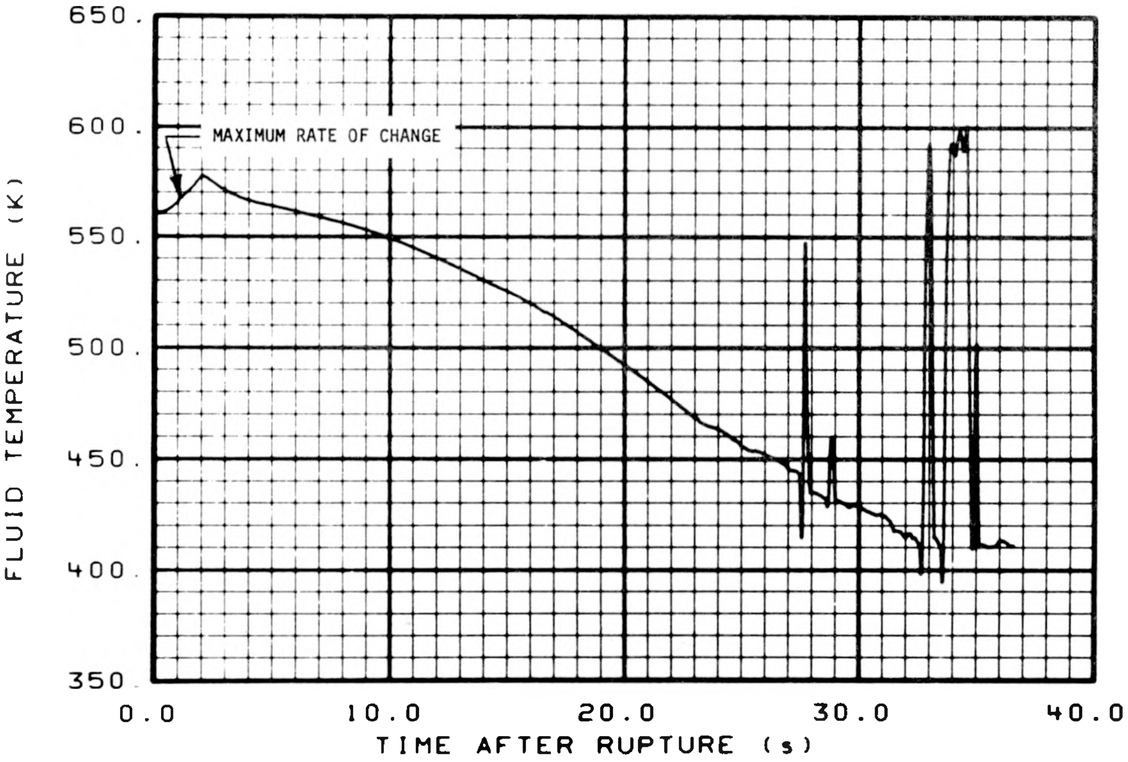


Fig. A-3 Temperature in reactor vessel lower plenum.

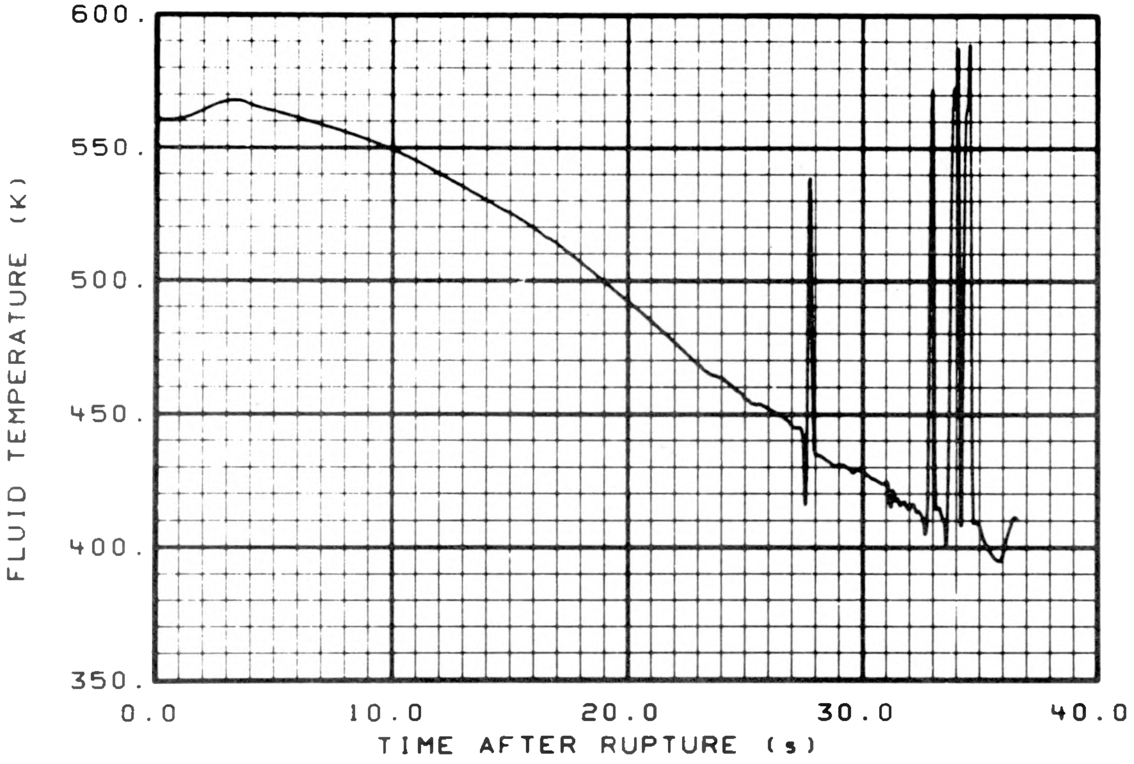


Fig. A-4 Temperature in reactor vessel downcomer.

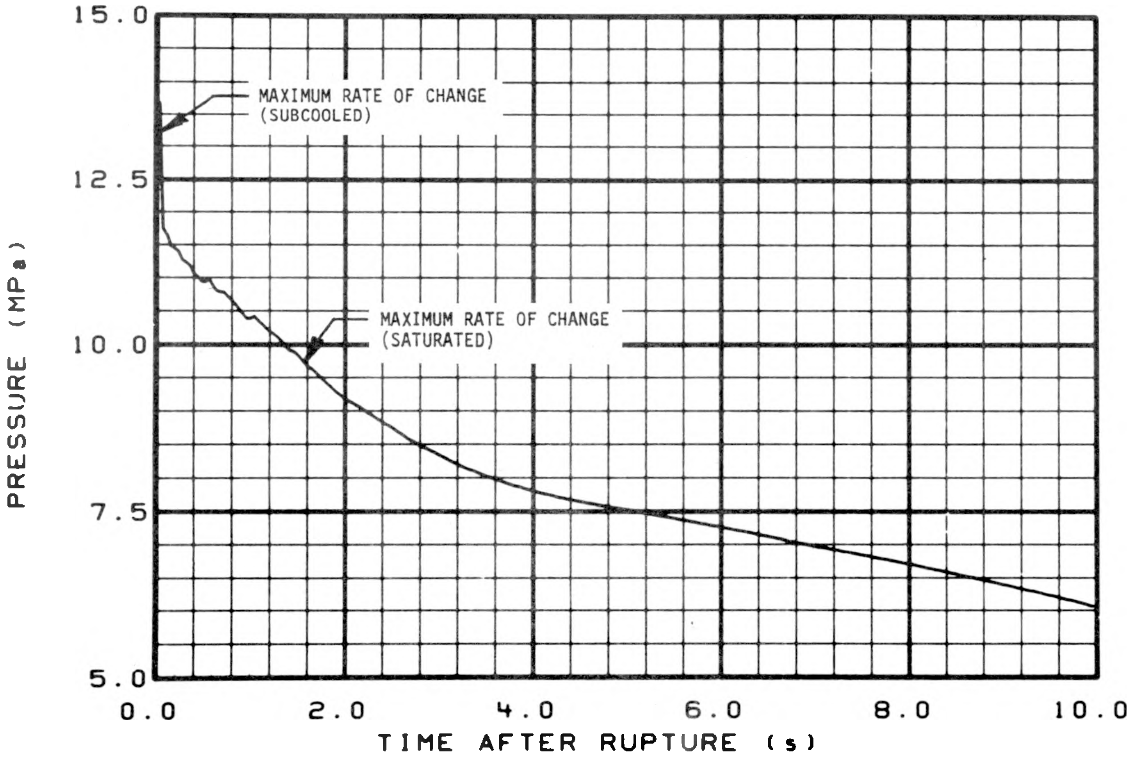


Fig. A-5 Pressure in reactor vessel upper plenum.

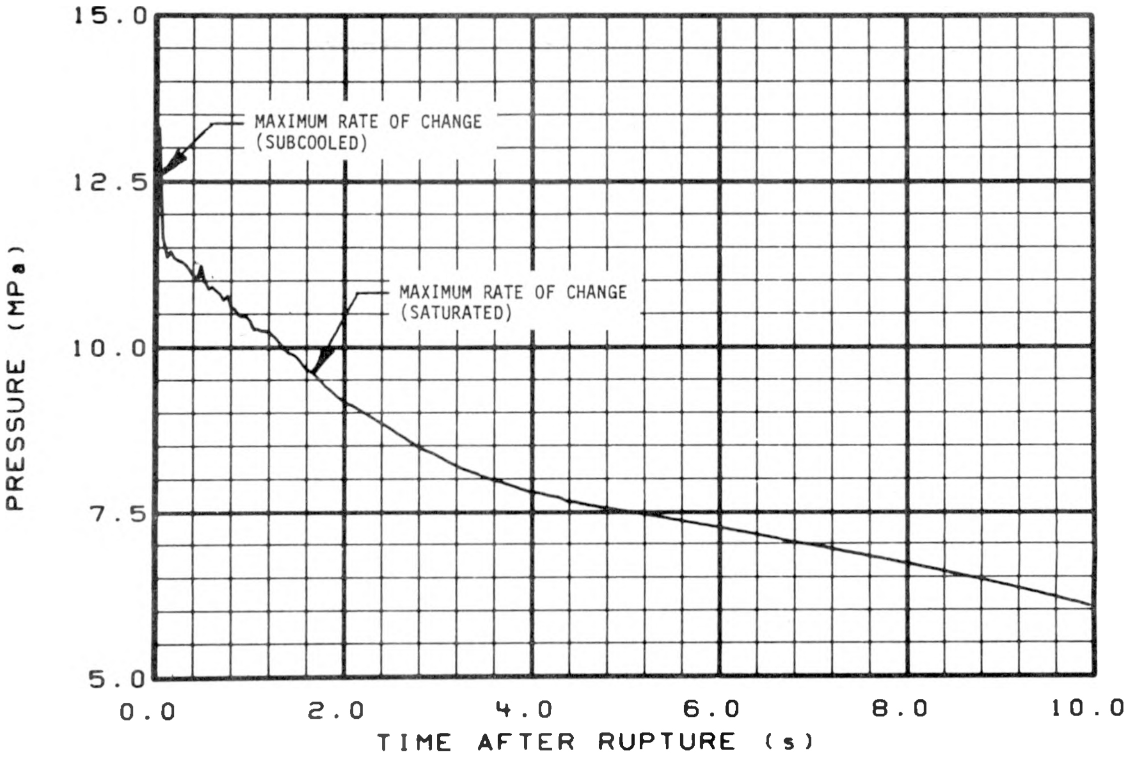


Fig. A-6 Pressure in reactor vessel lower plenum.

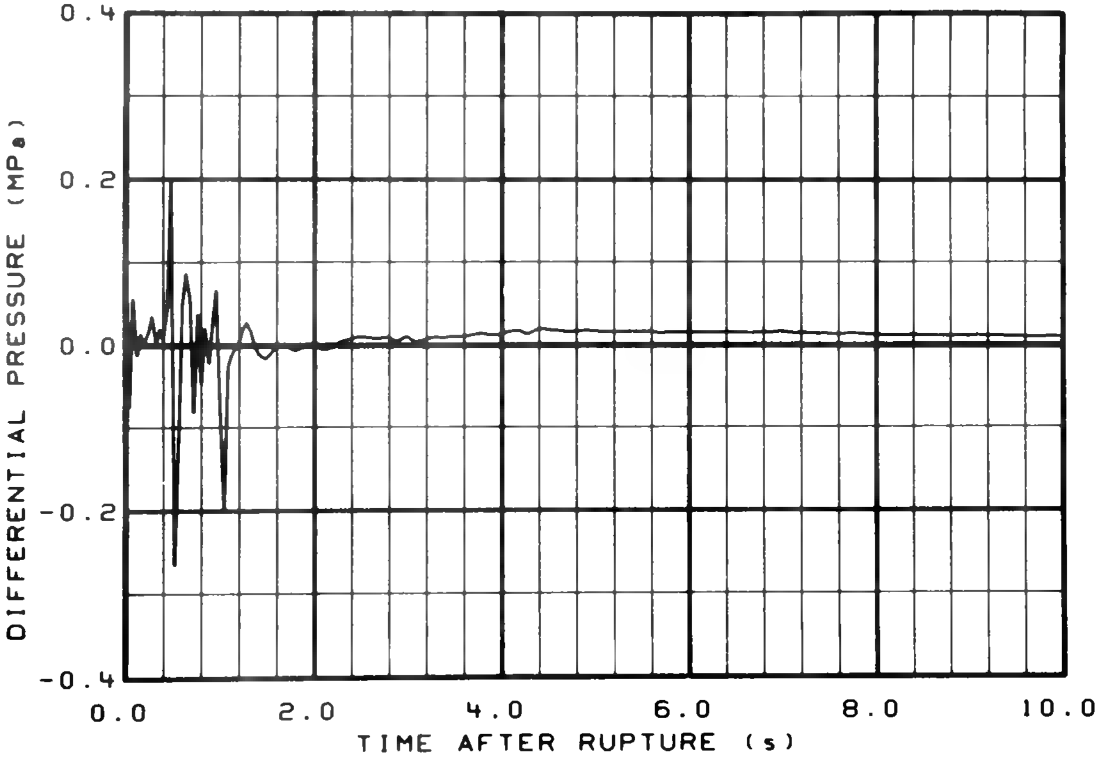


Fig. A-7 Differential pressure in reactor vessel upper and lower plenums.

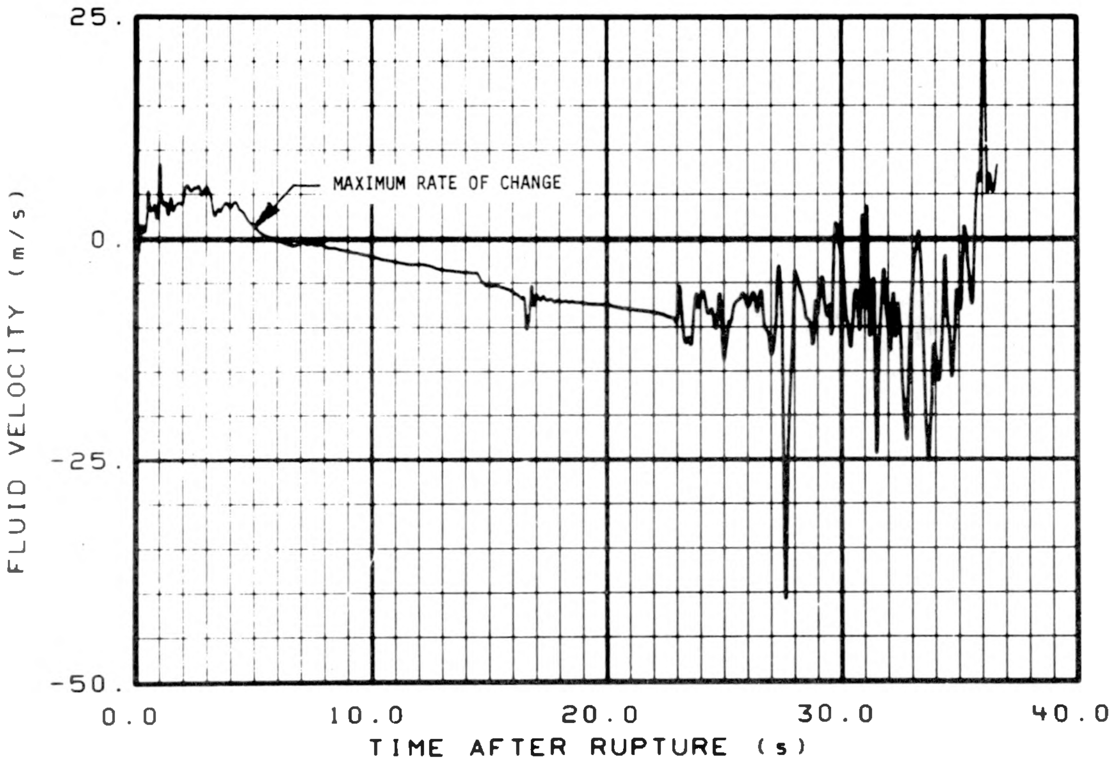


Fig. A-8 Fluid velocity in reactor vessel upper plenum.

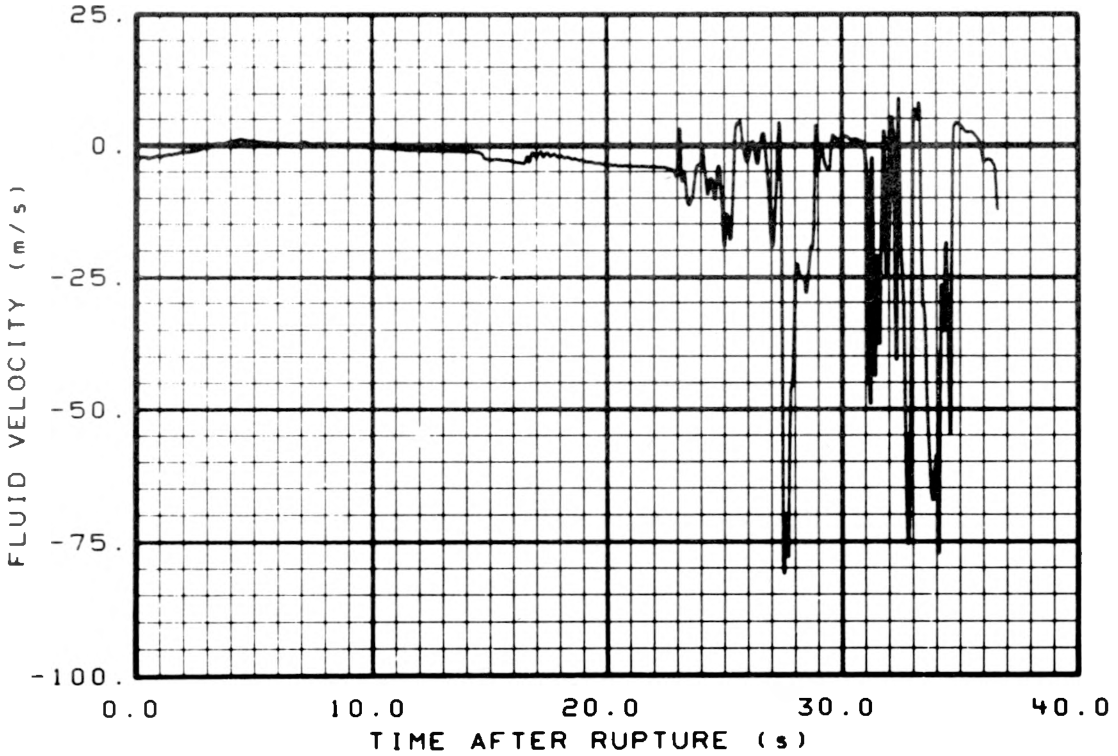


Fig. A-9 Fluid velocity in reactor vessel downcomer.

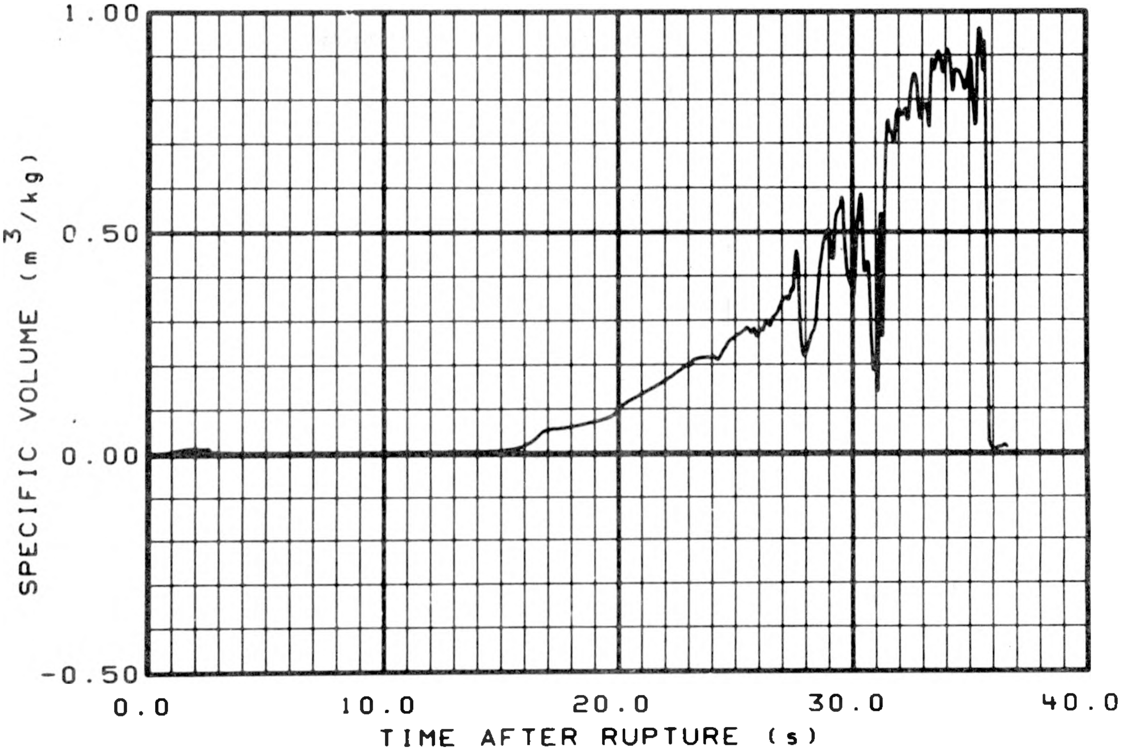


Fig. A-10 Specific volume at reactor core inlet.

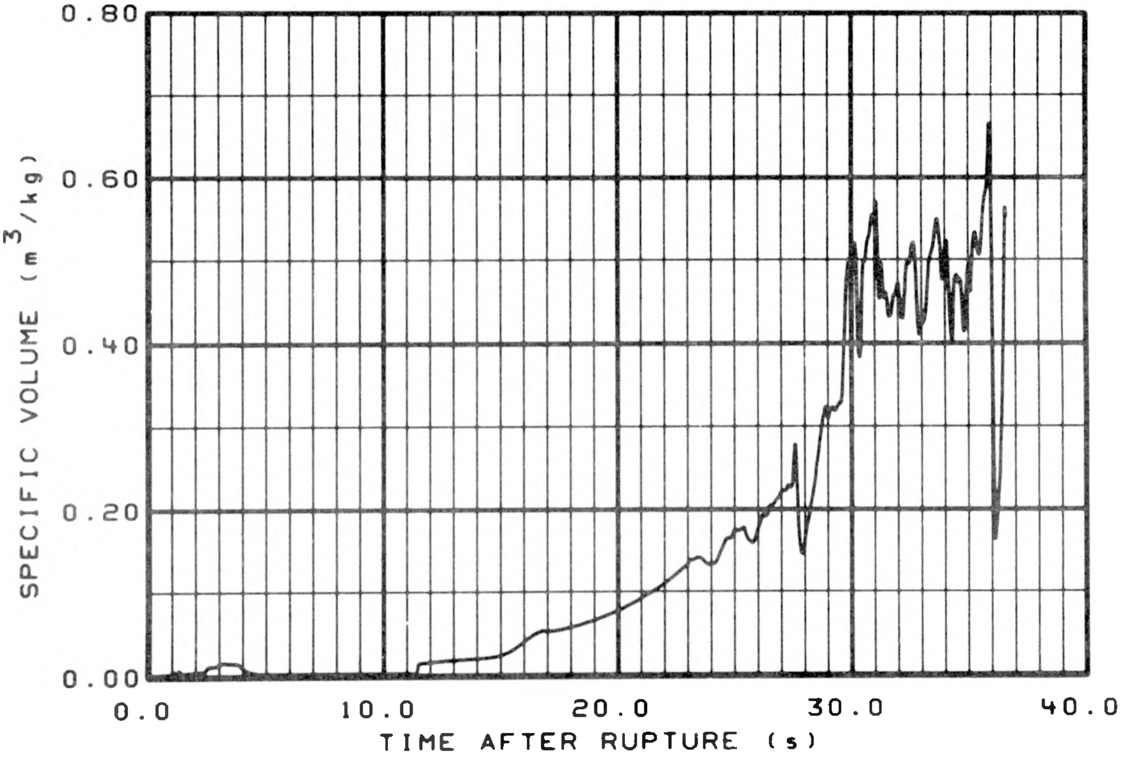


Fig. A-11 Specific volume at reactor core outlet.

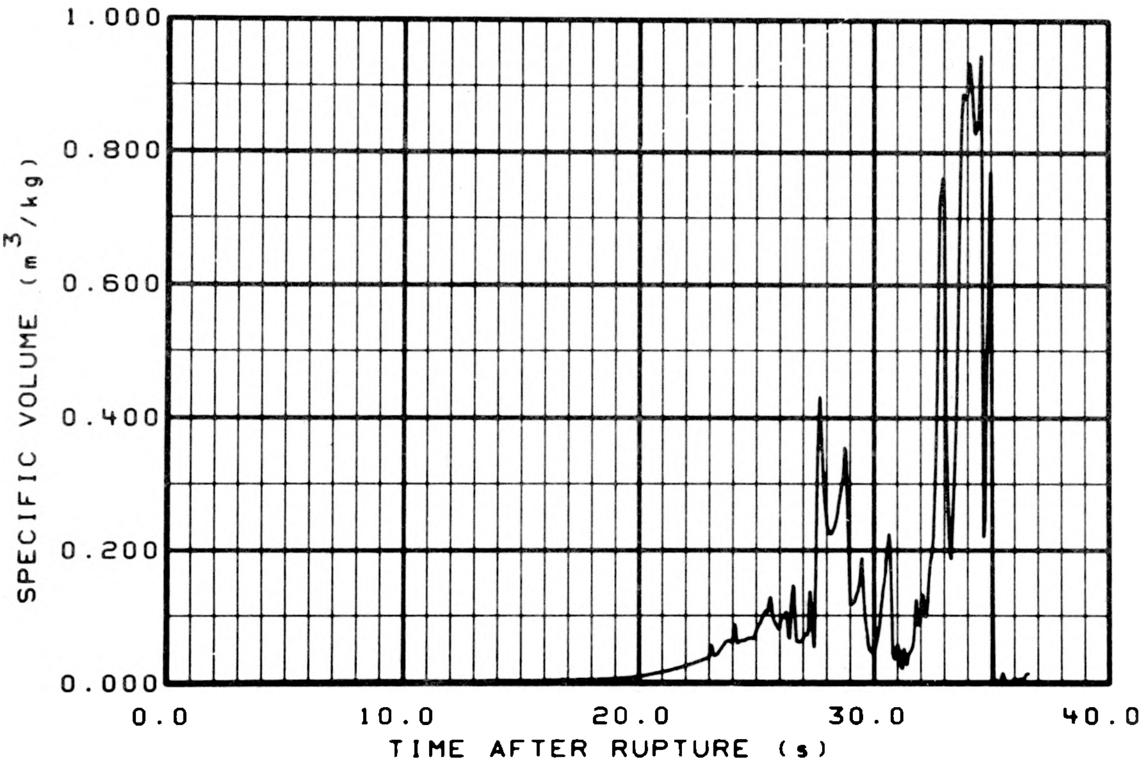


Fig. A-12 Specific volume in reactor vessel downcomer.

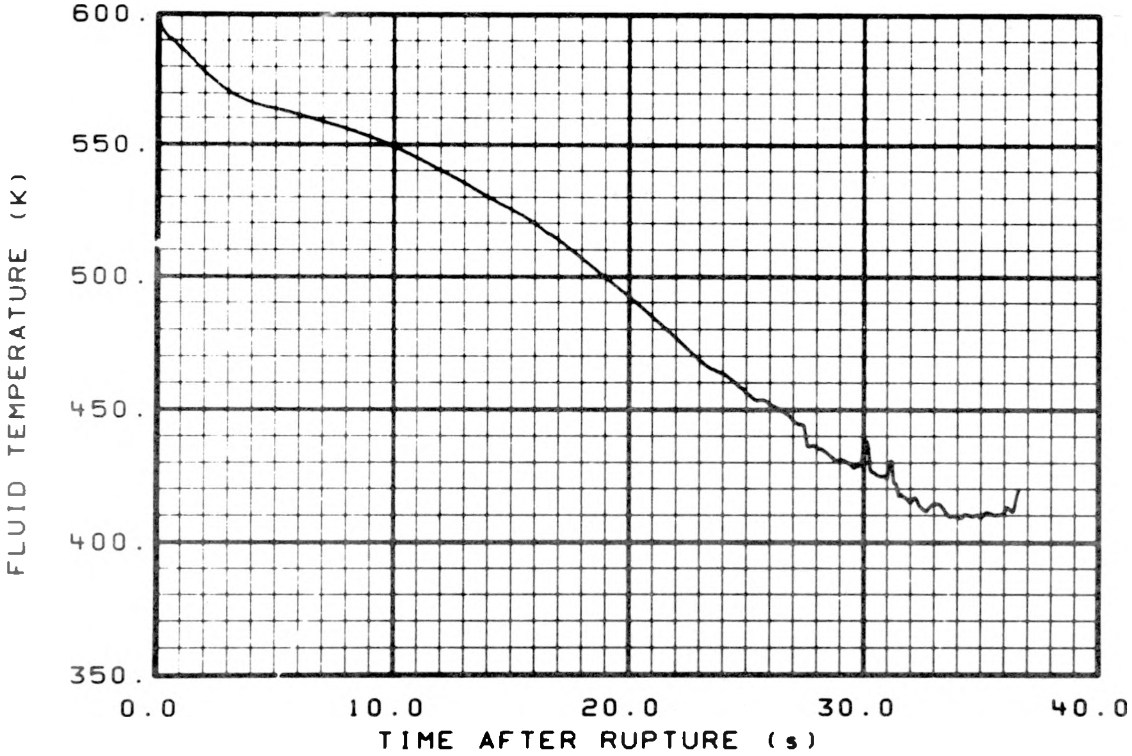


Fig. A-13 Temperature in intact loop hot leg.

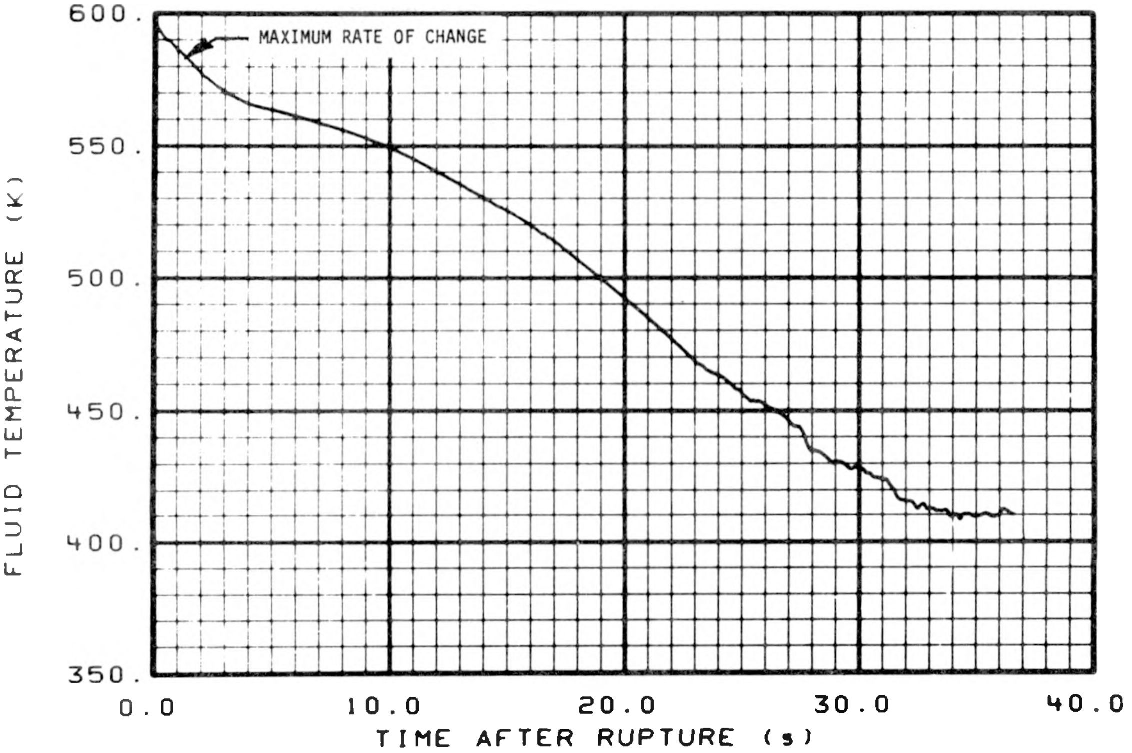


Fig. A-14 Temperature in intact loop at steam generator inlet.

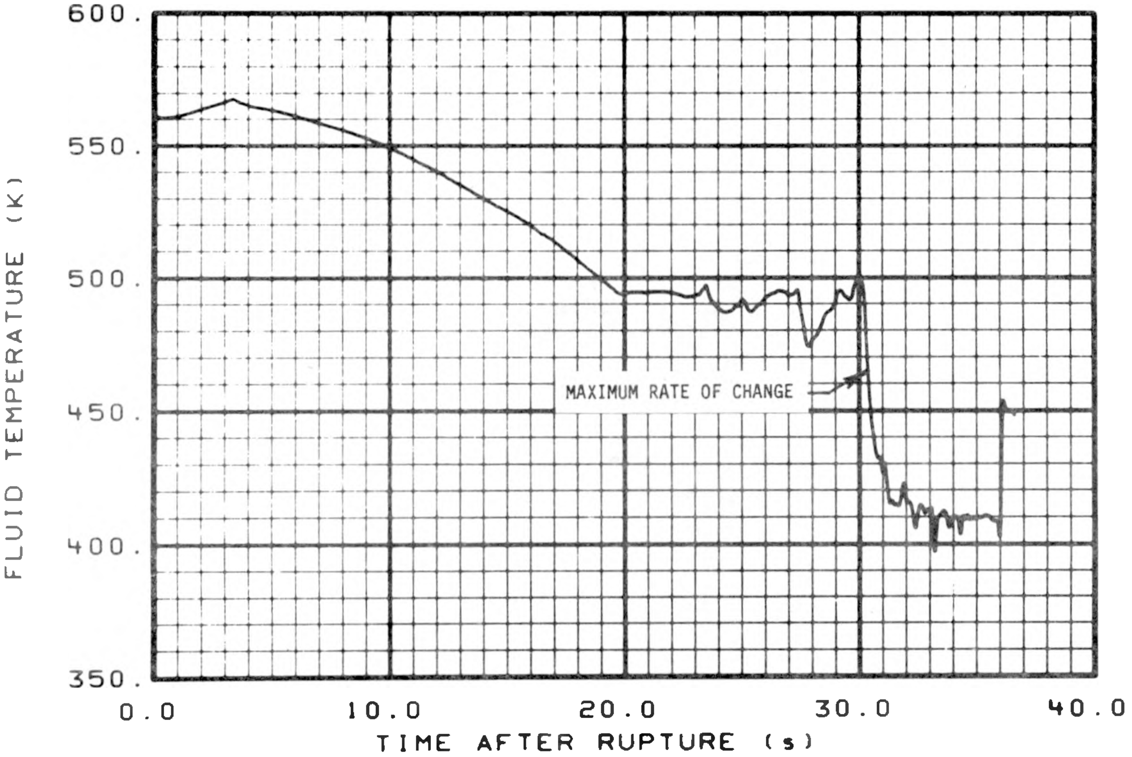


Fig. A-15 Temperature in intact loop at pump inlet.

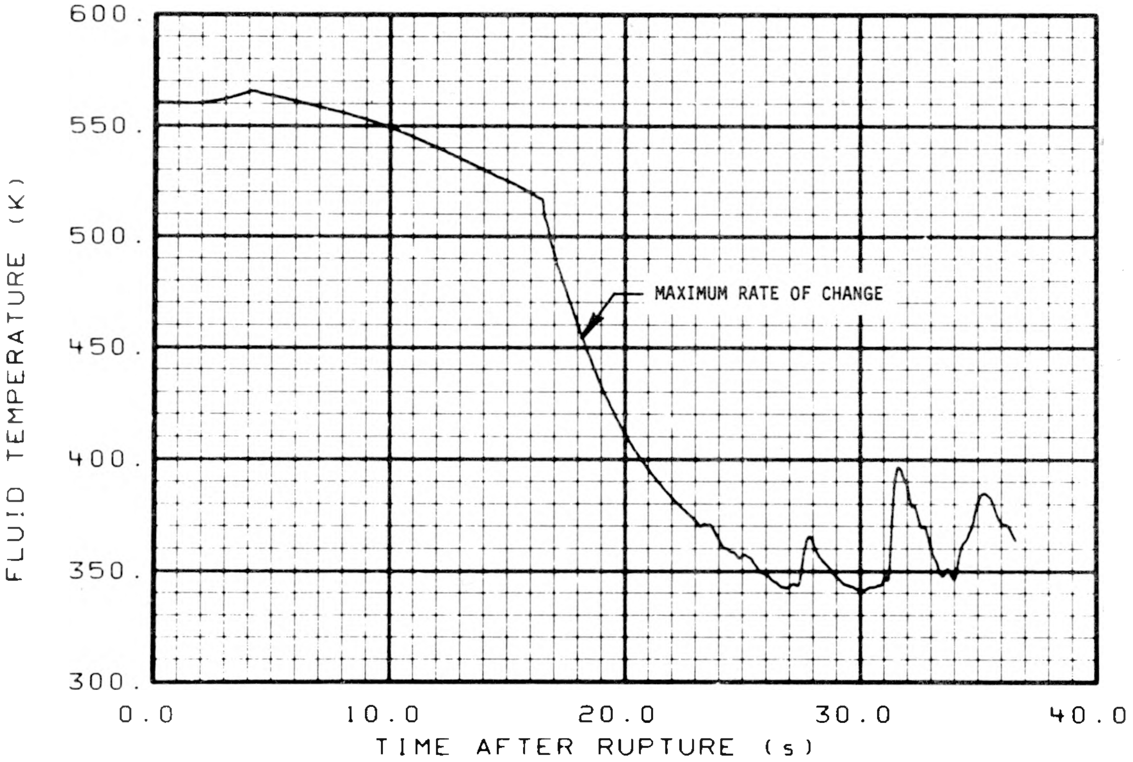


Fig. A-16 Temperature in intact loop cold leg.

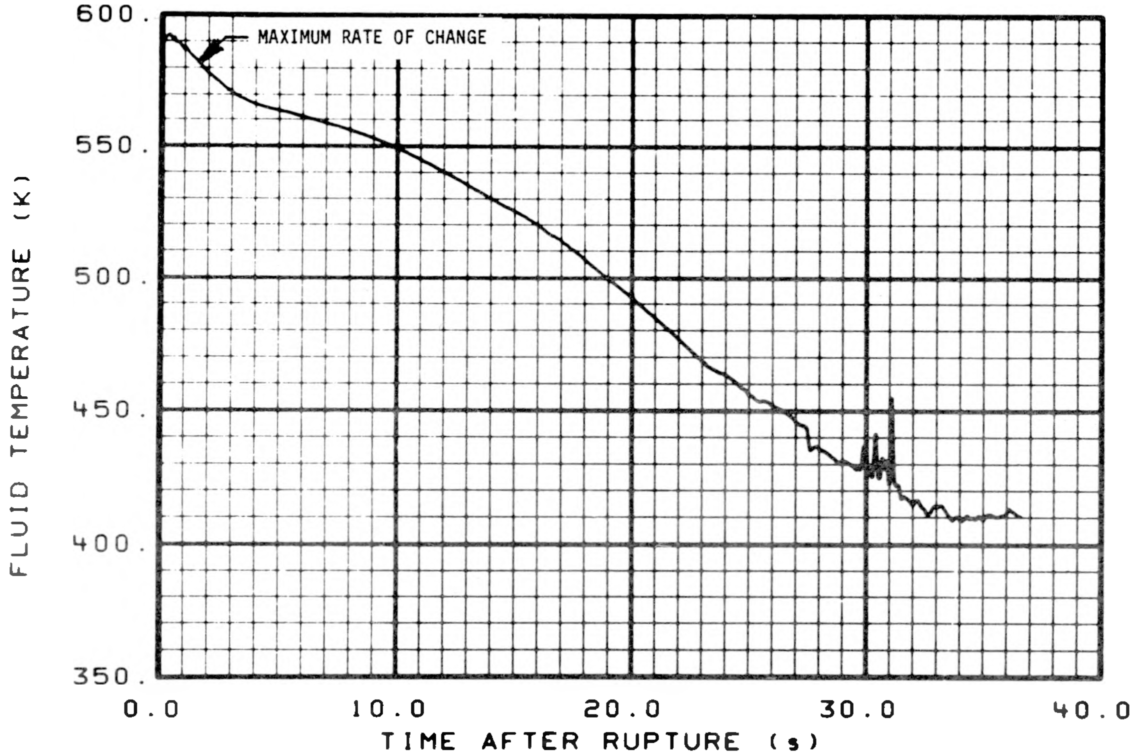


Fig. A-17 Temperature in broken loop hot leg.

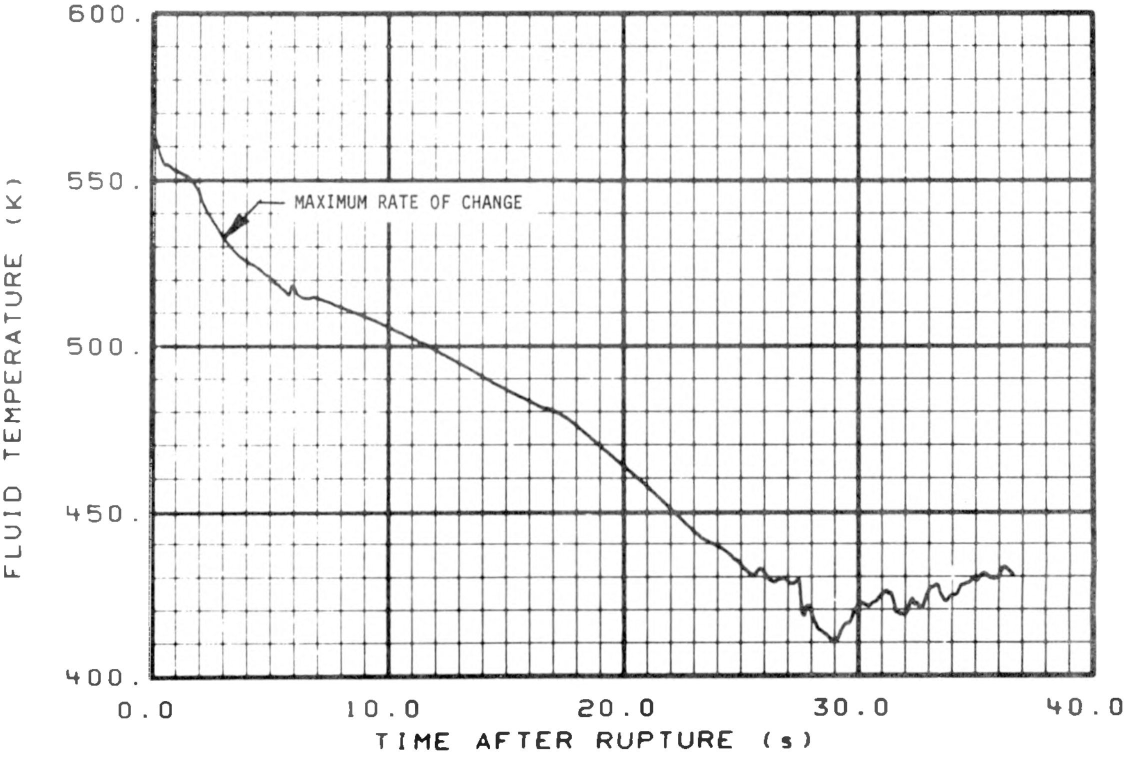


Fig. A-18 Temperature in broken loop cold leg.

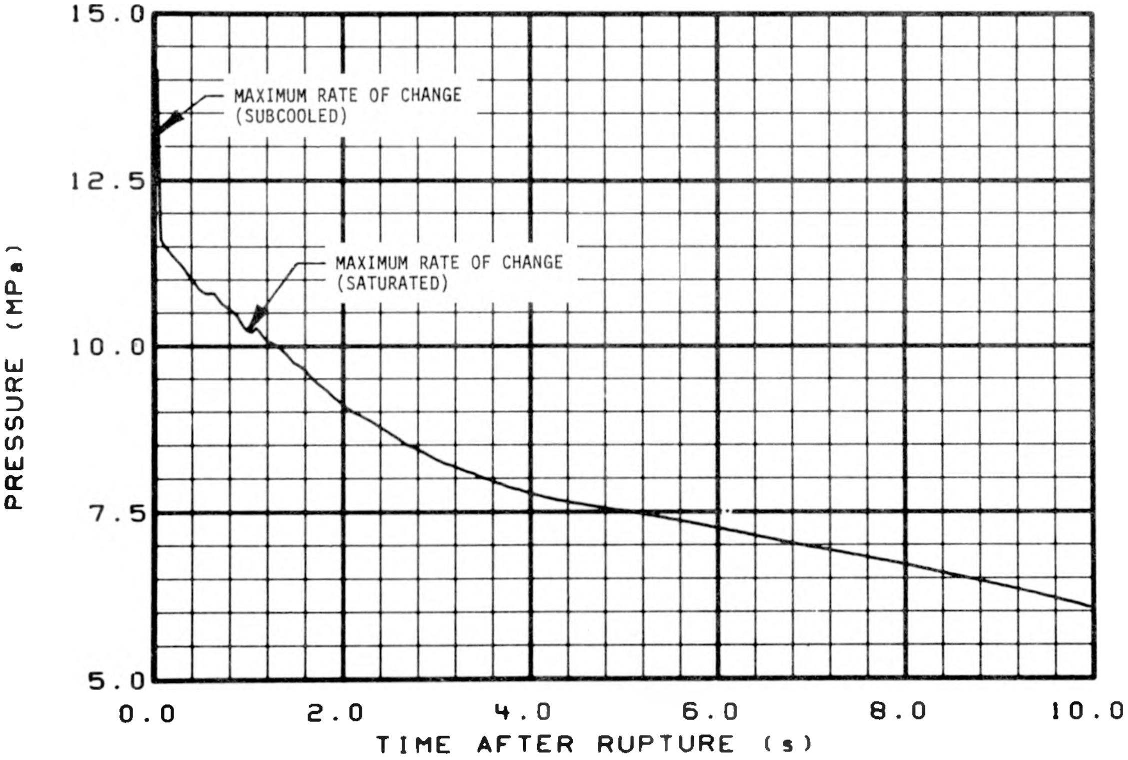


Fig. A-19 Pressure in intact loop hot leg.

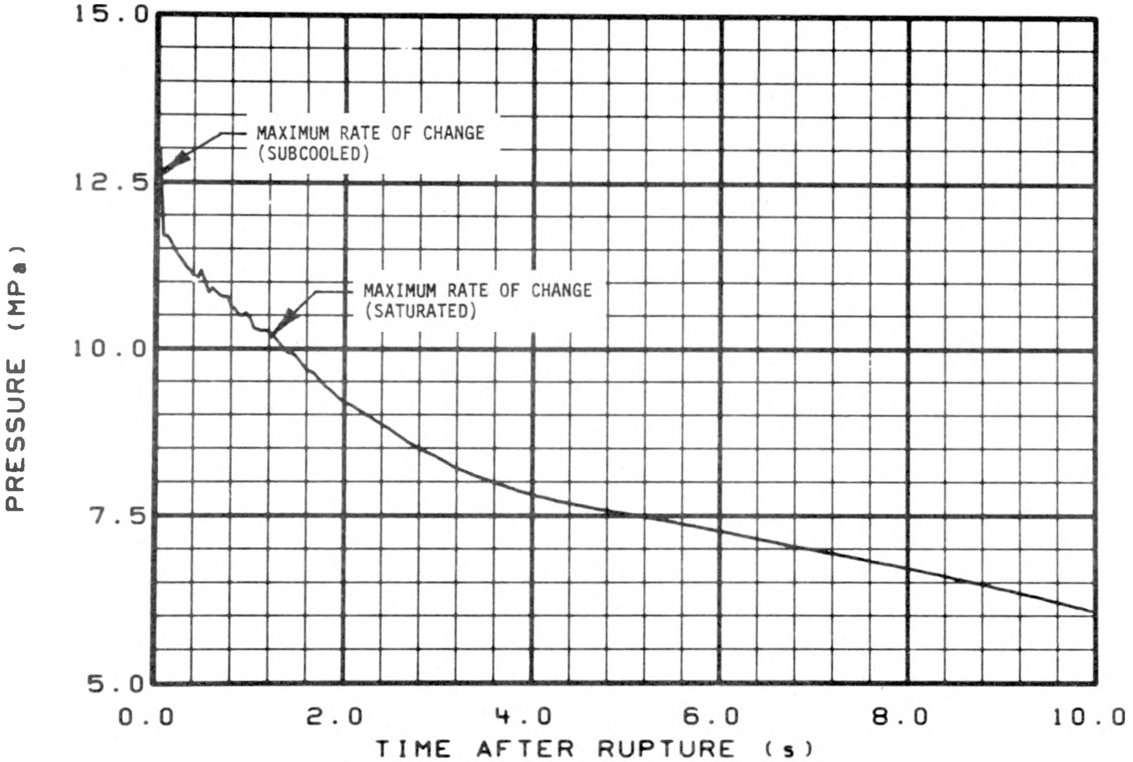


Fig. A-20 Pressure in intact loop cold leg.

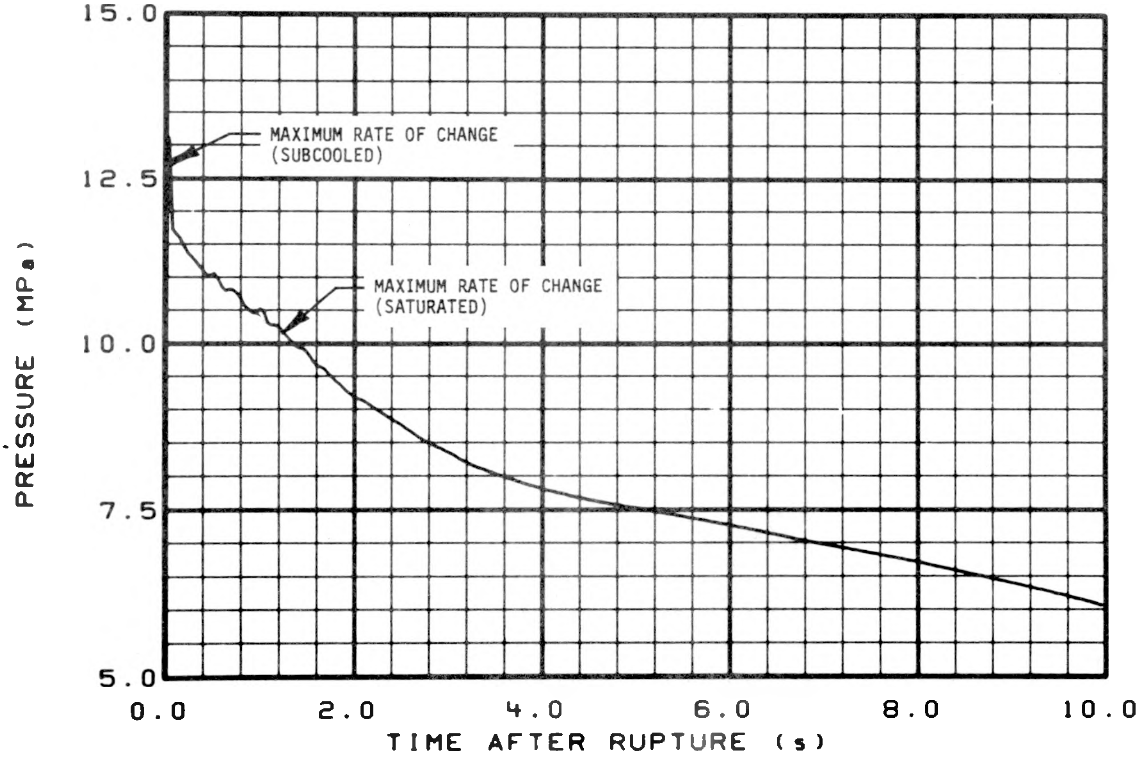


Fig. A-21 Pressure in intact loop at steam generator inlet.

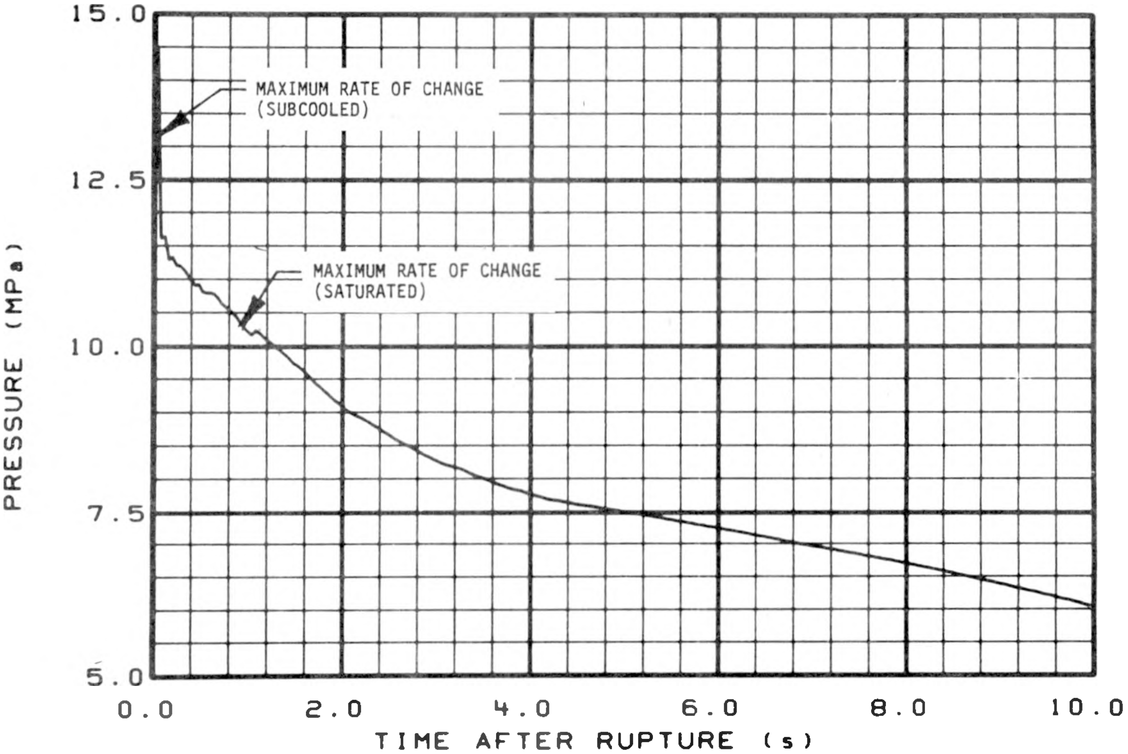


Fig. A-22 Pressure in intact loop at steam generator outlet.

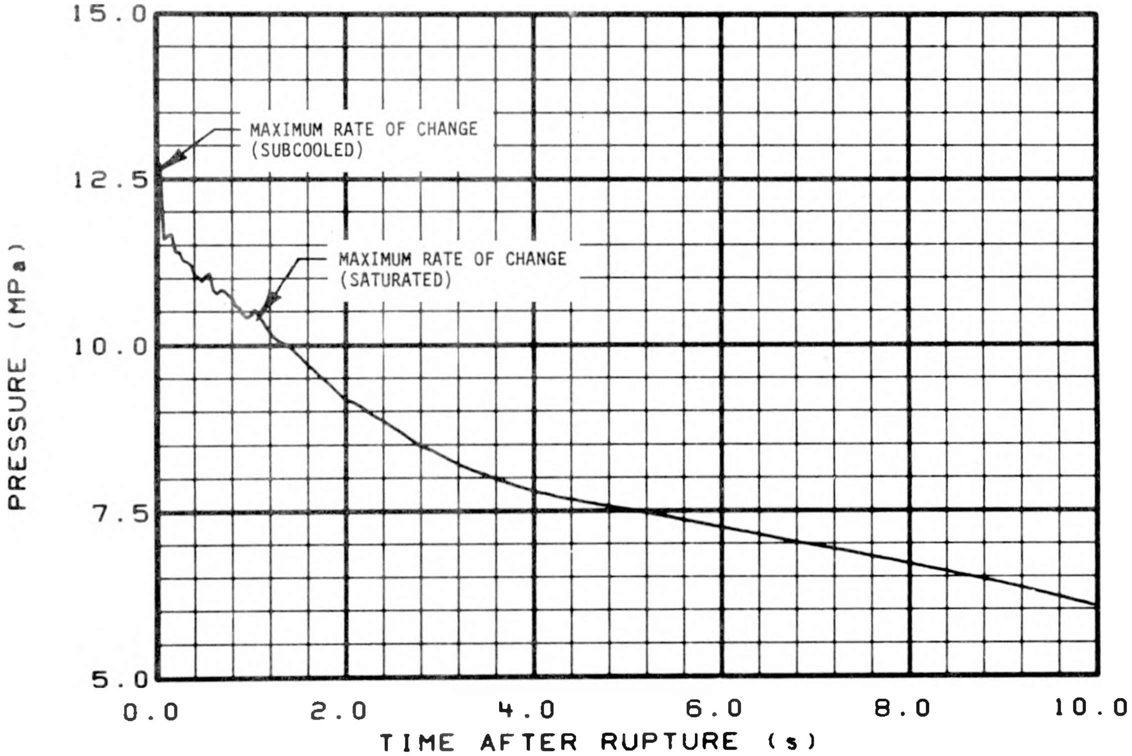


Fig. A-23 Pressure in broken loop hot leg.

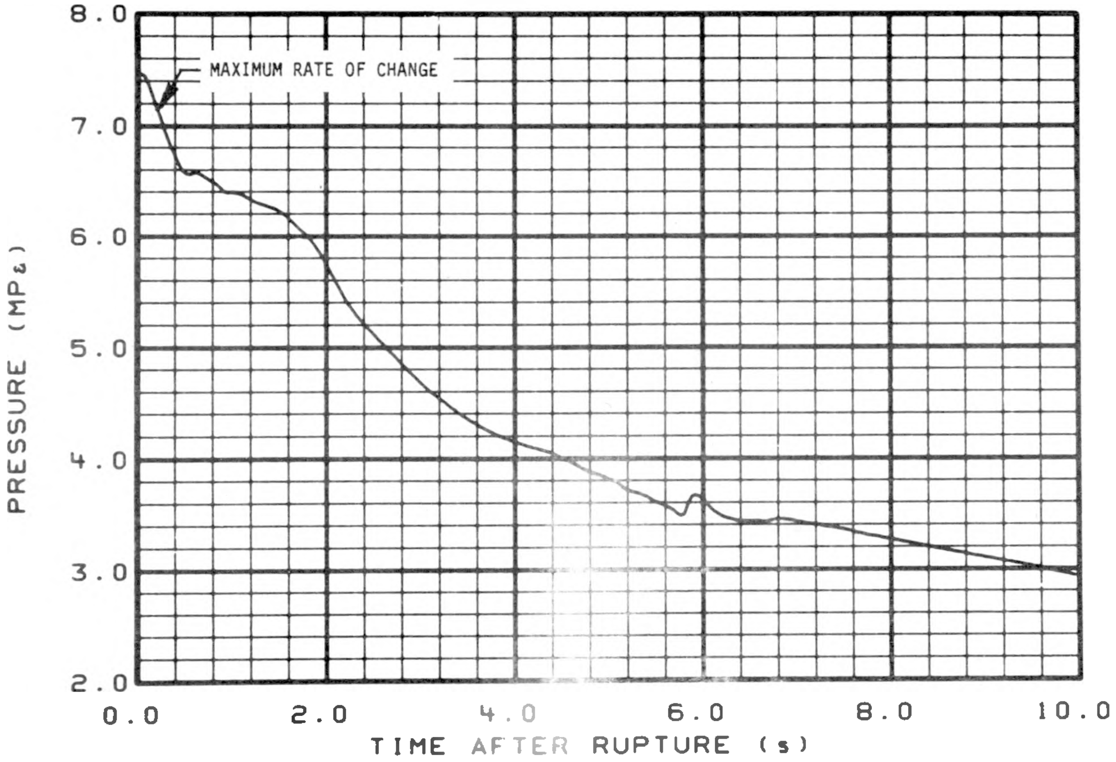


Fig. A-24 Pressure in broken loop cold leg.

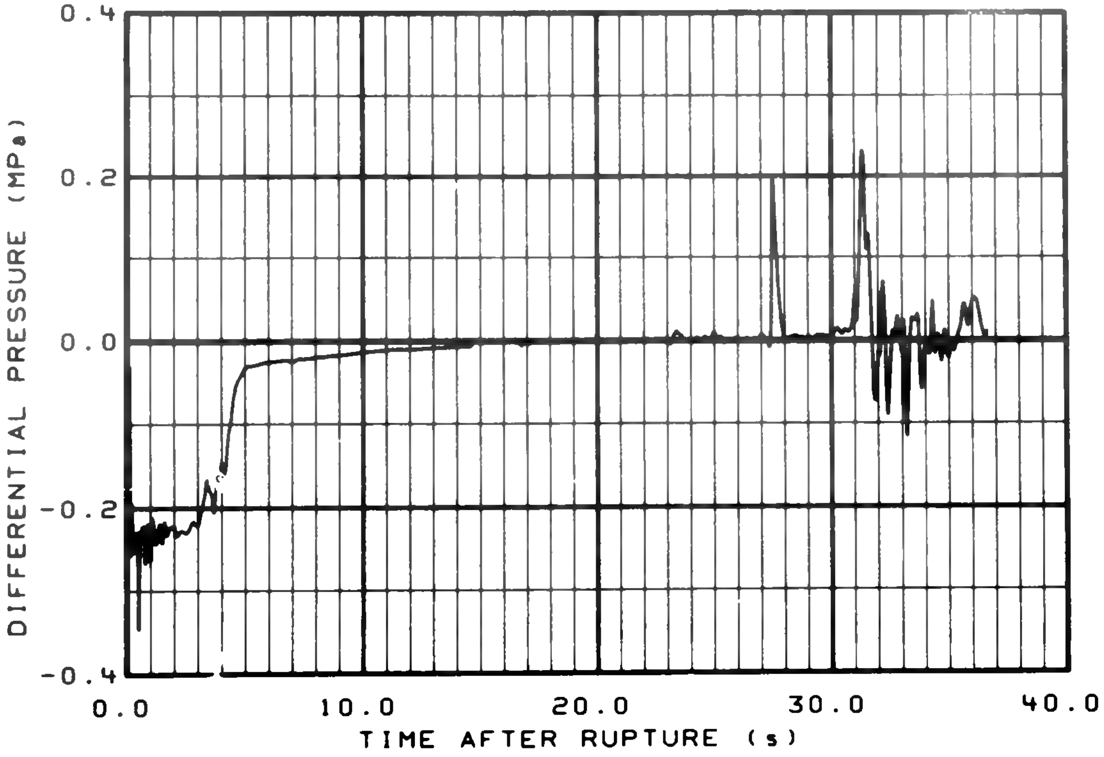


Fig. A-25 Differential pressure in intact loop across pump A.

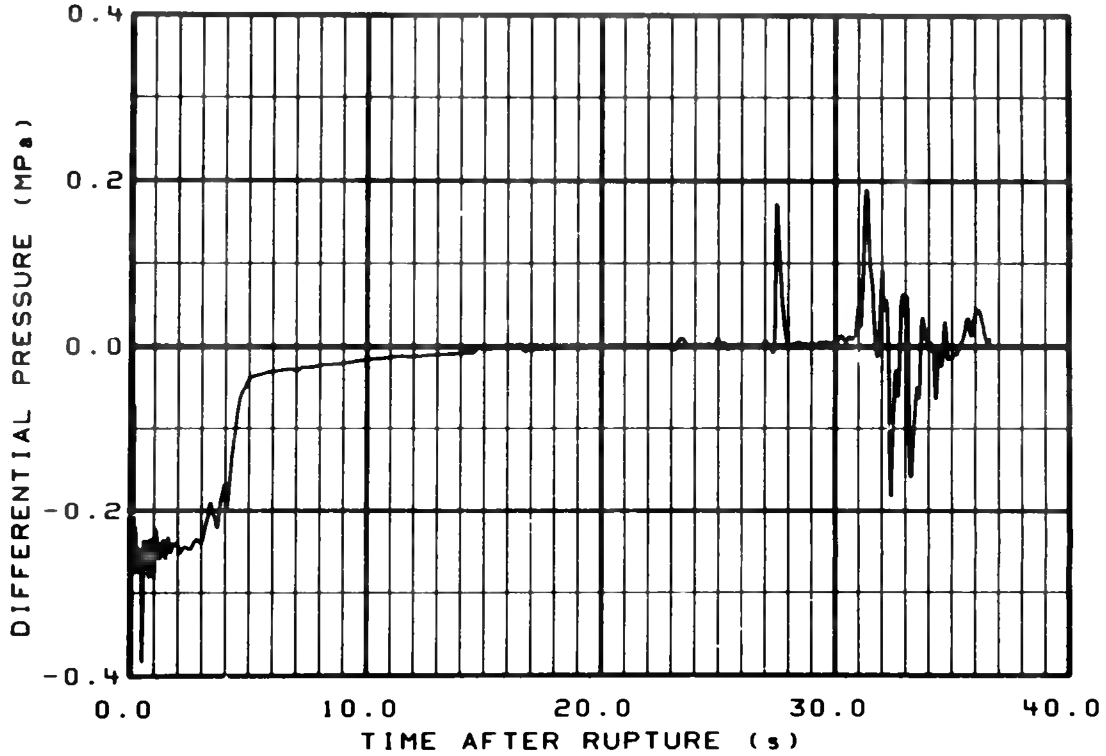


Fig. A-26 Differential pressure in intact loop across pump B.

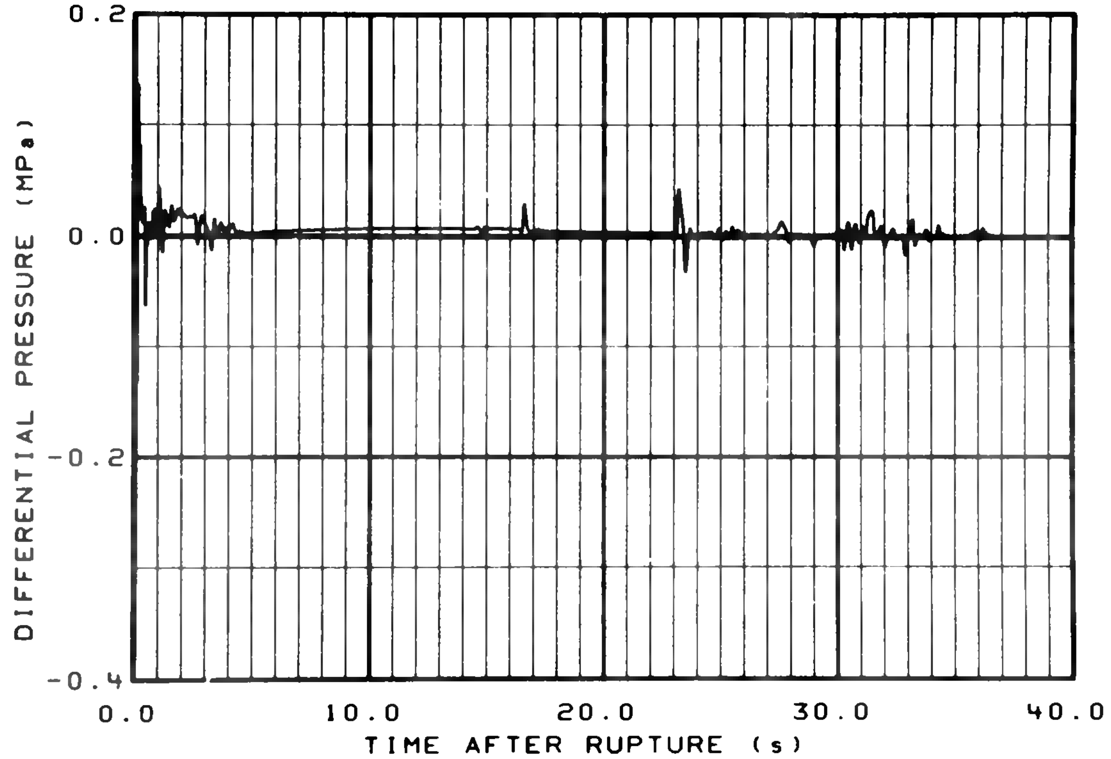


Fig. A-27 Differential pressure in intact loop across steam generator.

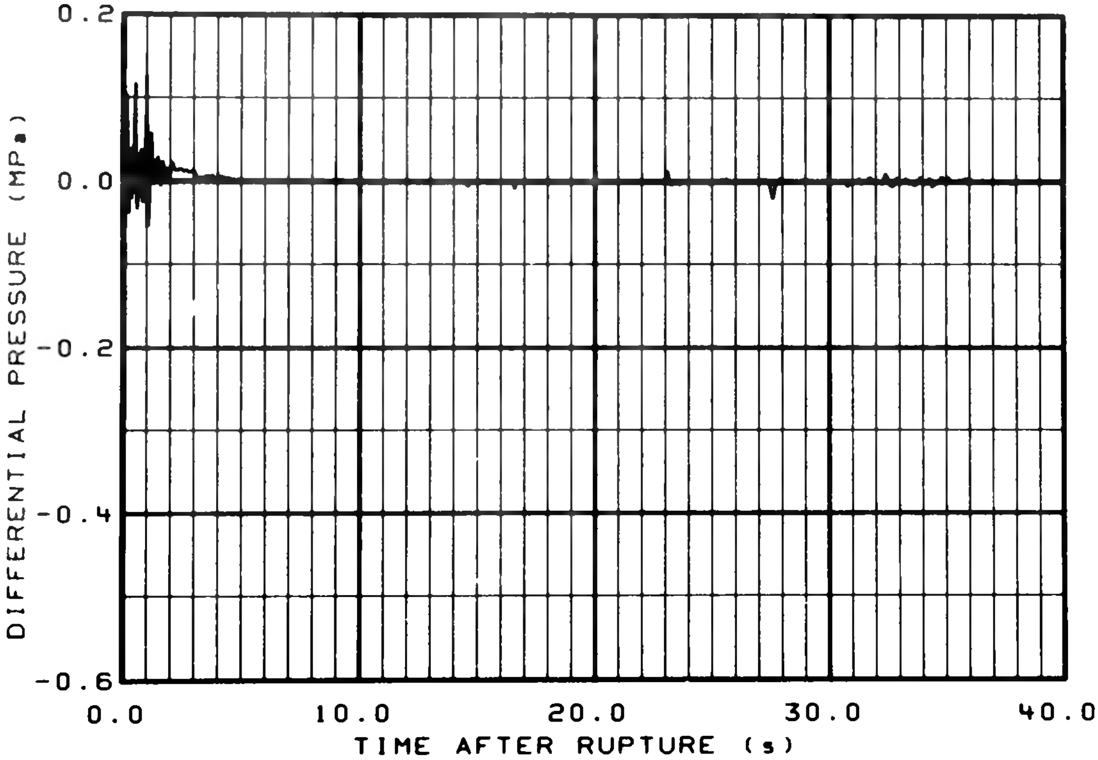


Fig. A-28 Differential pressure in intact loop between reactor vessel and pressurizer surge line.

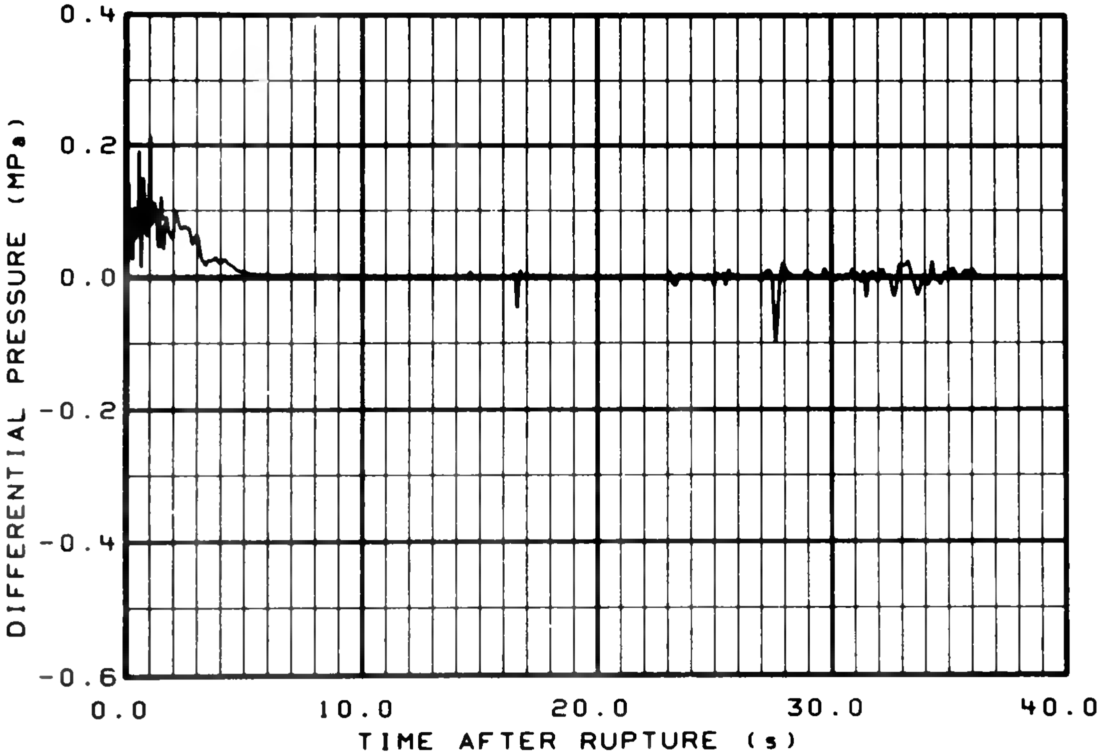


Fig. A-29 Differential pressure in intact loop between pressurizer surge line and steam generator inlet.

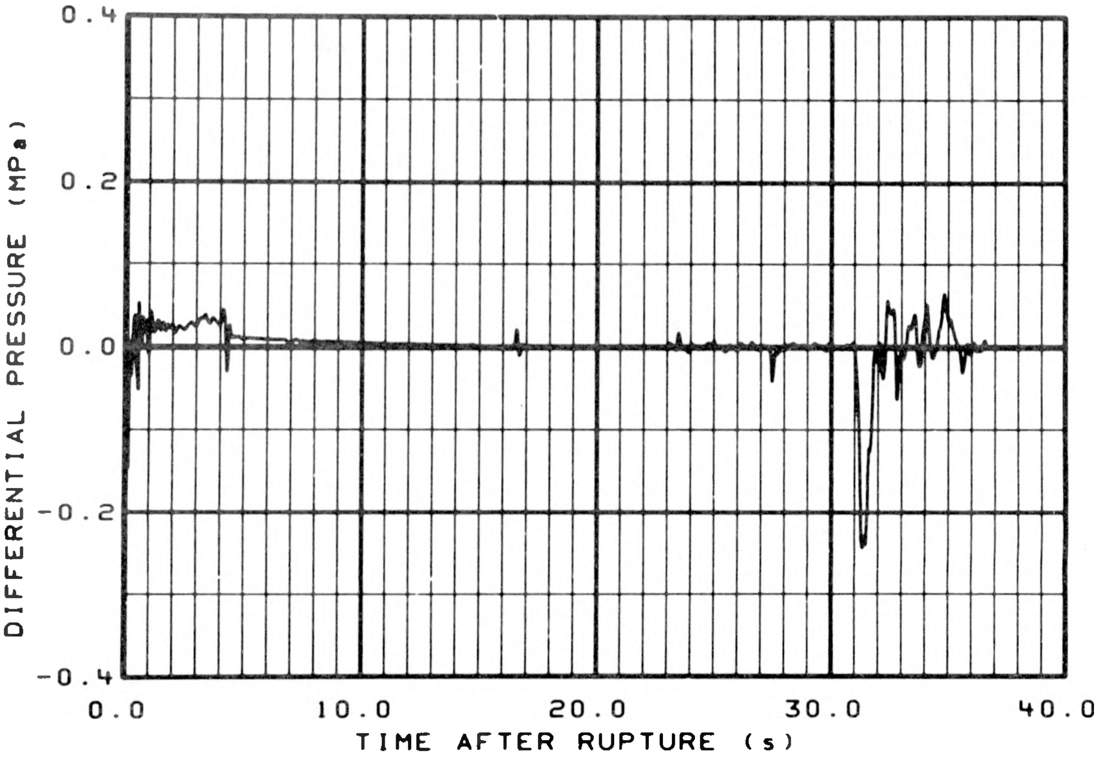


Fig. A-30 Differential pressure in intact loop between pumps and reactor vessel.

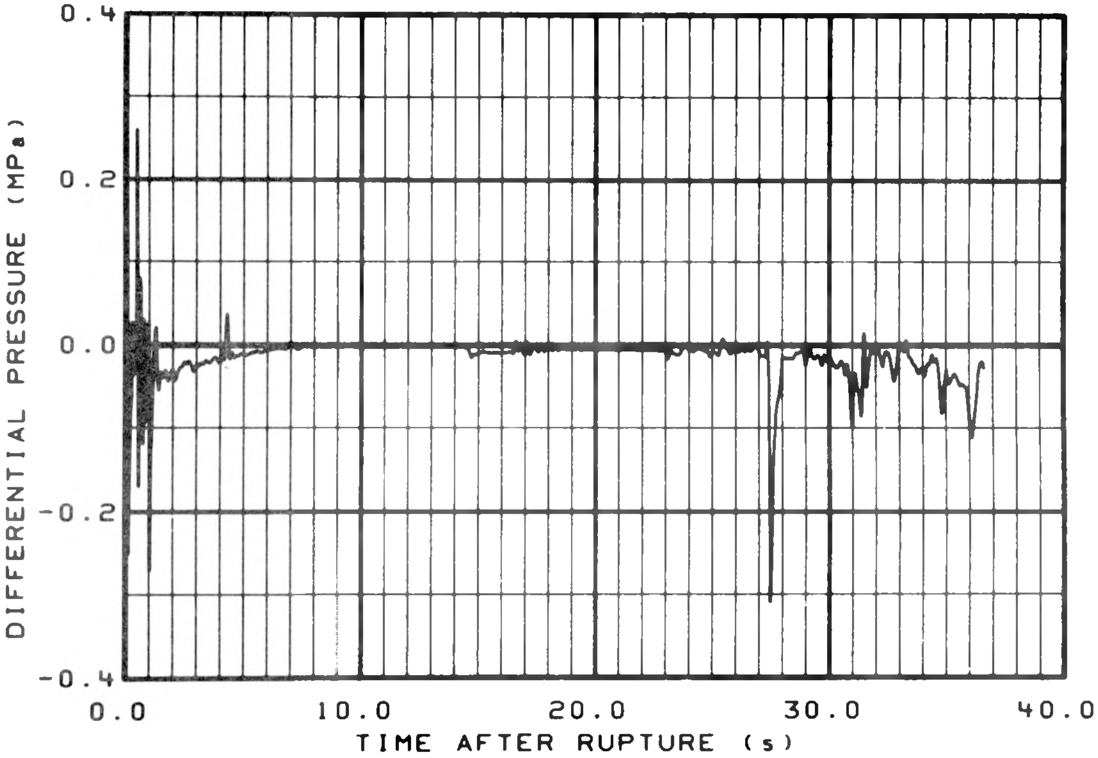


Fig. A-31 Differential pressure across reactor vessel.

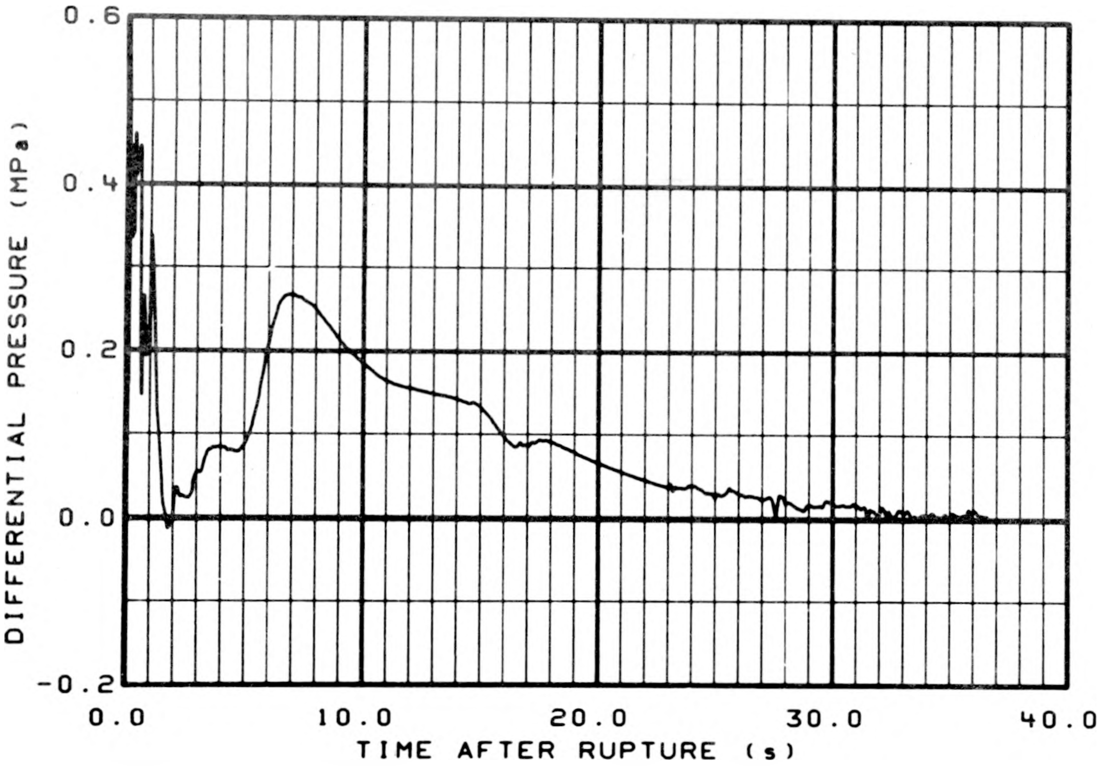


Fig. A-32 Differential pressure in broken loop across 14-to-5-in. contraction.

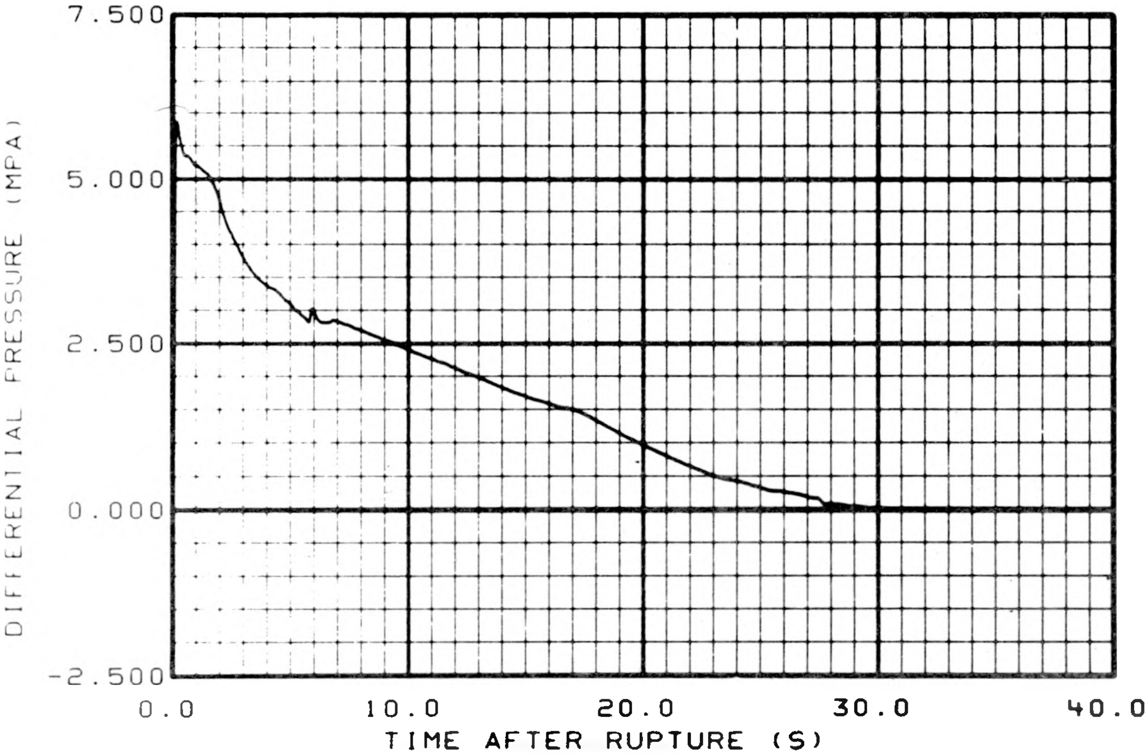


Fig. A-33 Differential pressure in broken loop across hot leg break plane.

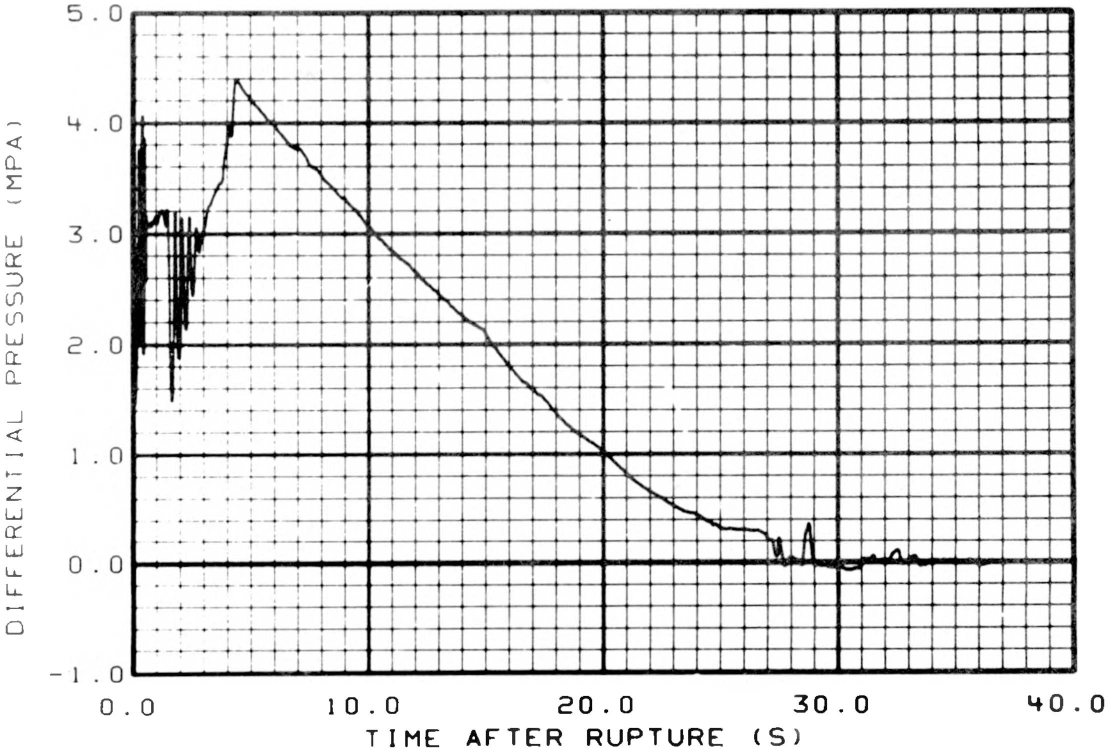


Fig. A-34 Differential pressure in broken loop across cold leg break plane.

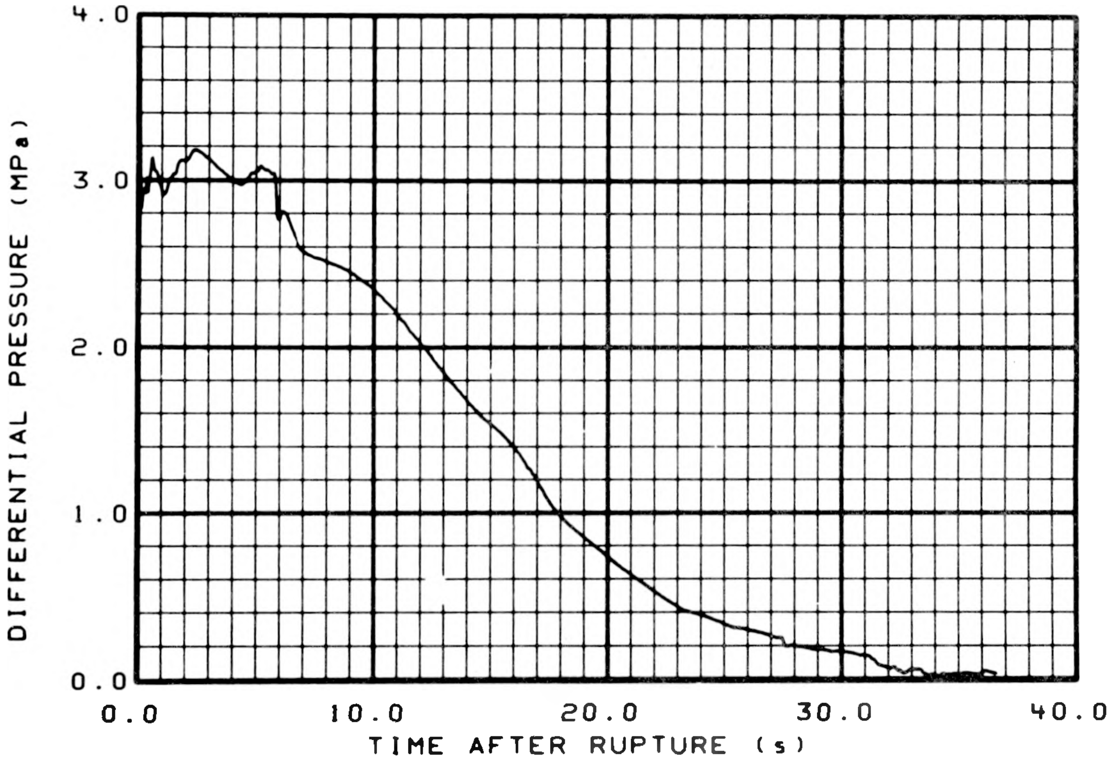


Fig. A-35 Differential pressure in broken loop across pump simulator.

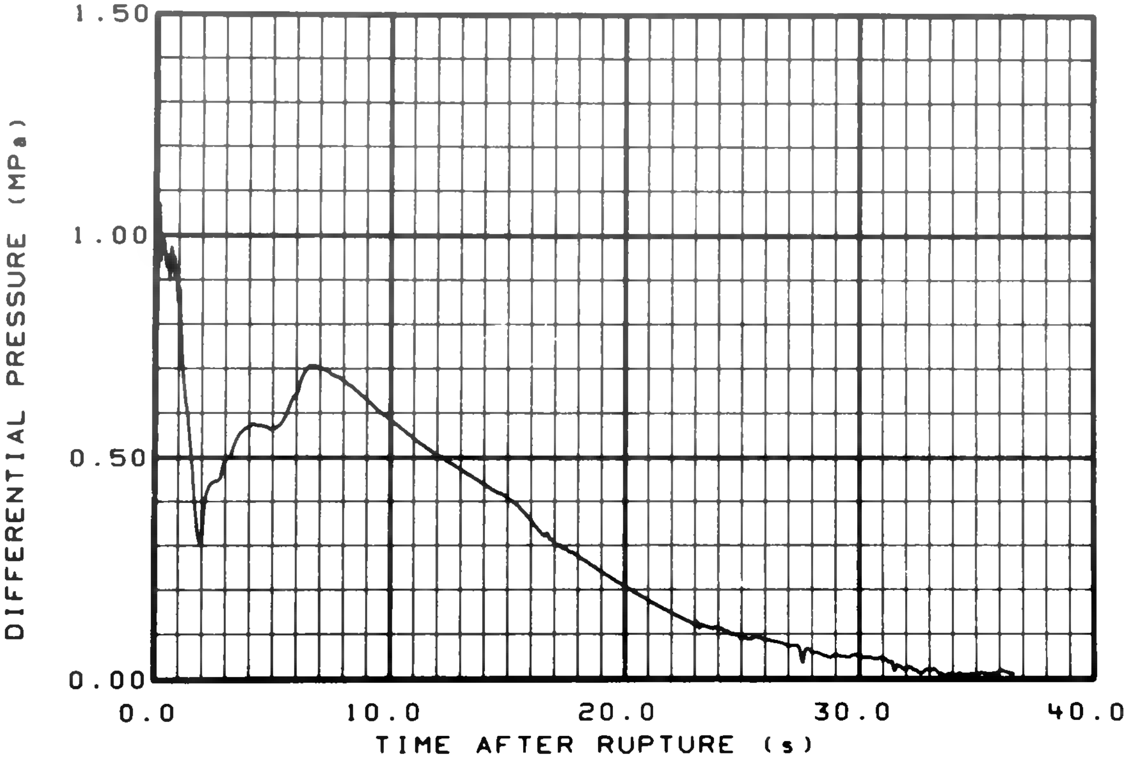


Fig. A-36 Differential pressure in broken loop across steam generator simulator.

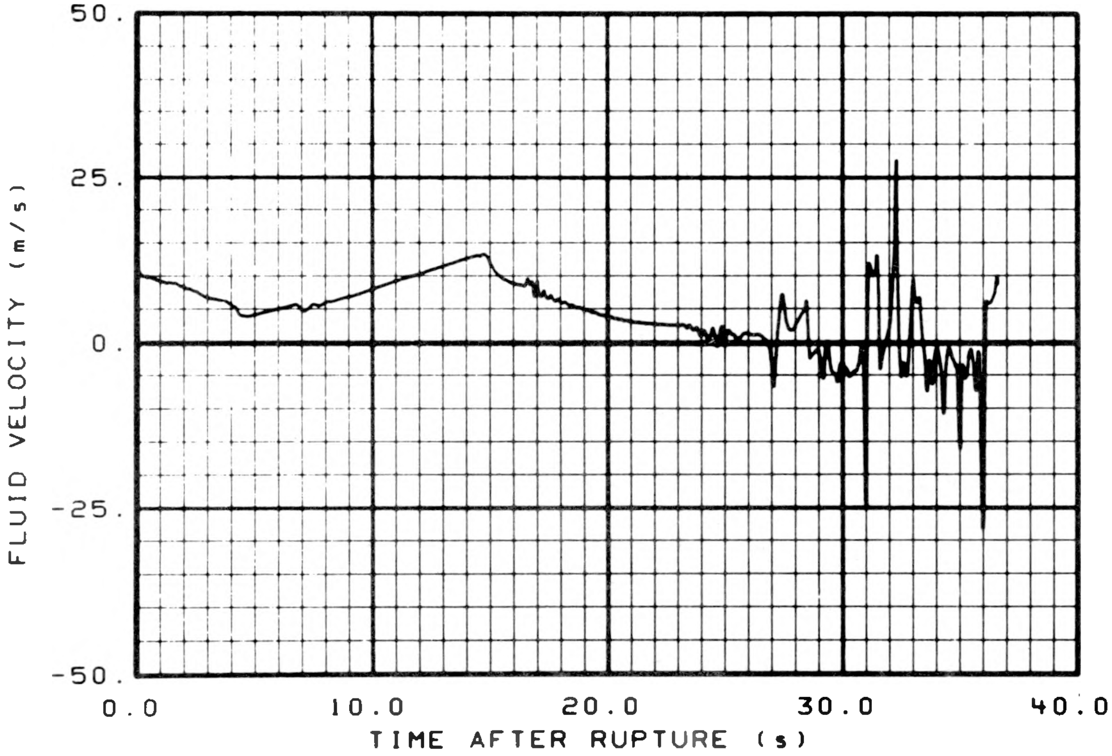


Fig. A-37 Fluid velocity in broken loop cold leg.

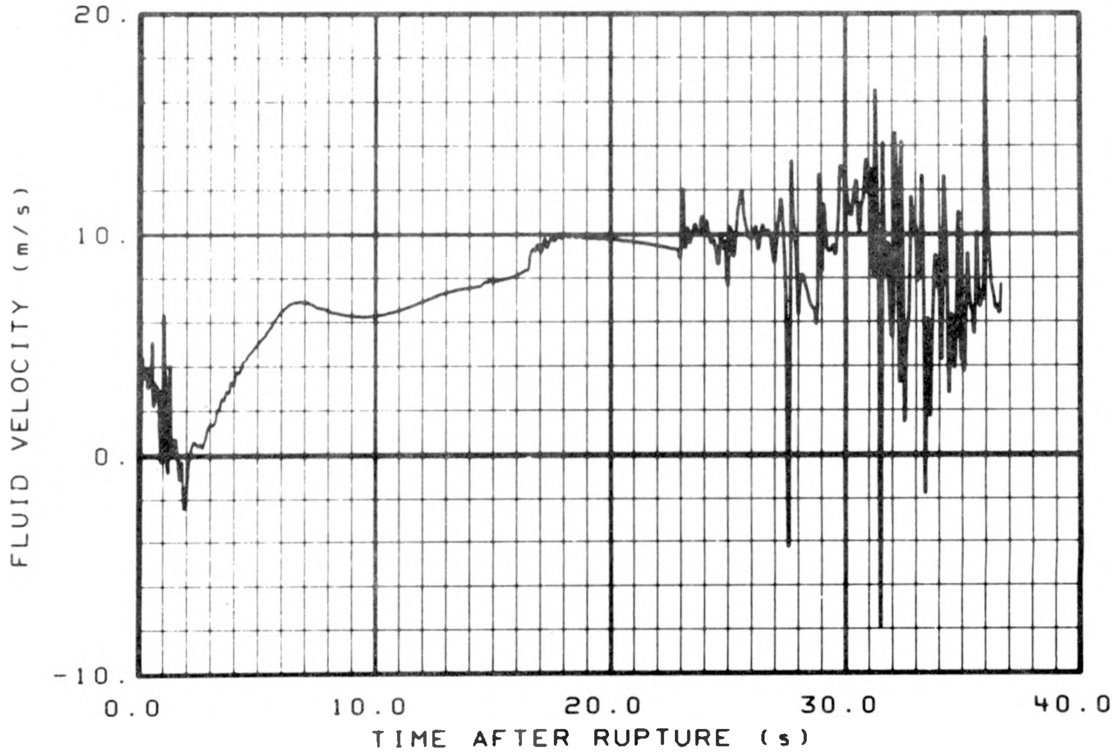


Fig. A-38 Fluid velocity in broken loop hot leg.

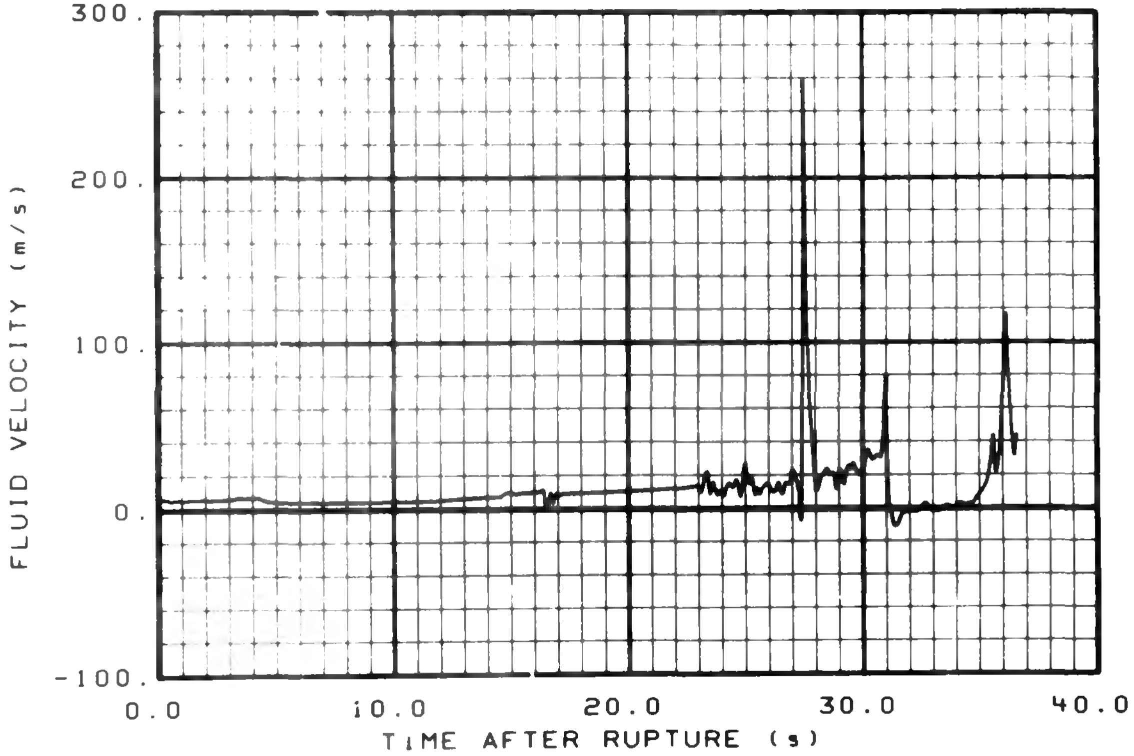


Fig. A-39 Fluid velocity in intact loop cold leg.

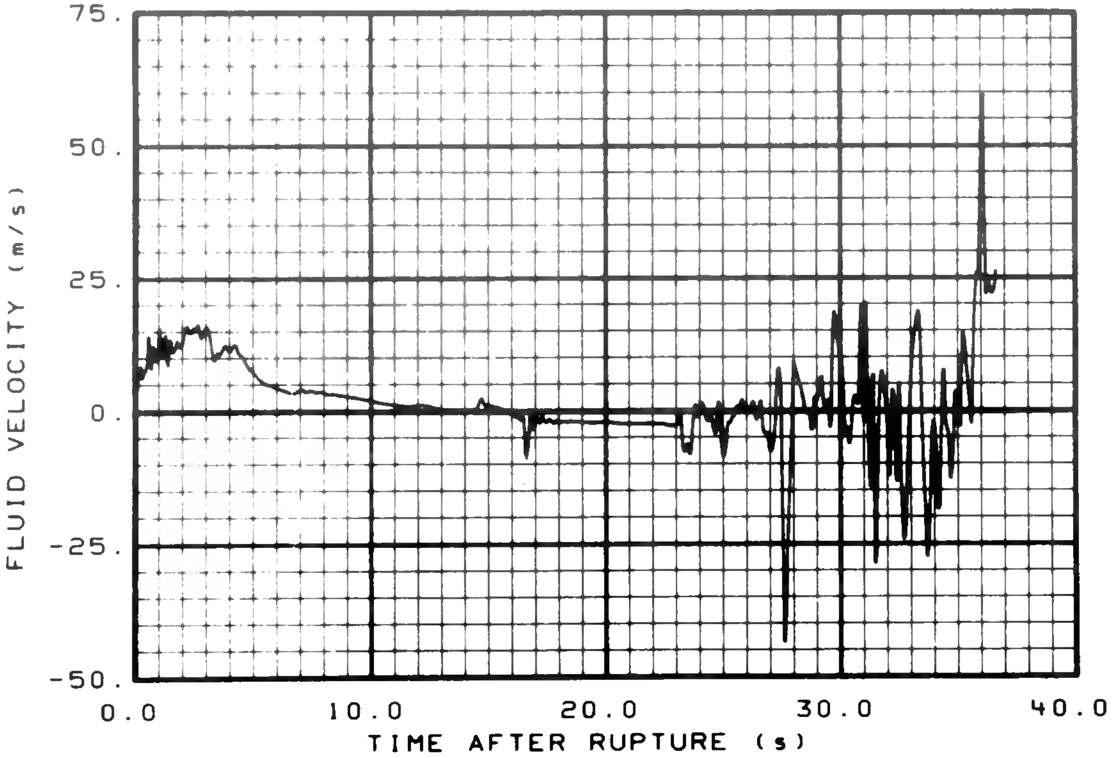


Fig. A-40 Fluid velocity in intact loop hot leg.

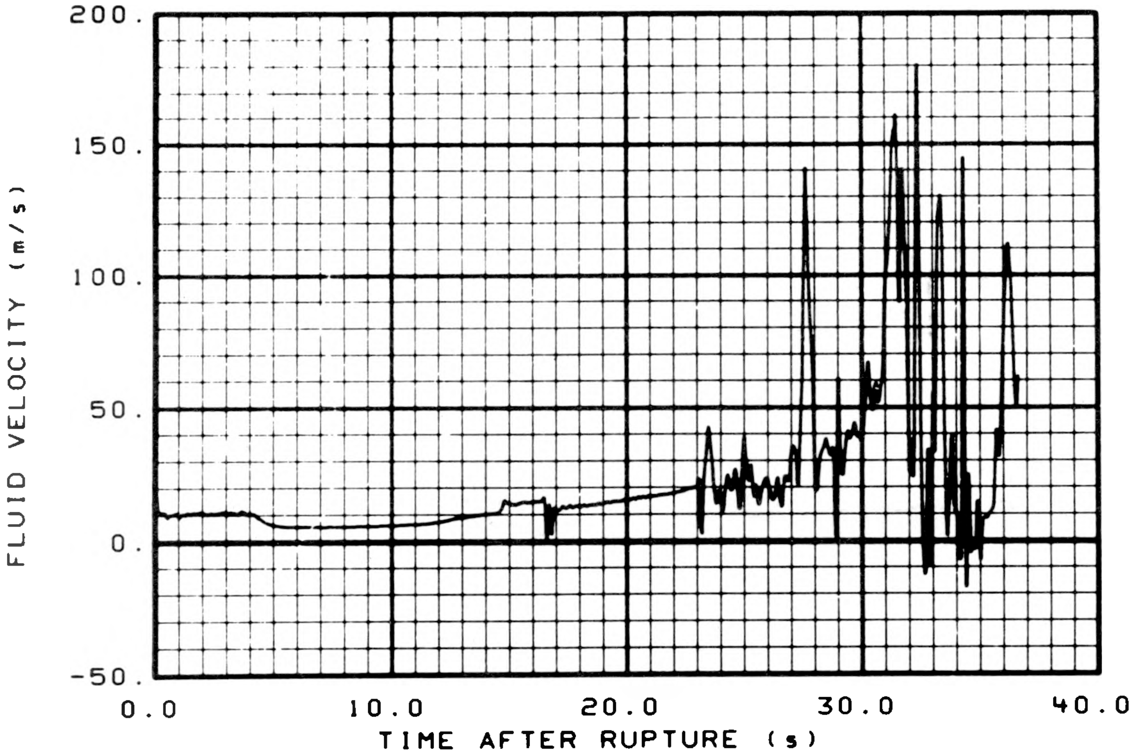
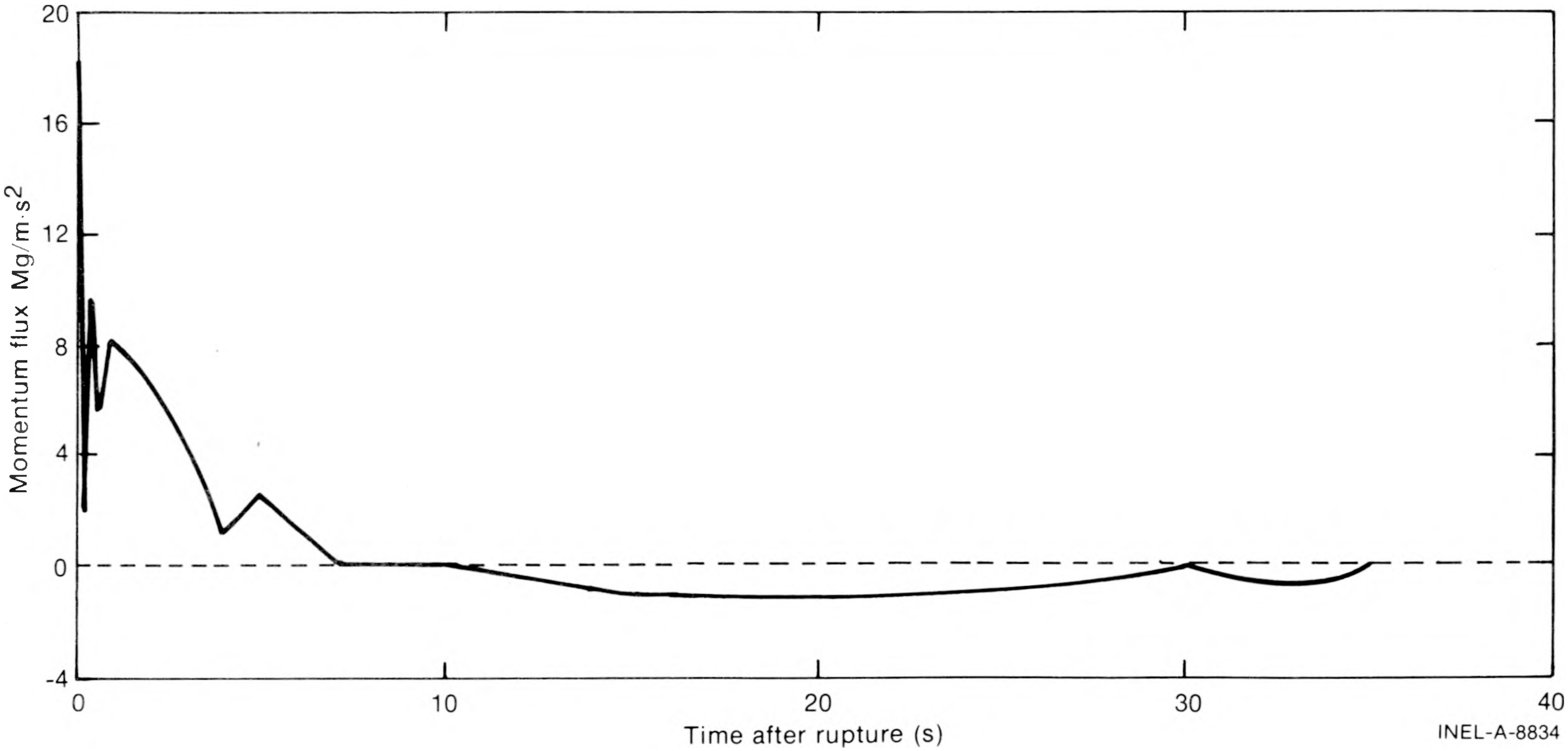


Fig. A-41 Fluid velocity in intact loop at steam generator outlet.



INEL-A-8834

Fig. A-42 Momentum flux in intact loop hot leg.

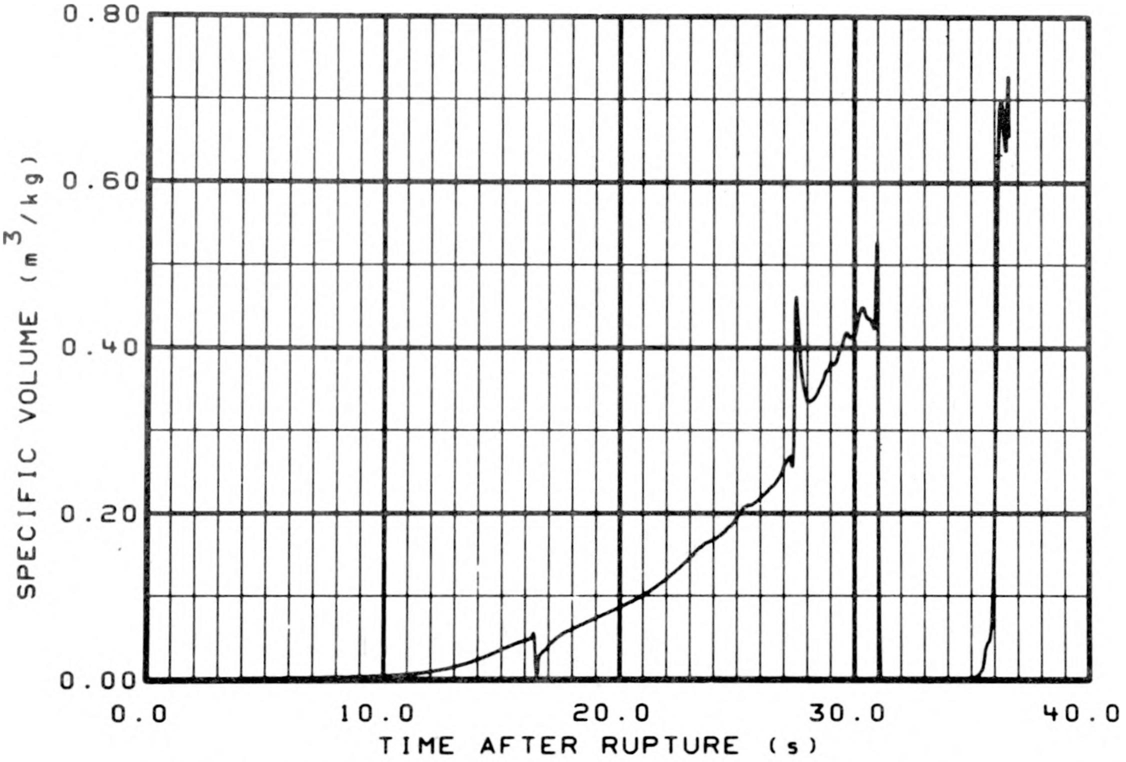


Fig. A-43 Specific volume in intact loop cold leg.

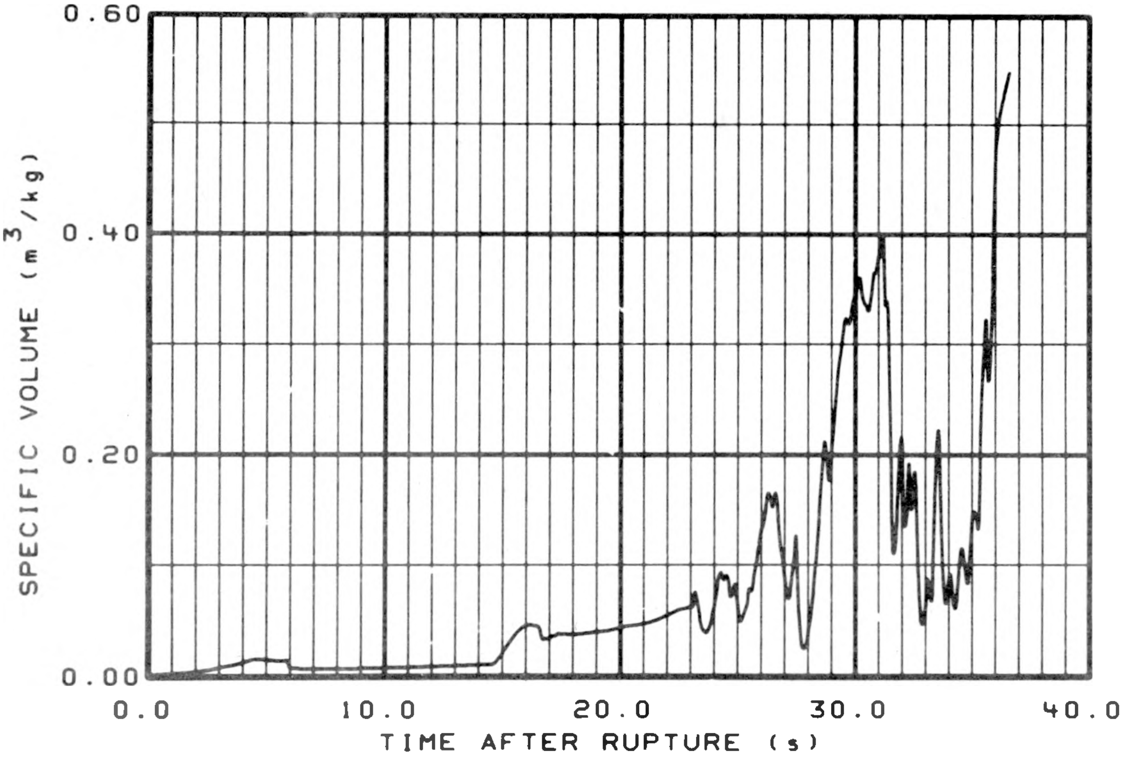


Fig. A-44 Specific volume in intact loop hot leg.

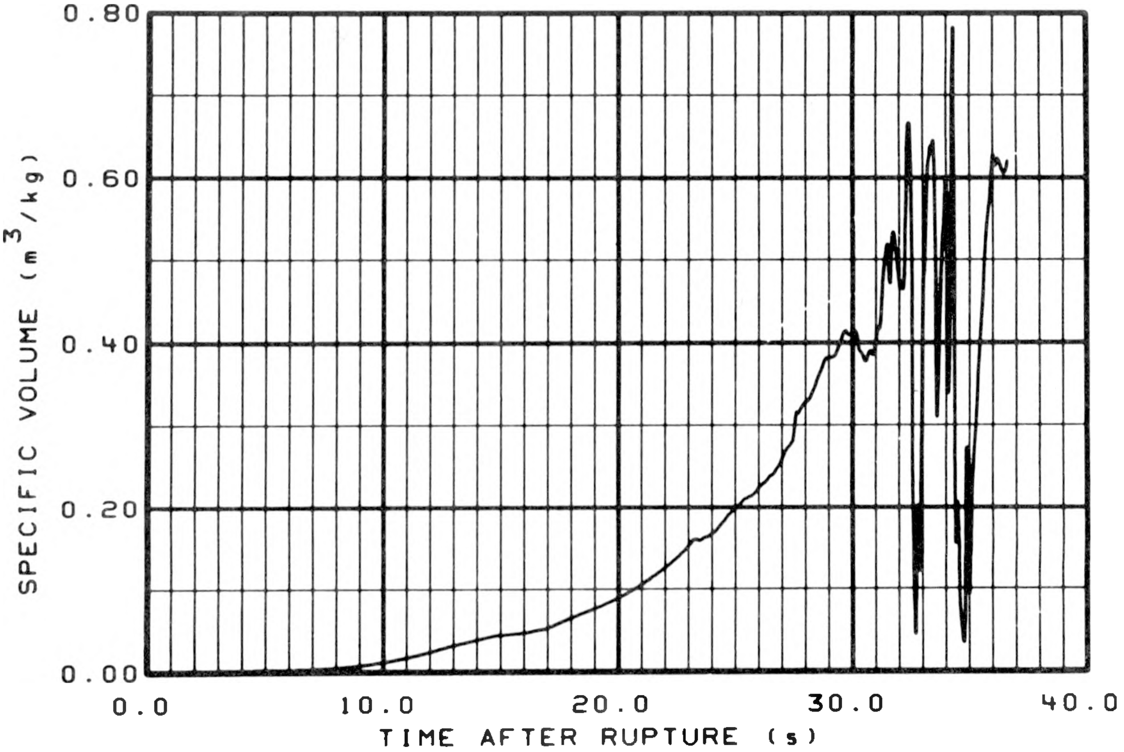


Fig. A-45 Specific volume in intact loop at pump inlet.

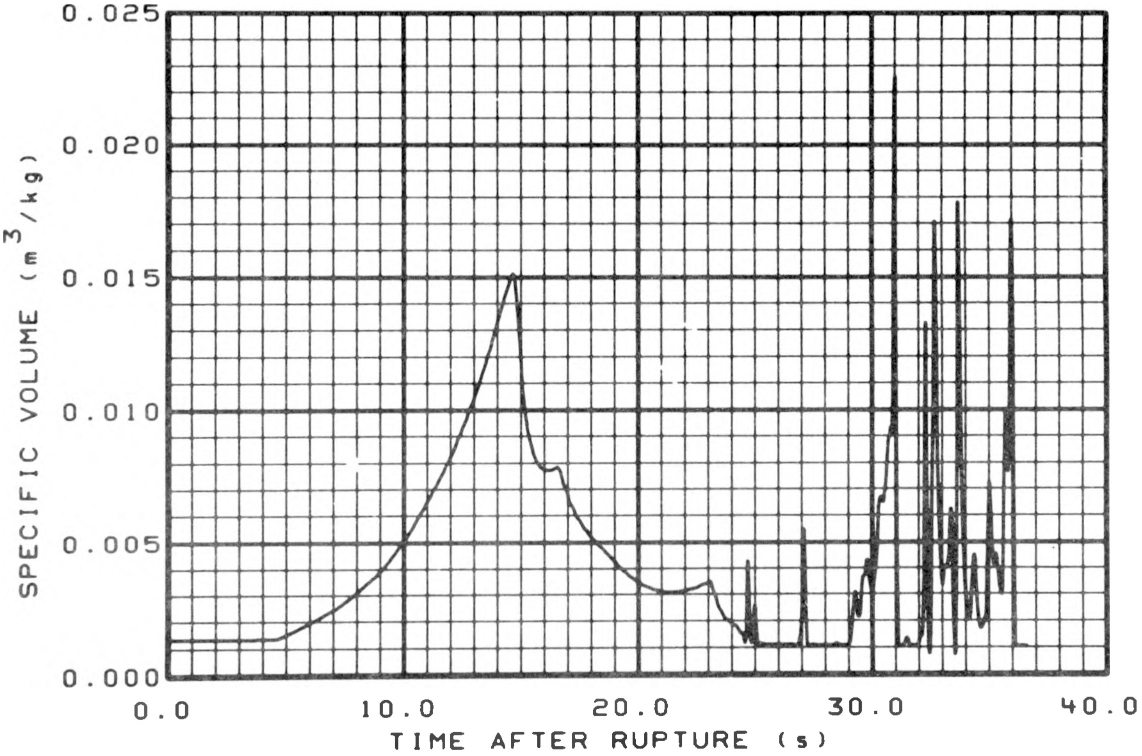


Fig. A-46 Specific volume in broken loop hot leg.

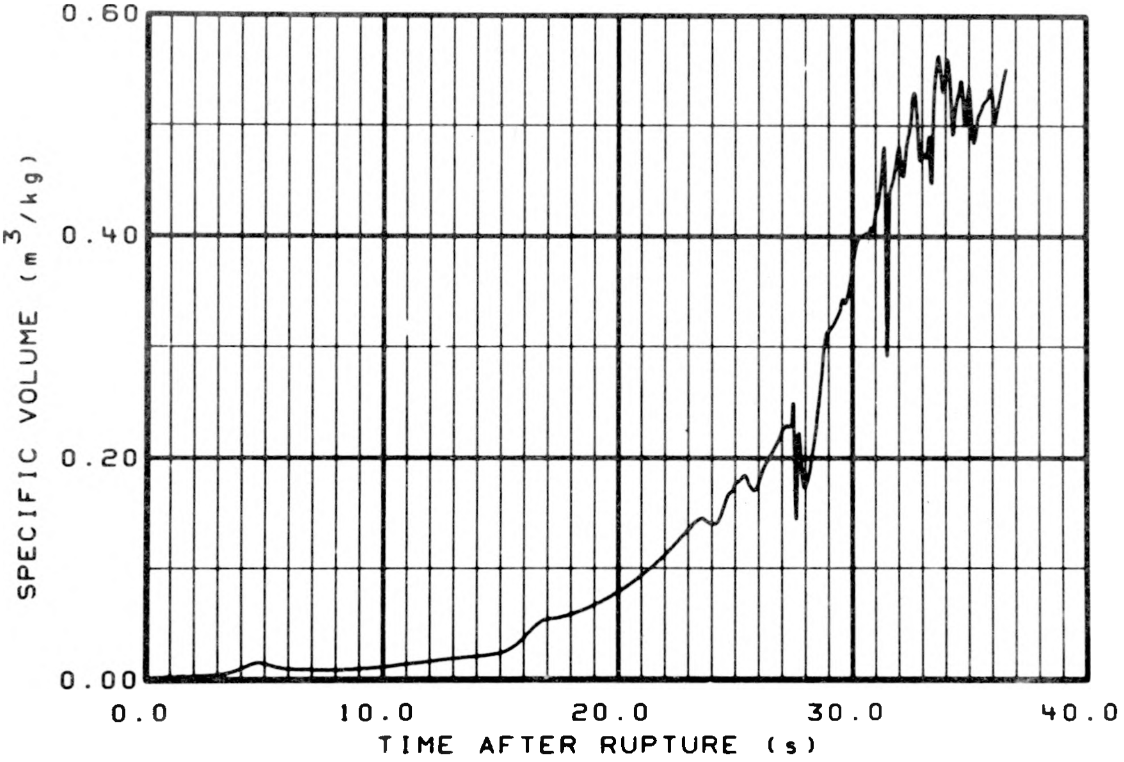


Fig. A-47 Specific volume in broken loop cold leg.

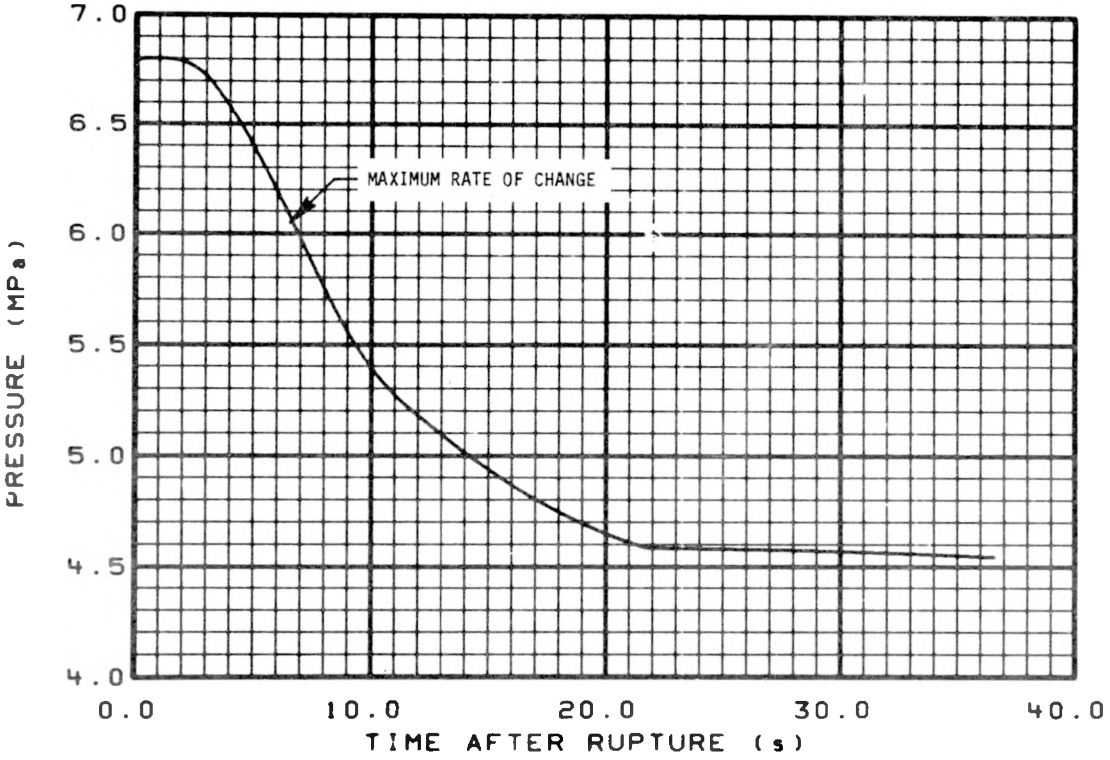


Fig. A-48 Pressure in steam generator secondary side.

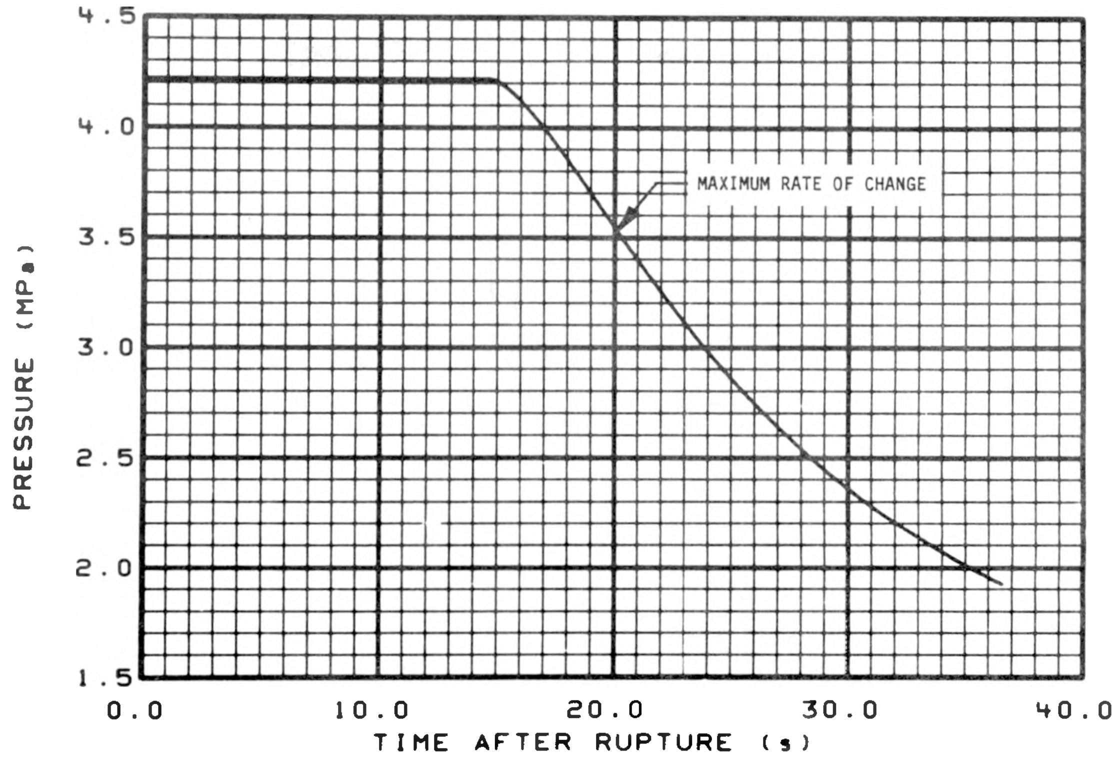


Fig. A-49 Pressure in accumulator.

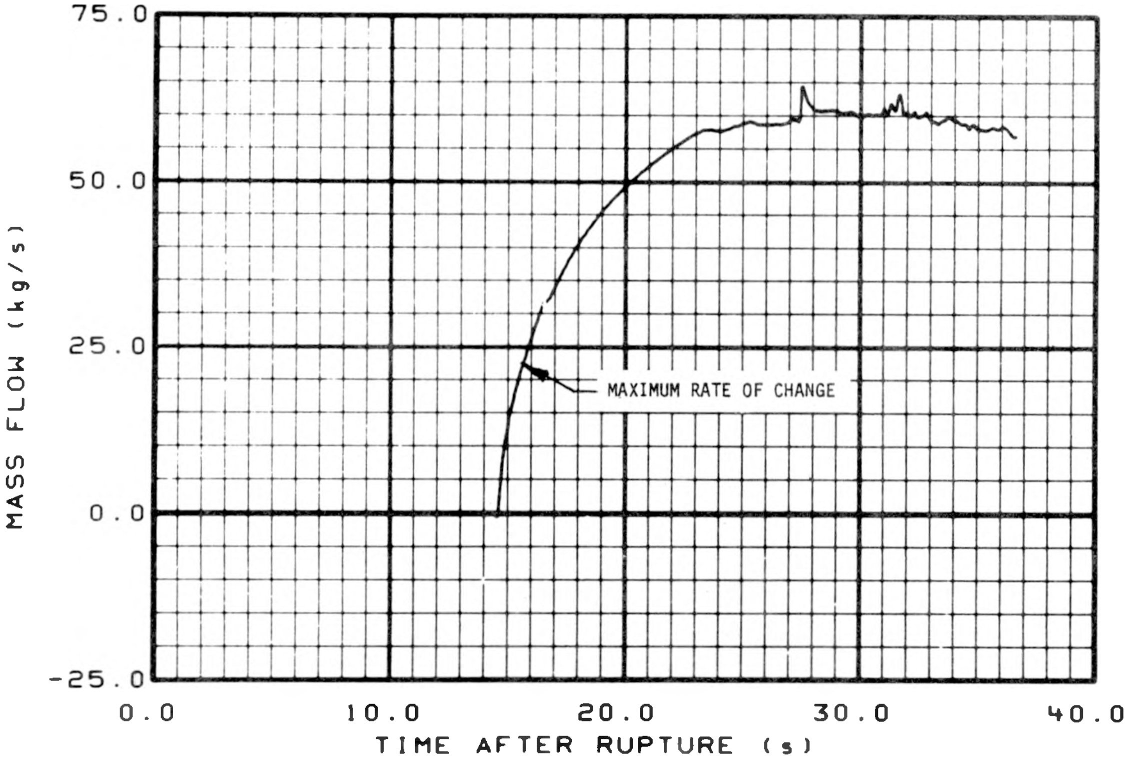


Fig. A-50 Mass flow rate for accumulator.

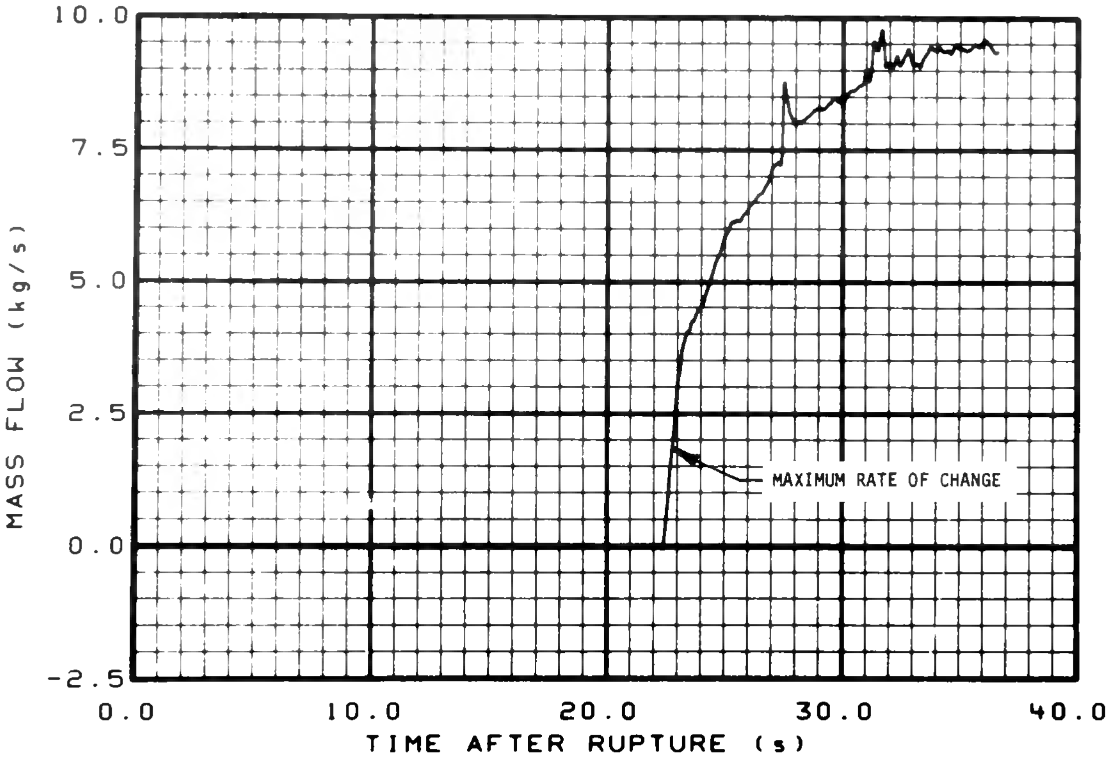


Fig. A-51 Mass flow rate for low-pressure injection system.

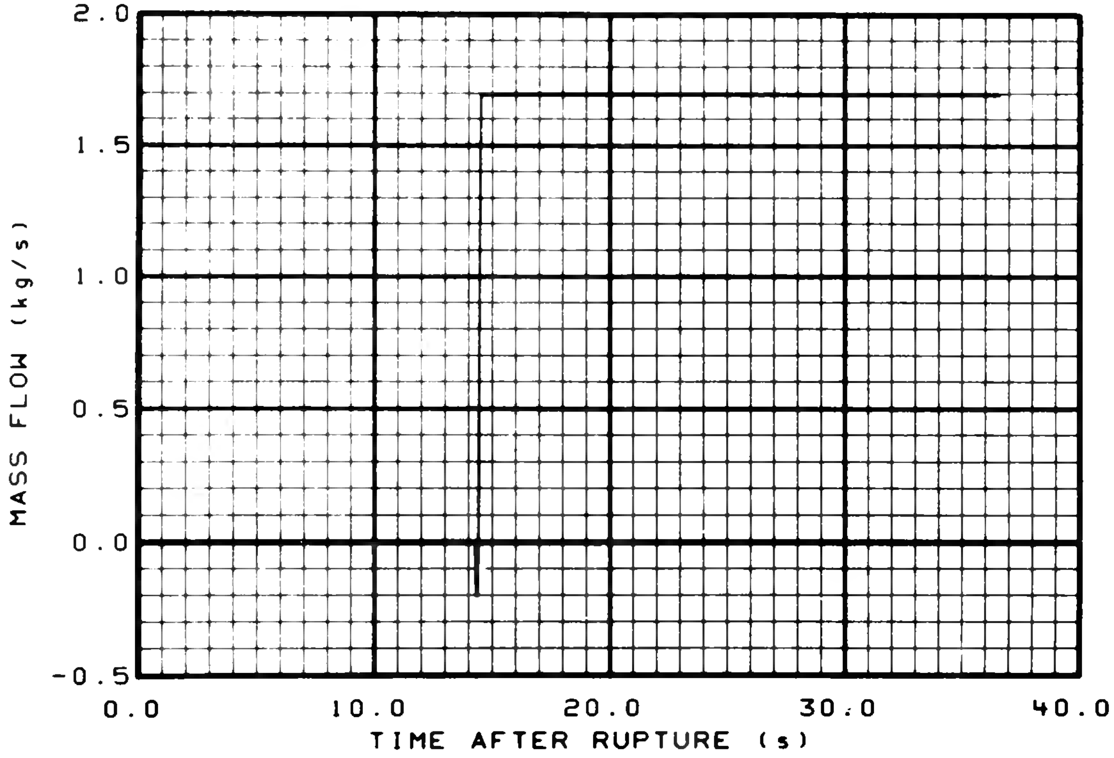


Fig. A-52 Mass flow rate for high-pressure injection system.

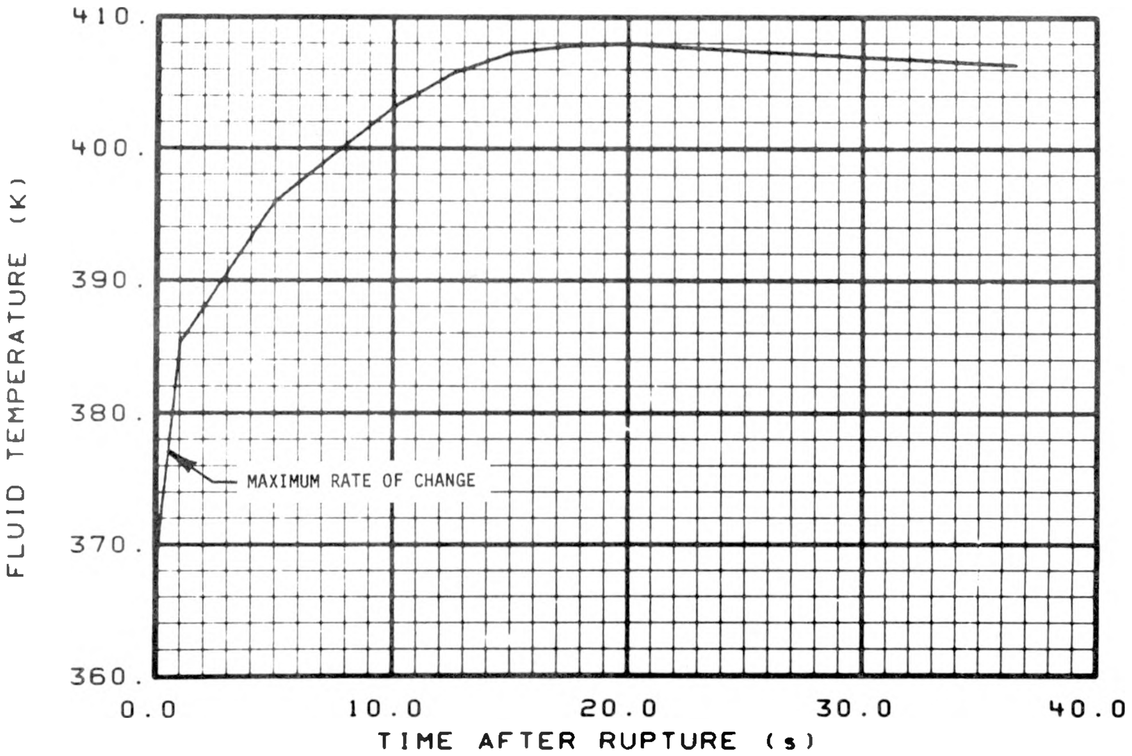


Fig. A-53 Temperature in blowdown suppression tank.

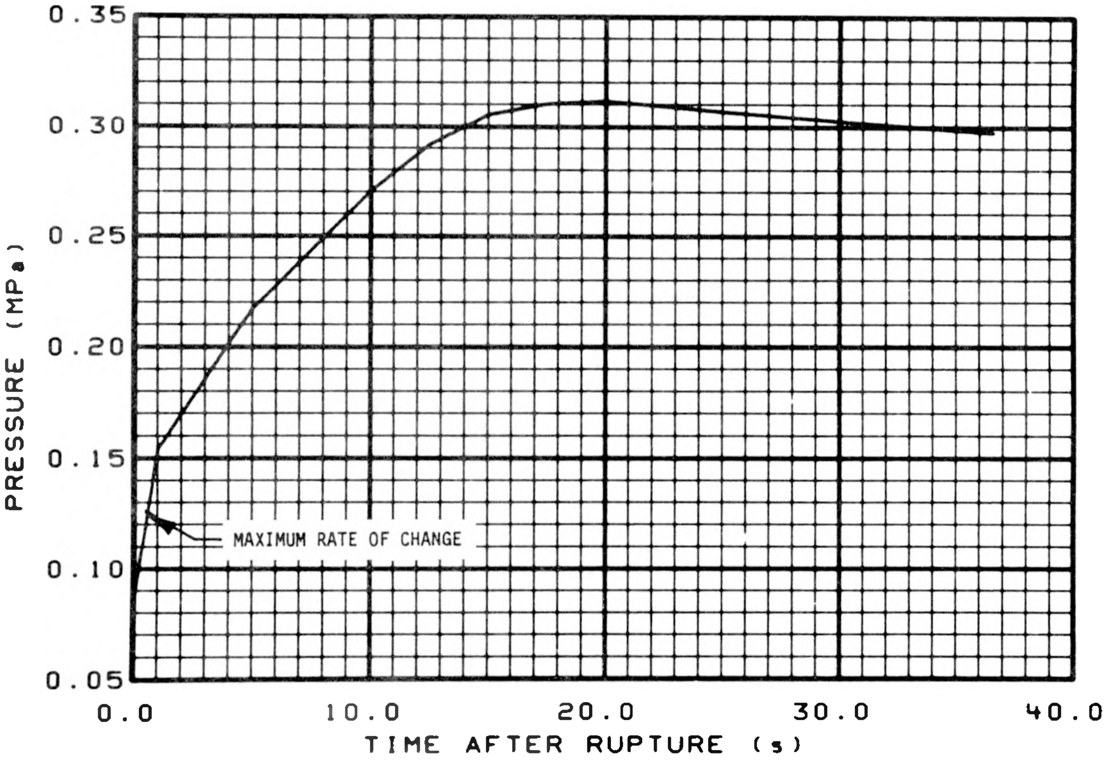


Fig. A-54 Pressure in blowdown suppression tank.

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A-2. U. S. Atomic Energy Commission, Code of Federal Regulations, Title 10 - Atomic Energy, Part 50, Licensing of Production and Utilization Facilities, Appendix K, "ECCS Evaluation Models", Docket No. RM-50-1 (January 1, 1976).

A-3. D. L. Batt Experiment Data Report for LOFT Nonnuclear Test L1-4, TREE-NUREG-1084 (July 1977).

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