BMW-1463
UC-80

COOLANT BLOWDOWN STUDIES
OF A REACTOR SIMULATOR VESSEL
CONTAINING A PERFORATED
SIEVE PLATE SEPARATOR

February 1971

AEC RESEARCH &
DEVELOPMENT REPORT

BNWL-1463

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

PACIFIC NORTHWEST LABORATORY

RICHLAND, WASHINGTON

operated by

BATTELLE MEMORIAL INSTITUTE

for the

UNITED STATES ATOMIC ENERGY COMMISSION" UNDER CONTRACT AT(45-1)-1830

3 3679 00052 7285

BNWL-1463
UC-80, Reactor
Technology

COOLANT BLOWDOWN STUDIES OF A REACTOR
SIMULATOR VESSEL CONTAINING A PERFORATED
STEVE PLATE SEPARATOR

by

R. T. Allemann
A. J. McElfresh
A. S. Neuls
W. C. Townsend
N. P. Wilburn
M. E. Witherspoon

February 1971

BATTELLE MEMORIAL INSTITUTE
PACIFIC NORTHWEST LABORATORIES
RICHLAND, WASHINGTON 99352

Printed in the United States of America
Available from
National Technical Information Service
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

COOLANT BLOWDOWN STUDIES OF A REACTOR
SIMULATOR VESSEL CONTAINING A PERFORATED
SIEVE PLATE SEPARATOR

R. T. Allemann
A. J. McElfresh
A. S. Neuls
W. C. Townsend
N. P. Wilburn
M. E. Witherspoon

ABSTRACT

Safety studies simulating pressurized water and boiling water reactor hypothetical piping breaks were conducted in a 150 ft³ vessel. High pressure water blowdowns (up to 2100 psi, 600 °F) were studied using orifice diameters of 0.9 to 5.2 in. at three different nozzle locations on the vessel. A sieve plate separator was used to divide the vessel into upper and lower volumes. Internal pressure and temperature, liquid level, thrust reaction forces, weight of fluid in the vessel, and movement of the sieve plate during the flow transient were measured during the blowdowns, and the data is given herein. Anomalous depressurization behavior was shown to be the result of dissolved nitrogen and instrument configuration. A steam dome below the plate formed in some cases during downward flow of the fluid in the vessel. The forces on the plate inferred from the plate deflection were less than predicted. The nozzle length had little effect on the mass flux during blowdown. Comparisons were made with subcooled depressurization predictions for both the subcooled and saturated regimes. The predictions showed good agreement where realistic orifice pressure functions and orifice flow coefficients were used.

CONTENTS

NOMENCLATURE	vii
LIST OF FIGURES.	viii
LIST OF TABLES	xi
1. INTRODUCTION	1.1
Purpose and Scope	1.1
Background of the Loss-of-Coolant Accident	
Licensing of a Nuclear Reactor	1.1
Design Basis Accident	1.2
Importance of Blowdown Calculations in Licensing	1.3
Importance of Experimental Confirmation	1.3
Containment System Experiment Blowdown Program	1.5
Containment System Experiment	1.5
Blowdown Program	1.7
2. SUMMARY AND CONCLUSIONS.	2.1
3. REVIEW OF PREDICTIVE METHODS FOR DESIGN BASIS ACCIDENT	3.1
Subcooled Regime	3.1
Two-Phase Transition Regime	3.2
Saturated Regime	3.3
4. EXPERIMENTAL FACILITY AND EQUIPMENT.	4.1
CSE Blowdown Facility	4.1
Description	4.1
Operation	4.5
Instrumentation Arrangement on the CSE Reactor Simulator Vessel	4.8
Sieve Plate Strain Bolts	4.17
Strain Gage and Bolt Assembly.	4.18
Static Calibration Tests	4.20
5. RESULTS AND DISCUSSION	5.1
Run Conditions	5.1
Subcooled Decompression Regime	5.1
Comparison of Experimental and WHAM-Calculated Pressure Histories	5.1

Pressures in Nozzles Other Than the Blowdown Nozzle	▪	5.20
Effect of Dissolved Gases	▪ ▪	5.25
Force on Sieve Plate	▪ ▪ ▪	5.29
Saturated Regime	▪ ▪ ▪ ▪ ▪ ▪	5.46
Liquid Level	▪ ▪ ▪ ▪ ▪ ▪	5.46
Comparisons of FLASH2 Predictions and Experimental Data for Liquid Level and Vessel Pressure		5.48
Liquid Remaining	▪	5.70
Mass Velocities	▪ ▪ ▪	5.73
Thrust	▪ ▪ ▪ ▪ ▪ ▪ ▪	5.77

NOMENCLATURE

	Break area (Flow area of square cornered test orifice).
A_V	Vessel area - nominal fluid area of horizontal plane cross section.
c	Acoustic velocity.
C_d	Discharge coefficient.
f	Frequency - hz.
G	Mass velocity.
g_c	Dimensional constant.
L	Duct or pipe length.
M_o	Initial mass of water in vessel.
P	Pressure in vessel.
P_o	Initial pressure of water in vessel.
P_{up}	Pressure upstream of a critical flow section.
p	Period (sec).
t	Time after blowdown.
t^{**}	Dimensionalized time.
T	Thrust Force
V	Velocity.
v	Specific volume.
W	Weight flow rate.
x	Quality.
α	Void fraction.
λ	Wave length.
ρ	Density.

SUBSCRIPTS

f	Liquid.
g	Vapor or gas.

Note: Runs are specified by numbers with the suffixes BN, MN, and TN referring to bottom, middle and top nozzles (nozzles C, B, and A, respectively, occasionally being included).

LIST OF FIGURES

4.1	Setting Plan for Reactor Simulator Vessel	4.2
4.2	Reactor Simulator Vessel in Blowdown Framework	4.3
4.3	CSE Reactor Simulator Vessel and Primary Restraint System	4.4
4.4	Vessel Volume Calibration	4.6
4.5	Test Sieve Plate	4.7
4.6	CSE Reactor Simulator Vessel with Core Plate	4.9
4.7	Schematic of Sensor Locations on Blowdown Vessel	4.10
4.8	Nozzle Extension Assembly	4.13
4.9	Sensor Location Details	4.14
4.10	Location of Inside Thermocouples, Bottom Head	4.15
4.11	Pressure Sensor Configurations	4.16
4.12	Weldable Nickel-Chromium Alloy Strain Gage	4.19
4.13	Core Plate, Lug, Bolt Assembly and Calibration Apparatus	4.21
4.14	Strain Gage Response from Support Bolt No. 8 Inner	4.22
5.1	Typical WHAM-Calculated and Measured Orifice Pressure Histories at P-8 (Run B-51)	5.7
5.2	LOFT Semi-scale Nozzle Extension and Rupture Disc Assembly	5.11
5.3	Measured and Revised WHAM-Calculated Orifice Pressure Histories for Run B-51	5.14
5.4	Typical WHAM-Calculated and Measured Pressure Histories in the Blowdown Pipe, P-4 (Run B-51)	5.15
5.5	Measured and Revised WHAM-Calculated Blowdown Pipe Pressure Histories of Run B-51	5.16
5.6	Typical WHAM-Calculated and Measured Pressure Histories in the Vessel at PLUG7 (Run B-51)	5.18
5.7	Typical WHAM-Calculated and Measured Pressure Histories in the Vessel at the Instrument Ring (Run B-51)	5.19
5.8	Measured and Revised WHAM-Calculated Pressure Histories at the Instrument Ring for Run B-51	5.21
5.9	Measured and Revised WHAM-Calculated Pressure Histories in the Vessel for Run B-51	5.22

5.10	Typical WHAM-Calculated and Measured Pressure Histories in Nozzle, Run B-51	5.23
5.11	Measured and Revised WHAM-Calculated Pressure Histories in Nozzle H for Run B-51	5.24
5.12	Typical WHAM-Calculated and Measured Pressure Histories in Nozzle C, Run B-22B	5.26
5.13	Effect of Dissolved Nitrogen-2 in. Blowdown	5.27
5.14	Effect of Dissolved Nitrogen-4 in. Blowdown	5.28
5.15	Pressure in Vessel During Subcooled Decompression	5.30
5.16	Strain in Bolt Supporting the Perforated Plate in the CSE Reactor Simulator Vessel	5.31
5.17	CSE Blowdown (6 in. 1000, 500, 214) High-speed Strain on Support Bolt 8 inner, Run B-21	5.32
5.18	Blowdown B-19B - Bottom Nozzle	5.34
5.19	Blowdown B-24 - Bottom Nozzle	5.35
5.20	Blowdown B-21 - Bottom Nozzle	5.36
5.21	Blowdown B-22 - Middle Nozzle	5.37
5.22	Blowdown B-25 - Middle Nozzle	5.38
5.23	Blowdown B-27B - Middle Nozzle	5.39
5.24	Blowdown B-51 Top Nozzle	5.40
5.25	Liquid Level Versus Time for a Blowdown in Which a Sieve Plate Was Used	5.47
5.26	Level of Fluid Remaining in Vessel, Run B-23MN	5.50
5.27	Level of Fluid Remaining in Vessel, Run B-25MN	5.51
5.28	Level of Fluid Remaining in Vessel, Run B-19BBN	5.53
5.29	Pressure Decay in Vessel	5.55
5.30	Level of Fluid Remaining in Vessel	5.57
5.31	Level of Fluid Remaining in Vessel, Run B-50TN	5.60
5.32	Level of Fluid Remaining in Vessel, Run B-51TN	5.61
5.33	Level of Fluid Remaining in Vessel, Run B-52TN	5.62
5.34	Liquid Level of Fluid Remaining in Vessel, Run B-53BTN	5.63
5.35	Pressure Decay in Vessel, Run B-50TN	5.66
5.36	Pressure Decay in Vessel, Run B-51TN	5.67
5.37	Pressure Decay in Vessel, Run B-52TN	5.68
5.38	Pressure Decay in Vessel, Run B-53BTN	5.69

5.39	Residual Water in Vessel After Blowdown from Full Vessel	5.72	
5.40	Residual Water in Vessel After Blowdown of Full Vessel	5.74	
5.41	Outlet Test Section for Runs B-25 and B-40.	5.76	.
5.42	CSE Blowdown (2 in. 2115, 603, 2) Cross-Plot of Vessel Pressure Versus Thrust Force from LC-3	5.78	
5.43	Thrust Coefficient	5.80	'

LIST OF TABLES

4.1	List of Instrumentation	4.12
5.1	Initial Conditions Plate Series of Blowdowns	5.2
5.2	Minimum Measured Pressure for All Runs	5.6
5.3	Data for Pressure Gages P-8 and P-10	5.9
5.4	Summary of Strain Bolt Data	5.45
5.5	FLASH2 Parameters	5.49
5.6	Nominal Mixture Velocities Through the Sieve Plate Orifices	5.56
5.7	FLASH2 Parameters	5.59
5.8	Liquid Remaining After Blowdown	5.71
5.9	Thrust Coefficients	5.79

COOLANT BLOWDOWN STUDIES OF A REACTOR
SIMULATOR VESSEL CONTAINING A PERFORATED
SIEVE PLATE SEPARATOR

1. INTRODUCTION

PURPOSE AND SCOPE

This report describes the experiments made with a large reactor simulator vessel as part of the water reactor safety program to study loss-of-coolant accidents. The overall objective of the experiments was to make comparisons of data and results of analytical prediction methods. The results are given for 21 blowdown experiments which were made using various initial conditions and different size blowdown orifices in the exit section at three locations on the vessel. The vessel had a perforated plate dividing it into upper and lower portions. Blowdown nozzle locations used were both above and below the plate. These tests were continued from the simple vessel series described in BNWL-1411.⁽¹⁾ The plate which separated the vessel into upper and lower volumes was used as a preliminary simplified mockup of a reactor core but being relatively thin is more representative of mixer, support, and grid plates used in nuclear reactors. The report discusses the main features and conclusions resulting from data reduction and analysis. These include aspects of computer modeling, flow rate, liquid level, forces on the plate, thrust forces, and subcooled decompression effects. Data is included as part of these discussions, but a complete package was too voluminous for inclusion so an abbreviated set is available in the Appendix.

BACKGROUND OF THE LOSS-OF-COOLANT ACCIDENT

Licensing of a Nuclear Reactor

The AEC maintains nuclear safety control before construction or operation of a new reactor through its licensing

procedure. The utility company or other organization desiring to build and/or operate a reactor submits a preliminary safety analysis to the AEC Division of Reactor Licensing. The DRL reviews the report and requires the submission of appropriate information concerning the public safety of the reactor. This information is usually provided by the reactor designer through the utility. After DRL has been satisfied that the reactor concept is safe, the safety analyses are reviewed by the Advisory Committee on Reactor Safety. This committee then assigns a subcommittee to conduct detailed review. Informal hearings and questions are followed by formal questions requiring answers from the utility and the designer. When review questions of the subcommittee have been satisfactorily answered, formal meetings are held with the ACRS, and final safety questions are reviewed and resolved. After public hearings with the Atomic Safety Licensing Board and resolution of any public objections, a construction permit is issued.

DESIGN BASIS ACCIDENT

The assumption of a double-ended pipe break in the main coolant loop piping of a nuclear power reactor followed by blowdown (a rapid loss of coolant through the break) has been considered as the worst possible loss-of-coolant accident and is called a design basis accident or DBA. Studies evaluating the sensitivity of events subsequent to such a piping break have been numerous enough to lend an air of likelihood to an accident originally considered almost impossible and postulated only to provide a basis for design and review. The assumption has been that lesser pipe breaks, which have a probability of occurrence greater than that of the DBA, would cause less serious results throughout any chain of events subsequent to the break. The loss-of-coolant accident is expected to be followed immediately by operation of an emergency core cooling

system (ECCS). The design and operation of an ECCS is very dependent on the assumed accident itself and on the calculated sequence of events occurring during the loss-of-coolant from the postulated piping break.

While extremely unlikely, this type of accident has been postulated and used as a means of assessing the safety of a reactor. This is done by assessing all possible consequences of such an occurrence.

Importance of Blowdown Calculations in Licensing

Blowdown theory has influenced many aspects of the licensing procedure, the preparation of the safety analysis report, and the questions and answers concerning safety. Information sought by the AEC often concerns problems not specifically included in the DBA sequence. These areas have included reliability and functioning of safeguards in less-than-maximum accidents.

Predicted from the theory or model describing the blowdown applicable to a given reactor are flow rates, core temperature, water remaining, pressure loading on core barrel and fuel assemblies, emergency core cooling behavior, and containment pressure transients. From these analytical determinations, the safety of the reactor during and after blowdown is assessed, and specific safety questions can be answered. The blowdown flow rate is usually calculated by means of two-phase critical flow theories consisting of one-dimensional treatments evolved from small-scale (1/8 to 1-in. diameter pipe) laboratory tests.

Importance of Experimental Confirmation

One problem in evaluating the adequacy of a blowdown model is the lack, thus far, of well-instrumented large-scale experimentation concerning the performance of reactor internal parts.

Such experimentation with internal parts is needed to determine the true effects resulting from the constitutive relations (heat transfer, friction, mass transfer) of the fluid taking place in real time, independent of the size of the experiment. For instance, a simplified bubble rise model has been used to predict the entrance conditions for the blowdown nozzle in several computer codes (FLASH2,⁽²⁾ RELAP2,⁽³⁾ RELAP3,⁽⁴⁾ BURP⁽⁵⁾). The correctness of this model has been indirectly evaluated through comparison of the mass remaining in the vessel for top blowdowns of small scale tests at LOFT (Loss of Fluid Test). In comparisons with tests of this size, the assumed bubble rise velocity gives a bubble disengagement time of the same order of magnitude as the blowdown time. Thus, true evaluations of the theory as applied to a reactor 10 times the scale of the model has not yet been accomplished. The performance of such large-scale experiments would provide a basis for checking a particular type of analysis as well as rule-of-thumb measures of the expected flow rates and forces. Such approximation techniques would be useful to the licensing officials since they often do not have the personnel to make detailed numerical checks of complicated (often computerized) blowdown analyses. However, the licensing body can check the approach to such an analysis, recognize it as a successful one, and then check the results against numbers obtained from the approximate methods.

The following excerpts from the Report of the Advisory Task Force in Power Reactor Emergency Cooling,⁽⁶⁾ published by the AEC, show the current knowledgeable thinking concerning the description and analysis of the loss-of-coolant accident.

"The key phenomena during a loss-of-coolant and core heatup are:

- The hydraulic effects of blowdown on the core and other components within the primary coolant system.

- The hydraulic effects of blowdown on the primary-coolant envelope and the emergency core-coolant system piping and components.
- The pressure-time history within the primary coolant system.
- The transient thermal response of the core.

"In the quantitative prediction of these phenomena, the specific plant design features and operating conditions play an important role. These features and parameters determine the response of the system to a loss-of-coolant and, in turn, define the boundary conditions under which emergency cooling systems must function. Experiments have been conducted to assist in verification of the analysis techniques in the areas of critical flow, hydraulic loads external to the system, and acoustic effects during flow initiation for simple geometries. However, experiments to date have not provided detailed information on fluid conditions within a geometry representative of a reactor-coolant system. Such tests are recommended, and it is understood that planning is underway to perform them."

CONTAINMENT SYSTEM EXPERIMENT BLOWDOWN PROGRAM

Containment System Experiment ^(7,8)

The containment system experiment (CSE) at Battelle-Northwest was a large scale program to evaluate the effectiveness of containment vessels and other engineered safeguard systems in reducing the release of radioactive fission products resulting from a serious accident in a nuclear electric power plant. The main objective of the CSE program was to obtain experimental information for use in testing calculational models and for developing improved models. The following specific program objectives were identified as a basis for development of engineering tests and related research and development.

- Determination of the effect of natural processes such as agglomeration and settling, diffusional deposition, and condensation of water vapor on reduction of airborne fission product concentration in containment systems; and application of experimental data to the evaluation of available analytical models.
- Determination of the effectiveness of both active and passive engineered safeguard systems in reducing fission product concentration in the containment atmosphere. Active safeguard systems employ water sprays and air filtration methods, whereas a passive system might achieve pressure suppression by means of a containment water pool. Measured values will be compared with those calculated from analytical models.
- Evaluation of the effectiveness of different methods of pressure reduction in containment vessels. Methods include water pool pressure suppression, cooling the contained atmosphere, and heat transfer to low temperature materials inside containment and through the containment membrane to the atmosphere.
- Determination of the amount of leakage of fission product activity from containment under a range of postaccident conditions and comparison of these values with those calculated from both low and high temperature air leakage rate tests and fission product concentration in the containment vessel.
- *Determination of (both inside and outside a reactor vessel) the transient and dynamic pressures, temperatures, stresses, coolant flow rates, and hydraulic forces resulting from the sudden rupture of a high temperature water system. Measured values will be compared with those calculated from analytical models.*

The results furnish a better technical basis for reactor site evaluation and for those aspects of reactor plant design affecting public safety.

The experiments and results for the first four tasks of the CSE program are reported elsewhere. The first phase of work on the blowdown task is described below.

Blowdown Program

Background

The blowdown program is designed around the vessel built to simulate a water-moderated reactor inside the CSE containment vessel. Originally, only a small amount of blowdown transient experimental work was proposed for CSE, primarily because of the interference between aerosol and blowdown transient tests inside the containment vessels, along with space limitations and resulting low test frequency. To increase both the frequency of tests and extent of data gathered, a special test stand for the simulator vessel was built close to the containment vessel so that common facilities, personnel, and power could be used.

The reactor simulator vessel tests outside containment have provided both a better environment for the experimental instrumentation and greatly improved access to the vessel and its instrumentation for repair of sensors and for experimental modifications. In addition, there has been an increased interest in the acquisition of large scale experimental data which would permit the testing of analytical techniques intended to provide detailed and sophisticated analyses of both the thermal and mechanical or structural effects on the reactor vessel internals during the blowdown transient. Aspects of particular interest include mechanical damage to the core or to the

emergency cooling system which might adversely affect or prevent adequate functioning of this emergency cooling system in the event of a major loss-of-coolant accident. Most of the information presented herein has been published previously in a series of quarterly reports. (9,10,11,12)

Problem Areas

The two principal problem areas to be investigated consist of the mechanical and structural aspects and the thermal aspects. The mechanical and structural aspects primarily include the hydraulic resistance effects of the core structure and of the typical reactor vessel internal parts such as thermal shields, core barrels, and flow baffles on the discharge rate of coolant during the blowdown transient. Forces resulting from sudden coolant system rupture must be known in order to evaluate the tendency to dislodge or deform reactor vessel internals. Such relative movements between parts may compound the effects of the coolant loss. Deformation, for example, by preventing control rod entry or movement of the fuel elements relative to the rods, might produce a reactivity excursion. Motion of core internals could block the normal or emergency coolant paths, damage the emergency cooling system, or so change the core geometry as to impair the required effectiveness of the emergency cooling.

Forces of interest arise during the first few hundred milliseconds of the transient because of the passage and reflection of acoustic waves into the interior of the reactor vessel from the point of coolant system rupture. These waves relieve fluid compression until flashing begins. Longer term forces result from the friction forces accompanying rapid coolant outflow. Also, temperature differences between hot and cold portions of the coolant system create differences in saturation

pressure of these water volumes when the subcooled blowdown is complete. With a break in the hot portion of the system, this difference may lead to a water-mass compressibility oscillation bounded by the saturation-pressure difference between the volumes. This oscillation could continue until fluid and mechanical damping causes it to die out. All of the forces discussed herein have the potential for developing lateral loads as well as the symmetrical loads usually calculated with a one-dimensional treatment. The physical processes such as bubble and void formation, heat transfer, and liquid level swell occurring in the reactor vessel when the pressure is suddenly relieved have a bearing on the design of the reactor safeguards and of the reactor itself.

There are important effects external to the reactor, which include, for example, forces from the impact of the fluid jet, vessel reaction forces, and whiplash of piping between the reactor vessel and the point of the coolant system rupture.

Data needed for evaluating all of these effects can be obtained during blowdown transient tests through the use of a series of unheated dummy cores. The initial tests performed prior to this report were conducted without dummy core parts in order to check blowdown theories against a simple test and to provide a **check** of the test instrumentation and data processing methods being developed.

Purpose of CSE Blowdown Tests

CSE blowdown tests are conducted to:

- Provide data with which to design models and to check modeling assumption and calculations so that these can be applied to full scale reactor plants. The blowdown results are used as input in calculations and design for stress, heat transfer, fission product distribution, emergency core cooling, and engineered safeguards.

- Perform blowdown tests at large enough scale to measure liquid level, void fraction, and thrust forces, and of sufficient size to observe effects of bubble formation and rise and effects of geometry upon a full size reactor.
- Provide actual-blowdown results for use in empirical formulations of blowdown rates and, in particular, to accurately predict blowdown times expected in the CSE containment vessel—reactor simulator, joint tests.
- a Contribute to the knowledge of two-phase critical flow, liquid-vapor action, and thermal hydraulic effects in a water-cooled reactor and thus increase safety and reduce the expense of engineering, construction, and licensing. Perhaps, this knowledge will eventually allow the codification rules to cover safety aspects of the loss-of-coolant accident. Until that time, detailed calculations must be made for each case, and confidence in the calculation methods can only come through comparisons with experiments.

2. SUMMARY AND CONCLUSIONS

Twenty-one blowdown tests designed to simulate loss-of-coolant accidents were made with a 150 ft³ vessel 17 ft tall, 3-1/2 ft ID. These tests were made from three different nozzle locations relative to a sieve plate separating the upper and lower regions of the vessel. The sieve plate was installed to give a very simple geometrical arrangement for blowdown tests. The simple geometry allowed direct comparison with computer-modelled theoretical predictions as an extension to work with simple, unobstructed vessels or with nearly one-dimensional piping systems. The report shows the application of typical current saturated and subcooled codes to the experimental arrangements and the resulting comparisons with the experimental data.

Square edge orifices were used to control the break size from 0.90-in. to 5.18-in. diameter. Pressure, temperature, liquid level, liquid remaining, weight of water, strain on plate support bolts, and nozzle thrust were measured, and comparisons were made with analytical models. The results show that:

- Liquid level predictions made by using constant bubble rise velocity models gave results within $\pm 10\%$ of measured values if a correct discharge coefficient was used.
- The discharge coefficient required to give the correct saturated flow mass velocity when applied to the Moody discharge model ranged from 1.09 to 0.6 and decreased with increasing break size.

- Subcooled decompression pressure patterns were predicted well by a one-dimensional model (WHAM) giving the correct frequencies and rates of decompression if the orifice boundary conditions were correctly chosen. Although some of the pressure data from the blowdowns did indicate the possibility of multi-dimensional effects, the evidence was inconclusive, and most of the data were consistent with the assumption of one-dimensional behavior. High frequency oscillations repeatedly measured at the instrument ring and previously attributed to multi-dimensional effects^(1,12) were found to be caused by the instrument configuration. Typical comparisons of pressure data with calculated values (using WHAM) indicated fair agreement. Difficulties in obtaining agreement were generally attributed to the simplified exit model. The velocity boundary condition at the break could best be expressed by $u = C \sqrt{2 \rho P}$, where P is simply the vessel pressure rather than the usually assumed difference between the vessel pressure and the saturation pressure (at the vessel temperature). Exit plane back pressures were found to be well below saturation for the CSE nozzle configuration. WHAM calculations of CSE blowdowns have demonstrated the importance of properly describing the exit region behavior. Realistic description of break opening characteristics such as orifice area and exit back pressure as a function of time are needed. Such characteristics as these would not be the same for the rupture disks used in the CSE experiments as for a pipe rupture, and the latter are not well understood. However, it is believed that the assumptions used in obtaining calculated values of transient

pressure to compare with CSE data are sufficiently conservative for application to loss-of-coolant accident analysis of full scale reactors.

- The liquid level remaining in the vessel after blowdown in these experiments was less than predicted by the FLASH2 code ($\sim 20\%$ low for high nozzles with 11 to 35% fluid remaining, 30 to 100% low for low nozzles with 2 to 10% remaining). In addition, judgement was required in the analysis in order to allow (through the use of a two-region model) the prediction of a steam dome that formed below the sieve plate in cases of downward flow in the vessel.
- The length-to-diameter ratio of the outlet pipe had much less effect on the efflux mass velocity than predicted by frictional pressure drop theories. Changing the L/D from 15 to 1 changed the flow rate less than 3%.
- Some inconclusive evidence was obtained in the pressure history showing two dimensional patterns of decompression during subcooled decompression. Such patterns, though minor, could involve undesirable structural resonances and should be considered in reactor component design.
- Thrust forces measured during saturated flow could be related to the discharge coefficient and in general were expressed by the formula $T = C (2 P A_b)$, where C ranged from 0.5 to 0.9.
- The forces on the plate as measured by strain gages on the supports were 2 to 5 times less than predicted by the subcooled decompression code coupled with the mechanical response calculations or calibration data. The data of plate response did not match the predicted wave forms. Predicted dynamic amplification of plate response did not occur.

- Nitrogen dissolved in the simulated reactor coolant water, to the extent of $\sim 1.9 \frac{\text{cm}^3 \text{ (STP)}}{\text{gm H}_2\text{O}}$, reduced the severity of the subcooled blowdown pressure oscillations, the rate of subcooled decompression, and the strain of the sieve plate support bolts from values resulting from blowdown of demineralized water normally used.

3. REVIEW OF PREDICTIVE METHODS FOR DESIGN BASIS ACCIDENT

The design basis accident has three regimes as defined in Reference 12. These are the subcooled, transition, and saturated.

SUBCOOLED REGIME

The rapid pressure loss at the break location induces a pressure difference which starts a flow toward the break. The initial rate of this flow is limited by fluid inertia so that the loss in pressure is transmitted as a wave to the rest of the hydraulic system. The wave propagates at close to the sonic velocity of the single phase system, and as long as no large changes occur in this velocity due to flashing, the system is said to be in the acoustic or subcooled regime. Methods of calculating the decompression are based on a solution of the continuity, momentum, energy, and state equations. Many solutions to this problem based on geometric assumptions have been developed, and they are described only briefly here in order to present a picture of how the calculations are done. The equations involved are often nonlinear and can be solved expeditiously only with a computer. Even then, one-dimensional treatments are used. Computer codes such as BURST,⁽¹³⁾ WATER HAMMER,⁽¹⁴⁾ WHAM,⁽¹⁵⁾ and the method of characteristics⁽¹⁶⁾ are typical of those used to solve the subcooled decompression problems.

BURST uses a multinode analysis and solves the four equations at all the nodes simultaneously through use of initial velocities, pressures, and exit pressures as boundary conditions. WHAM (or WATER HAMMER) assumes the solution to be in the form of waves that propagate with a velocity characteristic of the fluid. The code then organizes and keeps track of a series of these waves as they reflect in the matrix

of parallel paths and area changes. The characteristics method uses the property that second order hyperbolic partial differential equations can be reduced to two first order ordinary differential equations whose simultaneous solution can be found to solve the second order problem. The solutions are started at known boundary conditions and found along "characteristic" curves across which solutions can be discontinuous. This method has not yet been successfully reduced to a computer routine for the loss-of-coolant accident. The method is limited somewhat by its rigor in that it is applicable only to one-dimensional paths (however it may be that by using characteristic surfaces instead of lines, a two-dimensional problem may be handled, and it is understood such a treatment called CHARM is being developed at Westinghouse Corporation). Consideration of other paths would require the use of a bookkeeping code such as WHAM.

Several proprietary codes (including SHEILA, SATAN, and BLOWDOWN-2), developed by reactor manufacturers are not generally available.

Because of its availability and general ease of use, the subcooled data obtained here was compared mainly with WHAM. (15) More details on WHAM are given in Section VI.

TWO-PHASE TRANSITION REGIME

When subcooled decompression has reduced the pressure of the system sufficiently, and/or after a time delay the steam-water ratio will begin to increase in some parts of the system. This period, when parts of the system have rapidly changing steam water ratios is called the transition regime. The equation of state for water or the steam tables show at what pressure and temperature this change of state will occur if equilibrium is assumed. The rate of steam formation depends on additional factors such as heat transfer, contact area, nucleation sites, etc. When both steam and liquid exist in

the reactor, two phase calculations are used. A sharp change in sonic velocity occurring with the advent of the two-phase regime allows pressure differences between regions to exist for longer periods. However, they are controlled more by temperature differences and flowrates (that is, by state equation and rate process equations) than by hyperbolic equations typical of momentum-continuity-conservation in the subcooled regime.

Very little work has been done on the transition regime. Approaches to the problem made from the subcooled calculation technique may consider time delay for bubble formation or may allow a change to a new propagation velocity characteristic of a two-phase mixture. This change in velocity often allows the two-phase region to dominate the rate of decompression and the rest of the system to be considered at uniform pressures.

In the other approach, from the saturated regime discussed in the following section, the simple lumped saturated blow-down solution is applied to a series of connected volumes representing the various states and amounts of coolant in the circuit. Sophisticated computerized blowdown calculations involve logic circuiting in order to evaluate which treatments to use. Similar logic procedures are used to switch to the routines covering two-phase flow.

SATURATED REGIME

When the pressure in a vessel filled with hot water is reduced to the saturation value, the water will flash to steam. If this occurs uniformly throughout the vessel, the vessel flows can be considered saturated and will thus follow the saturation line of the equation of state. Even when the

saturation condition is not uniform, but some saturated region dominates the pressure, the system is said to be in the saturated regime. The assumption of the uniform pressure in the vessel simplifies the calculations for the conditions in the vessel and allows consideration of some of the details of the relative motion between the liquid and the vapor. The reason for considering these details is that the void fraction or quality of the fluid passing out through ducts to the break affect the blowdown rate and also the liquid remaining after blowdown, the level swell, the steam blanketing of the core, etc.

Calculations of the saturated portion of the blowdown have been carried out by many investigators. Many computer codes written to handle the equations of flow rate and state frequently include treatment of other variables such as heat transfer, pump characteristics, secondary loop flow, and parallel paths.

Only a few of the major aspects of the treatments in use are summarized here. Several codes such as CSEBACK,⁽¹⁶⁾ IITRI,⁽¹⁷⁾ BMI⁽¹⁸⁾ consider the distribution of steam in the fluid in the vessel to be uniform. This model is termed "homogeneous." Manufacturers have their proprietary codes, (for example, General Electric's RIP and LAMB, Westinghouse's SATAN and CHARM, Combustion Engineering's BARF,) which all divide the reactor vessel into from 3 to 9 control volumes. These codes are also generally "homogeneous" in any single node. In both the LOFT-developed code RELAP2⁽³⁾ and its similar predecessor (the generally available code FLASH-2)⁽²⁾ the void fraction or quality is assumed to vary linearly from the bottom to the top of a particular vessel node in such a manner that the average void equals that required by the state

and mass balance equations. The distribution of this void fraction depends on parameters called "bubble rise velocity" and "void distribution coefficient" whose values have been defined empirically by comparison with such blowdown data as pressure history and liquid level remaining after top blowdown. In most codes, the two-phase leak flow rate is governed by some critical two-phase flow formula. predictions of this flow developed by Moody⁽¹⁹⁾ or Fauske⁽²⁰⁾ are most generally used in this country, whereas in Germany^(21,22) or Japan,⁽²³⁾ similar models producing similar results are applied in the overall blowdown calculation.

The salient feature of most codes is that they assume the pattern of flow (bubble, all steam, or all liquid) within the node volume and switch from one pattern to another based on preplanned criteria. The layout is essentially one-dimensional, although parallel paths, such as those through the by-pass control rod cooling path and the core element cooling paths, can be treated. Treatments thus far have been verified by comparison with only simple-vessel blowdown data.

4. EXPERIMENTAL FACILITY AND EQUIPMENT

CSE BLOWDOWN FACILITY

Description

The full description of the CSE facility is contained in Reference 7. The CSE reactor simulator vessel (Figure 4.1) was fabricated and accepted in accordance with Section III of the ASME Pressure Vessel and Boiler Code. Design temperature and pressure is 650 °F and 2750 psig, respectively, and volume is 150 ft³.

The reactor simulator vessel was mounted within a support frame (Figure 4.2). The weight of the vessel and simulator support frame are supported by the vertical load cell. Thrust forces generated during the blowdown experiment are restrained by a thrust support system which include upper and lower thrust support members and load cells (Figure 4.3). The thrust loading in compression was transmitted through a saddle (preloaded against the vessel side) through adjustable linkage with spherical knuckle joints on each end and then through the load cell to the foundation or support tower. Sufficient adjustment was provided to align the centerline plane of the supporting members with that of the blowdown nozzle. Four stabilizer bars provided lateral (with respect to blowdown direction) restraint in the event of misalignment or fluid-induced lateral deflection of the discharge jet. The system was calibrated by filling and weighing and by jacking against the discharge nozzle with measured forces. Restraint cables were provided to prevent major damage in case of failure of restraint system used for measurement or in case the defected bottom head should fail.

FIGURE 4.1. Setting Plan for Reactor Simulator Vessel

FIGURE 4.2. Reactor Simulator Vessel in Blowdown Framework

MERGENCY RESTRAINT SYSTEM

0690250

FIGURE 4.3. CSE Reactor Simulator Vessel and Primary Restraint System

Operation

Operation procedure of the blowdown experiments was started by filling the vessel with cold water. This water was then circulated through an external loop containing a heater and pressurizer until the fluid in the vessel was at the prescribed experimental conditions. During these run preparations, the pressure in the cavity between the rupture discs was maintained at a fraction of the vessel pressure. After the desired conditions were established, the vessel was isolated (by valving off the circulation loop) and the rupture discs were broken by injecting nitrogen in the cavity between the two rupture discs until breakage occurred.

Control of the facility was switched to the on-line PDP-7 digital computer at a prescribed time (7 sec to 3 min) before the experiment started. Nitrogen injection into the rupture disc cavity and data logging were controlled by the computer. Triggering of memoscopes was done with a break wire glued to the outer rupture disk.

The blowdown facility was instrumented to measure pressure and temperature at selected locations, weight of water remaining, liquid level, void fraction of discharging fluid, and thrust reaction forces.

Figure 4.4 shows the volume calibration of the reactor simulator vessel with equivalent right cylindrical vessel elevations.

A perforated core plate was installed in the vessel to divide the vessel into two volumes with a flow resistant connection. The perforated core plate is shown in Figure 4.5. The plate had 108 threaded holes which could be blanked, or have a nozzle, a simulated flow tube, or a differential pressure transducer installed.

Neg 0682987-2

- NOTES:
1. PLATE 4 in. THICK
 2. CENTRAL HOLE CLOSED BY LEVEL PROBE
 3. EDGES HAD 3/8 in. SEAL PLATES RUBBING ON VESSEL WALLS
 4. SHIM WASHERS USED ON MOUNTING BOLTS
 5. OPEN AREA OF PLATE 0.56 ft²

DETAIL A - SIEVE PLATE ORIFICE

Neg 701425-1

FIGURE 4.5. Test Sieve Plate

The volume of the lower plenum under the core plate was 42.4 ft³ while that of the upper plenum above the core plate was 107.6 ft³. For these tests, sixty-four holes were left open using venturi-shaped insert, shown in Figure 4.5. It was thought that a venturi would allow more accurate calculation of through-the-plate flow rate from the pressure drop. Difficulties with two phase flow temperature effects and time delays did not allow successful use of the venturis. The free flow area of the core plate for this configuration is 79.2 in.². The remaining holes were blanked.

The core plate was supported by eight equally spaced lugs and bolts as shown in Figure 4.5. Each bolt was designed so that strain gages could be mounted on the bolt (described in the next section) to measure the strain on the bolts.

Three vessel nozzles were used during this reported series of experiments. They were nozzles A, B, and C. An instrumented nozzle extension test section (Figure 4.8) with rupture disk flanges and a square edge orifice was attached to the appropriate blowdown nozzle. The remaining nozzles were blanked off and instrumented with temperature and pressure sensors. Some special instrument assemblies were inserted in nozzles to obtain additional measurements. Nozzle "0" was used in an attempt to get wall heat transfer data, and nozzles 'S' and 'J' were used to insert a special pressure probe in an attempt to find pressure effects in a radial direction. Figure 4.6 shows the general appearance of the experimental set up with the blowdown nozzle installed in the middle position.

INSTRUMENTATION ARRANGEMENT ON THE CSE REACTOR SIMULATOR VESSEL

Several basic measurements are required to accomplish the objective of studying the fluid behavior during the simulated loss-of-coolant accident. Some of the measurements such as

Neg 0693300-1

FIGURE 4.6. CSE Reactor Simulator Vessel with Core Plate

FIGURE 4.7. Schematic of Sensor Locations on Blowdown Vessel

pressure and temperature can be made directly, but others such as mass flow rate or void fraction require an indirect approach because of inadequacies in state-of-the-art instrumentation or because of the general difficulties associated with basic correlations for two-phase flow.

The following tables and figures consolidate and describe the sensor designations, types and locations as an aid in interpreting the data presented in later sections of this report. Other information on the individual sensors such as model, manufacturer and a more detailed description of the liquid level device is included in an earlier report⁽²⁾ and will not be dealt with here. However, all sensors pertinent to the discussions herein are listed in Table 4.1. Figure 4.7 shows schematically the location of the pressure, temperature, strain and load sensors pertinent to this blowdown series. Figures 4.8, 4.9, 4.10 and 4.11 are provided to clarify the details of the sensor locations and scaled drawings of the vessel are included in Section 4. The outputs of these sensors were scanned by a multiplexer unit interfaced with a PDP-7 computer. The computer had the ability to scan sensors in two modes: (1) "normal" scan rates ranging from 5 to 50 times per second, and (2) "high speed" mode which scans at the approximate rate of 3000 times/second. The nominal scan rates for the sensors involved are tabulated with an indication of whether they have been scanned at "high speed" scan rates.

The measurement of state of fluid temperature were made with 0.040 in. diam. chromel-constantan thermocouples with stainless steel sheathing materials. Those thermocouples used for metal surface temperature measurements were spot welded to the surface, covered, and mechanically coupled to the surface with stainless steel shim stock which has also thoroughly

TABLE 4.1. List of Instrumentation

Sensor Designation	Nominal Scan Rate, PTS/sec	Type	Intended Measurement	Location
TDR	50	Time Domain Reflectometer	Liquid level during blowdown	Down axis of vessel through top nozzle
LC1	50	Strain Gage Load Cell	Weight of vessel, gage and contents	Coupling main frame and support cable
LC2	50	Strain Gage Load Cell	Reaction forces on vessel	Attached to simulator vessel
LC4	50	Strain Gage Load Cell	Supports as a result of blowdown	at two heights, coupled with main frame and pit
(a) p-2	20	Water Cooled Flush Diaphragm Pressure Sensors Type No. 1, Figure 4.11	Pressure state of fluid during decompression transient and subsequent blowdown	Nozzle J
(a) p-3	20			Blowdown nozzle extension piece
(a) p-4	20			Blowdown nozzle extension piece
(a) p-6	20			Nozzle R
(a) p-7	20			Nozzle H
(a) p-8	20			Rupture Disc Assembly
(a) p-10	20			Discharge Orifice
(a) p-15	20			Instrument Ring
(a) p-13	20	↓	Pressure transients along a radial probe insert	Inserted through Nozzle 'S' or 'J' depending on the blowdown
(a) Plug 1	20		Pressure state of fluid inside vessel, under core plate	Attached to lugs 1, 5, 7 below plate, see Photograph Appendix A
(a) Plug 5	20		Pressure state of fluid inside vessel, under core plate	
(a) Plug 7	20			
(a) p-16	20			
P-17	50			
P-18	50			
T-2				
T-3	5			
T-6	5	Chromel-constantan Thermocouples	Temperature state of fluid during blowdown	Nozzle J
T-7	5			Blowdown nozzle extension piece
T-8	5			Nozzle R
T-9	5			Nozzle H
T-10	5			In instrument ring
T-11	5			Nozzle Insert Heat Transfer Assembly
TL-1	5			Nozzle Insert Heat Transfer Assembly
TL-2	5			On liquid level probe
TL-3	5	↓	Temperature down Q_L of vessel	2' down from top No. 2 'F'
TL-4	5			6' down from top No. 2 'F'
TL-5	5			9' down from top No. 2 'F'
TL-6	5			11' down from top No. 2 'F'
T-7	5			14' down from top No. 2 'F'
T-10	5			17' down from top No. 2 'F'
T-15	5			Nozzle H
Miscellaneous	(5)			Instrument ring
(a) SB1I	50	18 Chromel-alumel thermocouples	Temperature of fluid	As shown in Figure 4.4
(a) SB10	50			
(a) SB5I	50			
(a) SB50	50			
(a) SB6I	50			
(a) SB60	50			
(a) SB80	50			
(a) SB88	50			
(a) SB1I	50	Immersion strain gage	Strain on bolt supporting core plate	On support lugs 1, 5, 6, 7, see Figure 4.3.
(a) SB10	50			
(a) SB5I	50			
(a) SB50	50			
(a) SB6I	50			
(a) SB60	50			
(a) SB80	50			
(a) SB88	50			

(a) Designates sensors scanned at the rate of 3000 data points per second on high speed multiplexers in addition to normal scan rates designated in Column 2

Neg 701424-1

FIGURE 4.8 Nozzle Extension Assembly

FIGURE 4.9. Sensor Location Details

FIGURE 4.10. Location of Inside Thermocouples, Bottom Head

TYPE NUMBER 2
TYPICAL FOR PLUG 1, 5, 7,
P-16

FIGURE 4.11. Pressure Sensor Configurations

attached to the surface with a spot welder. Measurements of pressure state of fluid were made with two basic sensor types, each of which was connected to the vessel fluid chambers in two different ways. Referring to Figure 4.11, it was possible to mount configuration 1 flush with the inside surface of the flange in which they were mounted (sensors P-2, P-6, P-7, P-13, P-14). This same sensor type used in other places (P-3, P-4, P-8, P-10, P-15) where it was not possible to mount the diaphragm of the sensor flush with the inside surface, and the connection with the vessel volume was made using adapters which resulted in the equivalent of short tubing connections to the vessel volume. This was also true for pressure sensor configuration 2. This type was immersed directly in the fluid below the plate (Plug 1, Plug 5, Plug 7) and was attached to the vessel using short tubings (P-16, P-17, P-18).

SIEVE PLATE STRAIN BOLTS

A discussion of the calibration and results obtained with the strain bolts is contained in Section 5 of this report.

One of the areas of primary interest in the study of blowdown transients is that of the effects of blowdown generated pressure differentials on reactor internal structures. Since the blowdown series reported here afforded an opportunity to generate a difference in pressure between two chambers (above and below the sieve plate) it was desirable to measure the load imposed on the septum between these two chambers in order to compare with and evaluate the computer code predictions available. The approach chosen was to instrument the bolts holding the sieve plate system, calibrate these bolts by imposing a load on the plate before the run series, and compare the readings obtained during the runs to the load calibration for an estimate of the integrated plate loading.

The following is a description of the instrumentation configurations, the calibration method, and the results of comparisons to date.

Strain Gage and Bolt Assembly

Since the results of several computer programs and calculational methods were in disparity by an order of magnitude, (24,25) a calibrated system with limited accuracy was judged to be acceptable for this measurement. The fundamental difficulties of obtaining strain measurements in high temperature, high pressure environments have been overcome to a great extent by the development of weldable nickel-chromium alloy gages mounted in compacted metal-oxide insulation materials (22) (see Figure 4.12). The additional requirement of service in hot water such as that encountered in the reactor safety experiments are usually fulfilled by construction of a special gage with integral leads and a silver-brazed connection joint. Experiments with these configurations at other sites⁽⁴⁾ had shown that a high failure rate existed which was associated with the dissolution of the braze joint and the resulting loss of insulation resistance. The failures were of two types: (1) those that occurred almost immediately and were attributed to the inclusion of flux materials in the joint, and (2) type in which the silver itself was eventually eroded in service. In the latter category, the gages lasted some length of time, usually from a few to several hundred hours, probably dependent on the thickness of braze at the point of failure. The problem of high failure rates on delivered gages was circumvented by requiring the vendor to pre-test all the gages in an autoclave at service conditions for 4 hours. The result was a high failure rate at the factory, but a relatively high confidence that the delivered gages would have a useful life.

b. TEMPERATURE COMPENSATION CHARACTERISTIC OF WELDABLE STRAIN GAGE

CSE OPERATIONS
WERE IN THE
500-600 °F RANGE

Neg 0682847-4

FIGURE 4.12. Weldable Nickel Chromium Alloy Strain Gage

Inconel X 750 was the material chosen for the bolt because its high yield strength (about 110,000 psi at 600 °F) exceeded that of the usual stainless steel materials by a factor of 4 at operating temperatures. A groove was provided across the threads so that the lead could be passed through the nut and thus simplify lead routing. The gage itself is attached by multiple capacitive-discharge spot welds on the attachment flange. A sample bolt was then calibrated in a tensile test machine to $\pm 30,000$ lb. Four out of eight of the core support lugs were provided with instrumented bolts with two strain gages each.

An apparatus was designed whereby a load could be transferred to the center of the core plate in either tension or compression to $\pm 1000,000$ lbf, (equivalent to about 77 psi of plate surface area). The sketch in Figure 4.13 shows the general appearance of the plate with the calibration apparatus and the arrangement of the plate-lug-bolt assembly. Figure 4.14 shows a calibration test curve made with this apparatus, and Figure 4.12 shows a picture of a strain bolt itself.

Static Calibration Tests

The performance of a single bolt in a tensile test machine was of interest to confirm the elementary performance of the strain bolt and gage unit. Although each lug was designed for a load of 12,500 lb, the sample bolt was calibrated for the range $\pm 30,000$ lb. Expected values for the simple P/A stress checked within 4% of the measured values. The output was linear, also as expected, with a slight nonlinearity at the point of stress reversal (from tension to compression). These results were considered satisfactory and the testing proceeded.

The apparatus in Figure 4.13 was installed and a successful tension and compression test was performed. Each bolt was used as a separate transducer of jacking force to electrical

FIGURE 4.13. Core Plate, Lug, Bolt Assembly and Calibration Apparatus

FIGURE 4.14. Strain Gage Response from Support Bolt No. 8 Inner

resistance with the result that a resistance versus load sensitivity factor was obtained. This sensitivity versus load factor was used to reduce the data firsthand, and a more detailed analysis was conducted to model the plate-lug-bolt system for the static stress state and to determine the natural frequencies, mode shapes, and associated stresses in the sieve plate and the bolt using the stress code SAMIS.⁽²⁶⁾ The details of the development of calibration results using this program are reported elsewhere.⁽²⁷⁾

These analytical approaches represented state-of-the-art efforts to model the system in detail, and the results and assumptions related to these tools were used to make best estimate calculations about possible responses of the experimental structures for the purpose of preventing failures of the apparatus.

It was found that the use of the simple calibration was not in substantial disagreement with the more sophisticated effort, and therefore the firsthand data reductions and all data reductions in this report were completed using the simple linear calibration factors obtained from the resistance versus load calibration tests from the data in Appendix A. There were two unapplied and compensating errors in the raw data, namely, the decrease in modulus of elasticity of the bolt material from the calibration condition to the run conditions and an excitation voltage drop in the long lead wires to the equipment building.

Other calculations were made to account for errors due to nominal lead resistance, changes of lead resistance due to temperature effects, errors in calculated strain for shunt test resistors, IR drop in excitation voltages, changes in the

modulus of elasticity due to the temperature of the bolt, and the sensor changes with temperature. The results of these calculations gave a most probable error in an observed signal of $\pm 7.5\%$.

However, this group of calculations served as an estimate of the probable static error in the measurement system and did not account for the most significant influence, namely, that of the noise obtained in dynamic signals. In practice, these errors were judged from individual plots.

5. RESULTS AND DISCUSSION

RUN CONDITIONS

The blowdown tests made were designed to study subcooled decompression and saturated liquid-vapor behavior by variation of initial water temperature, pressure, and amount; and nozzle location, size, and break area. Tests were also made to study the effect of nitrogen solubility.

Table 5.1 summarizes the initial condition for the test series, including the orifice size and location, and lists the time of transition from low to high quality flow.

The pressure was obtained from a sensitive direct reading gage immediately prior to blowdown. The temperature was obtained by averaging the initial values of the thermocouples on the central TDR probe in the vessel. The weight of water was determined from the liquid level and hence the initial volume, and the specific volume of water at the starting conditions. The transition time was determined from the time at which an inflection occurred in the pressure versus time history at the outlet orifice.

SUBCOOLED DECOMPRESSION REGIME

Comparison of Experimental and WHAM-Calculated Pressure Histories

Prior to the sieve plate blowdown series, the WATER HAMMER⁽⁹⁾ decompression code was obtained for application to CSE pressure data and prediction of sieve plate behavior. Later, however, an improved and extended version, WHAM⁽¹⁵⁾ became available. The WHAM code was thoroughly checked, debugged, and implemented for application to CSE data. This code has been applied to all CSE sieve plate blowdowns. Typical results of comparisons between measured pressures and

TABLE 5.1. Initial Conditions Plate Series of Blowdowns

Run No.	Date	Nominal Orifice Size	Loc	Pressure, psig	Temperature, °F	Weight of Water	Transition Time, sec	Notes
19A	12-16-68	2	C	2150	602	6400	~52	
19B	2-4-69	2	C	2100	602	6400	58	
20	2-20-69	4	C	990	500	7400	29.6	
20B	2-28-69	4	C	968	504	7300	27-28	
21	3-28-69	6	C	999	502	7300	13.5	
22	4-18-69	2	B	1315	NG	7400	72-74	No data logged
22B	4-30-69	2	B	1286	496	7400	74	
23	5-7-69	1	B	2137	498	7400	233	
24	3-8-69	4	B	810	504	4100	18	Nitrogen over pressure used to break liquid level ~9.5
25	6-19-69	4	B	1285	503	7400	25.8	
26	4-25-69	2	B	976	542	5500	46-47	Initial liquid level 11.5
27	5-23-69	4	B	1260	NG	5550-5800		Premature blowdown
27B	5-29-69	4	B	1075	549	5600	13.3	Initial level 14.4 ft
28	7-29-69	6	B	1032	545	5250	6.4	Initial level 12.9 ft
29	7-11-69	4	B	1302	515	7215	21.7	
40	8-1-69	4	B	854	504	7300	26.5	
50	9-11-69	2	A	2082	504	7400	14.5	
51	9-24-69	4	A	1682	499	7400	10 sec	
52	9-18-69	6	A	1289	499	7400	5.6	
53	9-26-69	2	A	1072	NG	3400	No Blowdown	Initial level 8.6 ft outer disc rupture only
53B	10-2-69	2	A	980	540	3750	0	Initial level 9.4 ft

Orifice Nominal Size, in.	Description Actual D, in.	Square Edge Area, ft ²
1	0.815	0.00362
2	1.687	0.01552
4	3.438	0.06447
6	5.187	0.1467

calculated pressures using a simple one-dimensional model are presented in this report. Difficulties in obtaining agreement were generally attributed to the simplified exit model. Exit plane back pressures were found to be well below saturation for the CSE nozzle configuration. Pressure data from most blowdowns indicated only one-dimensional behavior. Evidence of multidimensional effects was inconclusive. High frequency oscillations consistently measured at the instrument ring and previously attributed to multidimensional effects(11,28) were found to be caused by the instrument configuration and could be predicted by using the correct lengths of the pressure sensors taps. However, some measurements did indicate the possibility of multi-dimensional effects for some blowdowns. Comparison of calculated pressure histories using the analytical and the empirical exit functions with measured pressure histories demonstrated that the one-dimensional WHAM code correctly calculates pressure behavior when the exit conditions can be properly described.

Theoretical Considerations in the WHAM Model

In WHAM, the treatment of the exit region necessarily contains a large number of empirical parameters and assumptions. These include the break opening function, the break opening time, the back pressure, and the orifice coefficient. The break opening function for most predictions here was arbitrarily chosen to be a linearly increasing area, fully open at 0.56 msec. The opening time was determined from an early CSE blowdown(1,29) and was used for most predictions. Although this time was used as a standard, it did not necessarily reflect the actual opening time. The standard was originally considered representative of the elapsed time of the major decompression wave in the orifice region. However, later analysis revealed that the

break opening was a complex function, and that the standardized break time was probably too short. The orifice coefficients were determined from steady-state values for single-phase flow through sharp-edged orifices. (30) The back pressure used was atmospheric since previous data in orifice region indicated a large drop in pressure in this region. (12)

Other assumptions used include constant sonic velocity in any given region, constant fluid density, and frictionless flow with the exception of the hydraulic loss at an area change. The expression for the conservation of energy at an area change when the fluid moves from a large cross sectional area into a region of smaller area is the following:

$$\frac{144 P_L}{\rho} + \frac{V_L^2}{2g} = \frac{144 P_S}{\rho} + \frac{V_S^2}{2g} + 0.5 \left(1 - \frac{A_S}{A_L}\right)^2 \frac{V_S^2}{2g_c} \quad (1)$$

where A_L and A_S are the cross-sectional area, P_L and P_S are the pressures, V_L and V_S are the velocities in the large and small sections respectively, ρ is the fluid density, and g_c is the conversion factor. The friction loss used in WHAM,

$$0.5 \left(1 - \frac{A_S}{A_L}\right)^2 \frac{V_S^2}{2g_c},$$

implies the maximum steady-state entrance loss from a large reservoir (large cross sectional area) into a square-edged opening. (15) The loss coefficient for an area ratio $\frac{A_S}{A_L}$ of 0.6 is, in fact, closer to 0.3 than 0.5. (29) Equation (1) then becomes

$$\frac{144 P_L}{\rho} + \frac{V_L^2}{2g} = \frac{144 P_S}{\rho} + \frac{V_S^2}{2g} + 0.7 \left(1 - \frac{A_S}{A_L}\right)^2 \frac{V_S^2}{2g_c} \quad (2)$$

Sonic velocities and fluid density within the vessel were determined using initial temperature and pressure readings just prior to rupture. Initial vessel fluid temperature was determined by averaging the readings of several vessel and nozzle thermocouples. Generally, the temperatures were within 2 to 3 degrees of the average. The temperature in the blowdown nozzle was usually slightly lower than in the vessel even though liquid was bled from the extension. The nozzle extension was not insulated. The remainder of the vessel including nozzles and nozzle flanges was insulated. No significant temperature gradients were observed other than in the blowdown nozzle. The assumed sonic velocity in the blowdown nozzle was the value that corresponded to the measured nozzle temperature.

Pressures in the Blowdown Orifice

Pressures in the orifice generally dropped well below the saturation pressure. The minimum measured pressures for all runs are listed in Table 5.2. Also listed are the saturation pressure based on vessel temperature, the saturation pressure based on blowdown nozzle temperature, the initial pressure, and the minimum WHAM-calculated pressure.

A typical comparison of a WHAM-calculated and an experimental pressure history for a point 1-3/8 in. upstream from the orifice is shown in Figure 5.1. The disagreement between WHAM predictions and the results were caused mainly by the decompression pattern of the double ruptured disk break. The double-disc rupture system caused a characteristic two-step decompression. The experimental pressure histories typically showed a partial decompression followed by a 1-to-5 msec period of oscillating pressures. Then, a large decompression occurred with the pressure falling to approximately the minimum value. The same two-step behavior has been noticed in the LOFT

semi-scale results.^(28,31) LOFT semi-scale tests also use the double-disc overpressurization technique to initiate blowdown. Speculatively, the two-step behavior could be attributed to deflection and plastic yielding of the rupture disc causing a partial decompression near the orifice, followed by a brief period of no further decompression, and then complete rupture.

TABLE 5.2. Minimum Measured Pressure for All Runs

<u>Run Number</u>	<u>Initial Pressure, psig</u>	<u>Vessel Saturation Pressure, psig</u>	<u>Nozzle Saturation Pressure, psig</u>	<u>Minimum Pressures Measured</u>
B-19B	2100	1550	525	200
B-20B	968	665	365	100
B-21	999	685	345	20
B-22B	1286	640		100
B-23	2137	655	540	300
B-24	810	700	200	100
B-25	1285	665	605	300
B-27B	1075	1063	915	100
B-28	1032	990	885	700
B-40	854	690	515	400
B-50	2082	690	585	100
B-51	1682	660	540	
B-52	1289	660	530	50

The high frequency oscillations^(11,28) following decompression appeared to be related to the instrumentation rather than oscillations caused by reflected waves. The oscillating pressure behavior was not the same frequency predicted by WHAM. Nor were the reflected compression waves returning from the nozzle-vessel interface present in the large magnitude predicted. The oscillation frequencies found in the data for the

FIGURE 5.1. Typical WHAM-Calculated and Measured Orifice Pressure Histories at P-8 (Run B-51)

two orifice pressure gages, P-8 and P-10, (Figure 4.8) are listed in Table 5.3. The lengths of the tap from the pressure sensor to the hole are 10.5 in., 10.2 in., 9.3 in., 8.4 in., and 7.6 in. for the nominal 1, 2, 4, 6, and 8 in. diameter orifices respectively. The open pipe frequency (fourth harmonic) responses for these lengths are 1100 Hz, 1100 Hz, 1200 Hz, 1350 Hz, and 1500 Hz for the respective orifice sizes (sonic velocity assumed to be a nominal 3800 ft/sec which corresponds to 480 °F). These frequencies are close to the observed frequencies for P-8. However, for P-10, the observed frequencies were significantly lower than the natural frequencies and might be characterized by the response of a forced oscillation system or one that was considerably damped. For both sensors, however, the measured oscillations were most likely characteristics of the instrument and tap rather than actual pressure oscillations in the orifice.

Due to the oscillations mentioned above it is doubtful that the standard opening time assumed for the WHAM calculations was correct. The oscillations mask the true orifice pressure history. The major decompression waves might have been less steep than observed. The assumed break time was estimated from the steep portion of the measured pressure profiles. Therefore, the single parameter ramp opening time was probably not a good description of the actual opening history. Furthermore, to model closely the shape of the decompression wave, more sophisticated opening functions would be necessary as well as more accurate measurement of opening times. The assumption of a linear-area break opening resulted in distinctive reflected compression waves in the orifice. A more realistic function might predict greatly reduced compression waves and therefore more closely match the observed results,

TABLE 5.3. Data for Pressure Gages P-8 and P-10

Run Number	Instrument Ring Frequencies, Hz	Nominal Orifice Size, in.	Tap Length, in.	Outlet Orifice Frequencies, Hz	
				P-8	P-10
B-19B	850	2	10.2		700
20B		4	0.3	1300	800
21	1000	4	9.3	1200	1000
22B	1030	2	10.2	1400	800
23	1030	1	10.5	1200	None
25	1000	4	9.3		
50	1040	2	10.2	1400	800
51	1020	4	9.3	1400	1000
52	1000	6	8.4	1400	1400
40	980	4	9.3	1250	1000
28		6	8.4	1300	900
				1300	800

The measured pressures dropped well below the saturation pressure in the orifice. The approximate magnitude of this drop was predicted by WHAM for the large blowdowns. For smaller breaks, WHAM calculated a higher minimum pressure than the measured minimum pressure in the orifice. In all cases, the minimum measured pressure was well below saturation. The experimental and calculated pressures verify the use of back pressures well below the saturation pressure. For conservative calculations, the back pressures should be the ambient.

This result seems in contradiction of the work at LOFT where the analysts have successfully applied WHAM to semi-scale blowdown data^(31,32,33) using a back pressure approximately equal to the saturation pressure. A comparison of the two nozzle configurations suggest a probable explanation of the use of close-to-saturation at LOFT while CSE results indicate the use of ambient pressure.

In the CSE rupture disc configuration, the inner rupture disc was placed immediately next to the orifice plate on the

downstream side as shown in Figure 4.8. The only volume of pressurized water downstream of the orifice was the volume held by the rupture disc hemisphere. For a 1.69-in. diam break, this volume represents 0.37 times the volume contained within the orifice. For a full size break (6.813 in. diam), the fluid immediately expands into a larger flow area from the inner rupture disc and orifice. (The area ratio even for the largest breaks at this discontinuity was 1.38.)

For the LOFT semi-scale system with a limiting orifice, however, there was a considerable volume of pressurized water downstream of the orifice. The inner rupture disc was 1.5 in. downstream of the orifice as shown in Figure 5.2. The volume was approximately 10 times the volume contained in the 30% break-area orifice. This represents a considerable volume that must exit before the orifice controls. For a LOFT (semi-scale) 100% break, the fluid expanded into a length of pipe of the same cross sectional area as the break. The modelling of the fluid behavior following rupture becomes more complex since the expanding fluid represented a moving boundary with a changing boundary condition until flow was established at the exit. The exit was 18 in. downstream from the rupture disc. Comparison of CSE and LOFT exit nozzle configurations suggests that the LOFT geometry would result in higher back pressures than the CSE configuration.

For the best comparison and extrapolation to a design break accident, an ideal break configuration for blowdown studies would consist of a single brittle rupture disc or break away pipe placed on the end of an orifice flange. On rupture, the fluid would expand directly into the atmosphere. In the analysis of double-ended breaks for large reactors, the behavior of the rupture and resulting back pressure are currently not well understood. For conservative calculations, however, the back pressure should be atmospheric pressure.

5.11

$A = 0.5, 0.875 \text{ OR } 1.00$

FIGURE 5.2 LOFT Semi-Scale Nozzle Extension and Rupture Disc Assembly

Because of the typically poor comparisons of the WHAM-calculated results with measured results in the orifice region, a revised calculation was made for one run. It was apparent that the double-disc rupture system could not be readily described by a simple break area opening function with a constant back pressure. To obtain better results, it was necessary to model the two-step decompression observed in the orifice. It was also necessary to include the P-8 pressure tap length in the calculation to account for the observed oscillations.

The modelling of the orifice and inlet pipe pressure histories becomes mandatory if proper pressure histories are to be predicted in the vessel. If a calculation failed to describe the observed behavior in the orifice region with reasonable accuracy, the resulting anomalies in comparisons between calculated and measured vessel pressures could be attributed to the poorly modelled exit region. In this situation, the code would be used (undesirably) to describe exit behavior rather than to test the codes ability to accurately calculate pressure histories within the vessel. If the exit behavior could be modelled by empirical methods, the comparisons of measured and calculated vessel pressures would serve as more meaningful tests of the ability of one-dimensional codes to predict pressure histories.

A second prediction was made for run B-51, a top-nozzle PWR-type blowdown. To model the pressure history in the orifice, an arbitrary back pressure function was derived from P-10 data. The P-10 tap was located 1/4 in. from the exit and should have provided a good indication of the back pressure over the first few milliseconds. The back pressure function was decreased linearly from 1682 psig (the initial pressure) to 1300 psig in 1 msec, held constant at 1300 psig between 1 and 2 msec after the break, and then was decreased linearly

to atmospheric at 3 msec after rupture. The break area was fully open at the start in order to make the back-pressure control.

The revised WHAM-calculated pressure history at P-8, including the effects of the appropriate top, is shown in Figure 5.3. The decompression was successfully modelled. The calculated recovery after about 5 msec was greater than measured, possibly due to flashing in the tap pipe or orifice, or possibly due to a low pressure region near the top caused by a vena contracta. Note that if flashing did occur in the orifice, the constant density and sonic velocity assumptions in WHAM would not be valid. However, slope and behavior of the decompression within the important first few msec was accurately modelled. The oscillations caused by the instrument tap pipe were also predicted.

Pressures in the Blowdown Pipe

Measured pressures in the blowdown pipe generally showed a decompression wave reduced in magnitude due to orifice-to-pipe flow area differences. The amount of attenuation, of course, depended on the orifice/pipe area ratio. However, as shown in Figure 5.4, the WHAM calculations typically predicted much steeper and larger initial wave fronts than were measured. As a result, the corresponding reflected compression waves calculated by WHAM were greater in magnitude than the measured waves. The overpredicted amplitude of pressure oscillations in the blowdown pipe was a direct result of the improperly modelled exit.

The revised calculation for the B-51 blowdown, shown in Figure 5.5 showed excellent agreement for this region. Hence, the empirical back pressure function used to describe conditions at the orifice did result in a properly calculated pressure history in the blowdown pipe. Results of the vessel pressure comparisons for this revised calculation, then, should depend

FIGURE 5.3. Measured and Revised WHAM-Calculated Orifice Pressure Histories for Run B-51

FIGURE 5.4. Typical WHAM-Calculated and Measured Pressure Histories in the Blowdown Pipe P-4 (Run B-51)

FIGURE 5.5 Measured and Revised WHAM-Calculated Blowdown Pipe Pressure Histories for Run B-51

on the ability of the one-dimensional code to properly describe pressure histories in the vessel and not depend on the description of exit behavior.

Vessel Pressures

Typical vessel pressure histories calculated using the simple ramp functions for pressure exit showed more severe pressure oscillations than were measured as seen in Figure 5.6. The increased amplitude of oscillations was expected since the calculations using simple break functions also overpredicted the severity of oscillations in the blowdown pipe. The calculated frequencies were approximately correct, indicating that the wave transport times (and hence sonic velocities) were approximately correct for the one-dimensional model. Depressurization rates, denoted by the slope of the pressure history, were approximately correct for a majority of the blowdowns. Runs B-40, B-28, and B-52, showed slower decompression rates indicating either an effective back pressure higher than atmospheric or a lower exit orifice coefficient.

Multi-dimensional effects were erroneously thought to be important because of high frequency oscillations (approximately 1000 Hz) present at the instrument ring⁽¹²⁾ as shown in Figure 5.7. The oscillations at instrument ring were found to be a function of the length of the instrument connecting tap (11.3 in.). Observed frequencies for 500 °F runs were characteristically 1000 Hz which closely corresponds to the natural open pipe frequency ($c/4 \ell$)* of 970 Hz. For the 600 °F blowdown, B-19B, the observed frequency was 850 Hz which is close to the natural ($c/4 \ell$) frequency of 750 Hz. A radial probe was installed to check the relative amplitudes of oscillation at two radial positions (same elevation). Unfortunately, instrument problems precluded coincident measurements of both radial

* Where c = acoustic velocity in the medium of the pipe of length ℓ .

FIGURE 5.6. Typical WHAM-Calculated and Measured Pressure Histories in the Vessel at PLUG7 (Run B-51)

FIGURE 5.7. Typical WHAM-Calculated and Measured Pressure Histories in the Vessel at the Instrument Ring (Run B-51)

positions for most blowdowns. However, most pressure data did not show high frequency oscillations characteristic of two-dimensional effects. Nevertheless, some isolated cases did show high frequency oscillations, notably PLUG7 for B-19B and P-13 for B-25, B-28, and B-40. The PLUG7 sensor is entirely inside the vessel and is in direct contact with the fluid (no connecting tube). These anomalies coupled with the frequency limitation of the data acquisition equipment (1500 Hz) make it impossible to exclude the possibility of important multi-dimensional effects.

The revised one-dimensional WHAM calculation for B-51 which used the empirical exit functions showed excellent frequency and amplitude agreement with the measured data. The high frequency response at the instrument ring, shown in Figure 5.8 was predicted by using the proper tap pipe length. The calculated pressure history under the sieve plate also agreed closely with the measured history as shown in Figure 5.9. Although the calculations using simple analytical functions for describing exit behavior showed adequate agreement for vessel pressure histories, the excellent agreement shown by the revised calculation showed that WHAM is capable of properly describing CSE vessel pressure histories in this configuration when exit behavior can be adequately described.

Pressures in Nozzles Other Than the Blowdown Nozzle

WHAM calculation with a simple ramp pipe break function overpredicted the severity of pressure oscillations in nozzles as shown in Figure 5.10. Again, this overprediction was a direct result of the assumption used to describe the exit behavior. Although the calculations that used the ramp exit pressure function did a reasonable job of predicting pressure histories, the revised calculation for B-51 using an empirical exit showed excellent agreement with the measured data as shown in Figure 5.11.

FIGURE 5.8. Measured and Revised WHAM-Calculated Pressure Histories at the Instrument Ring for Run B-51

FIGURE 5.9. Measured and Revised WHAM-Calculated Pressure Histories in the Vessel for Run B-51

FIGURE 5.10. Typical WHAM-Calculated and Measured Pressure Histories in Nozzle H (Run B-51)

FIGURE 5.11. Measured and Revised WHAM-Calculated Pressure Histories in Nozzle H for Run B-51

Nozzle C represented a geometry which is difficult to model in one-dimension. The bottom hemisphere of the vessel was represented by step area changes. The position of the Nozzle C attachment within these step changes determines the response of the sensor at the end of the nozzle. For most calculations, the hemisphere was modelled by two reduced area regions with the nozzle attachment between them. The elbow was neglected.

Results of typical WHAM-calculated pressure histories substantially overpredicted the severity of pressure oscillations in Nozzle C, as shown in Figure 5.12. This was probably a result of the coarse treatment of both the exit and the bottom hemisphere. No revised calculations for the Nozzle C pressure history were made. However, had such calculations been made they should have indicated a reduced amplitude of oscillation.

Effect of Dissolved Gases (34)

The method of pressurizing the vessel with nitrogen in order to obtain subcooled conditions was found to have a large effect on the decompression history. This was due to the amount of nitrogen which could dissolve in the water during **heatup**. This problem was noticed during the empty vessel series⁽¹⁾ and the operation of blowdowns B-19 and B-19B (Figure 5.13) was done to prove the effect. Later, blowdown B-29 (Figure 5.14) was made in order to obtain a sample of water and determine the amount of nitrogen dissolved.

The method used was to pressurize the system with nitrogen before heating the partly full vessel. Pressurization prevented boiling in the heat exchanger and thermal expansion of the water caused the vessel to be full when the desired run temperature was reached. However, the initial dome of nitrogen at high pressure and temperature allowed appreciable concentrations of nitrogen to dissolve in the water during the heatup. The method of operation used in B-19B and other subcooled runs

FIGURE 5.12. Typical WHAM-Calculated and Measured Pressure Histories in Nozzle C (Run B-22B)

FIGURE 5.13. Effect of Dissolved Nitrogen-2 in. Blowdown

FIGURE 5.14. Effect of Dissolved Nitrogen-4 in. Blowdown

was to carry the liquid level in a cold chamber above the vessel and bleed off the expanding liquid during heatup. Bleeding from the test section had the additional advantage of providing it with hot water.

The effect of the nitrogen dissolved in the water was to reduce the rate of subcooled decompression (Figure 5.13). With no nitrogen the saturation pressure corresponding to the vessel temperature was reached very quickly, but with the nitrogen dissolved, saturation was not approached for many seconds.

The subcooled decompression pattern was also slower and less violent with the nitrogen dissolved (Figure 5.15), and the strain on the sieve plate support bolts was reduced with nitrogen present. (Figure 5.16)

Force on Sieve Plate

a. Data Reduction

Signals generated by the strain bolt configurations were fed to a small digital computer which then logged them. A multiplexer and an analog-to-digital conversion system was used. The signals from a data collection run were processed, resulting in a plot for each signal such as shown in Figure 5.17

The changes in resistance observed may be scaled either as strain or "equivalent psid" since in the first case a "gage factor" gives the strain represented by a given change in resistance and in the second case a calibration of total plate force versus resistance is known and may be divided by the free area of the plate. The scan rate is a nominal 3000 pts/sec for a typical logging duration of 80 msec. The sawtooth waveforms observed are a characteristic of the multiplexing data acquisition system when used on very low level signals and are analogous to the noise level in an analog system. The level of the signal shifted because a different amplifier was involved in the logging process for each 40 msec interval. The gains

Neg 0693898-2

FIGURE 5.15. Pressure in Vessel During Subcooled Decompression

Neg 0693898-1

FIGURE 5.16. Strain in Bolt Supporting the Perforated Plate in the CSE Reactor Simulator Vessel

FIGURE 5.17. CSE Blowdown (6 in. 1000, 500, 214) High-Speed Strain on Support Bolt 8 inner (Run B-21)

of each amplifier were not exactly the same. However, the shift was accounted for in the data reduction. The criteria for discriminating noise from signal was to compare spikes in individual bolt plots with the same time period in other plots. If there were no coincident spikes on the other signals the spike was discredited.

Further comparisons were made by overlaying available signal plots of different bolts. This was done for each run to get the estimate of disagreement between each gage for the peak "equivalent pressure" observed. In general, the results obtained from different bolts for the same run were in agreement within 25% of the average, although in some runs they were in disagreement as much as 80%.

b. Discussion of Sample Strain Bolt Data

Direct comparisons of data with predictions were made as shown in Figures 5.18 through 5.24 because the objective of this measurement was to provide an idea of the type and magnitude of forces experienced by a reactor internal structure for the purposes of comparison with a prediction of the type that might be made. For each blowdown, a WATERHAMMER or WHAM prediction was run and the values of nodes above and below the plate were differenced to get the expected pressure (psid) as shown on the top of each Figure. Since the gage-bolt transducer could possibly respond in resonance, a code (RESPON⁽²⁷⁾) was written to predict the response of the gage to the predicted WHAM excitation. This latter prediction of response was done for each blowdown to give the operating staff an estimate of the stress in structural members and as a result, more severe pressure levels and break size combinations were avoided.

In general, the predicted peak was two to five times the peak obtained by averaging the results from all bolts of a given run. The data presented Figures 5.18 through 5.24 have

FIGURE 5.18. Blowdown B-19B - Bottom Nozzle
(2 in., 2135 psia, 600 °F)

FIGURE 5.19. Blowdown B-24 - Bottom Nozzle
(4 in., 825 psia, 495 °F)

(1) WHAM PREDICTION OF PLATE LOADING
AS DETERMINED FROM DIFFERENCE
OF TWO NODES

FIGURE 5.20 Blowdown B-21 - Bottom Nozzle
 (6 in., 1000 psia, 500 °F)

FIGURE 5.21. Blowdown B-22 - Middle Nozzle
(2 in., 1330 psia, 500 °F)

FIGURE 5.22. Blowdown B-25 - Middle Nozzle
(4 in., 1300 psia, 500 °F)

FIGURE 5.23. Blowdown B-27B - Middle Nozzle
(4 in., 1092 psia, 545 °F)

FIGURE 5.24. Blowdown B-51 Top Nozzle

only a scale factor applied. The predicted plate pressure and observed equivalent pressure are plotted on the same scale, and the discrepancy of magnitude is consistent (low) for all the data. Direct comparison was made of the difference between the predicted peak and the largest observed value without regard to the occurrence of the peak in time. The result of this comparison is shown in Table 5.4. It is difficult to make valid "peak load" comparisons with this data since some peaks in the experimental data appear to be spurious noise while some peaks in the predictions appear to be contributions of higher frequency waveform components that do not appear in the data. The most valuable impressions are gained from direct comparison of the predictions and observations reduced to a common scale.

Referring to Figures 5.18, 5.19 and 20, predictions of blowdowns from the bottom nozzle showed an initial compressive (downward) load on the plate bolts, followed by subsequent wave additions resulting in complex waveforms. The B-19B and B-24 data were relatively noise-free; B-21 contains spikes from 15 to 25 msec, which are judged to be spurious when compared to other bolt signals from the same blowdown.

In B-19B (Figure 5.18), observed plate response was less in magnitude, the absence of "fine structure: or higher frequency components was noted, and a disparity in the sense and time for the peak loading was observed. The prediction gave peak loading in the tension (+) direction at about 14 msec, the data from the strain gage was that it occurred in the compression (-) direction at 17 msec. The predicted

gage response waveform (at the bottom of the page) appeared to follow the prediction with an absence of "fine structure." The dominate frequency in this lower plot is the calculated natural frequency of the plate-lug-bolt system and it is about 354 Hertz.

In B-24, which was a run with the vessel only 3/4 full of liquid, more high frequency "hash" was generated in the prediction with the introduction of a volume with a liquid-gas interface. The observed waveform was similar with regard to major structure, had little fine structure, and was smaller. The response prediction indicated some degree of resonance, or dynamic amplification apparent in the data.

In B-21, (Figure 5.20) the observed signal is again smaller than predicted, has fewer well-defined high frequency waveform components, and shows a lack of correlation time for the peak load event felt by the structure. The response prediction indicated a dynamic condition which was not observed in the data.

Figures 5.21, 5.22, and 5.23 represent data obtained with the blowdown nozzle in the middle "Nozzle B" location. Some change in the shape of the predicted waveform was expected because the blowdown nozzle length and the distance from the nozzle inlet to the plate was changed.

In B-22, (Figure 5.21) the magnitude of the loading observed was again less than predicted. Absence of fine structure, expecially the double and triple forked waveforms was noted. The small sawteeth in the data shown is

partially due to the high sensitivity of the scale used (8 psid/in.) and does not necessarily represent high frequency data but instead represents the lower limit of analog-to-digital conversion. Again, the expected dynamic response of the gage did not agree with the observed response.

In B-25 (Figure 5.22), the same characteristics are noted, the major waveform of the prediction was observed in the data with more of the well-defined spikes present in the WHAM prediction, and no evidence of dynamic amplification as shown in the response prediction.

In B-27B (Figure 5.23), some additional spikes are seen in the data that are judged to be noise, based on the overlay of other plots. The magnitude of the observed waveforms is less, and the absence of higher frequencies is consistent with previous observations. The gage response prediction shows dynamic amplification not noted in the data.

Sensor attrition limited the amount of data obtained in the top blowdown series, but in B-51, the remaining strain bolt gave a noise-free signal. Once again a different predicted waveform resulted from changing the location of the blowdown nozzle to the top of the vessel (Nozzle A). Since the volume above the plate was relieved first, the bolt went into tension first, but in a less violent manner than expected. A resonance condition was predicted by the response code which was not observed, and the magnitudes of the peaks were again much lower than predictions.

As mentioned above, comparisons of peak load are of limited value since the events do not correlate in time and direction. However, comparisons are useful for the purpose of getting a rough idea of the magnitude of the discrepancies. In Table 5.4, the individual strain gages for each run are tabulated with the peak observed strain and the "equivalent"

differential pressure load on the plate obtained by converting the resistance change represented by the strain to the corresponding load from the jacking test and dividing by the plate free area. The peak differential pressure WATERHAMMER or WHAM run is tabulated for the given run and a ratio of the magnitude of predicted-to-observed loadings are in column (4). These ratios range from 2 to 5. This discrepancy may come from several sources: The pressure waves directly measured were lower than the WHAM predictions (see section on WHAM) and therefore, would have given the direct effect of lower than a predicted plate response. This could have resulted from the stated equations or the possible two-dimensional propagation of the wave which should tend to reduce its impact in most locations from that predicted by the one-dimensional analysis. The possibility also exists that the vessel and core plate did not form the ideal attachment assumed in the RESPON code. Misalignments and untrue matings may have been present. Unknown effects of fluid damping, metal-to-metal, and fluid friction may have had nonnegligible effects. However, the analyses made were done with modern engineering techniques and the disagreements show the possible error which could result with these techniques. In this case, the error was a conservative one from the standpoint of nuclear safety.

TABLE 5.4. Summary of Strain Bolt Data

Blowdown Number	Strain Gage	Peak Observed Strain	(a) Equivalent DP Load on Plate, psid	Peak Predicted DP (WHAM or W.H., psid)	Ratio: Predicted Peak/ Equivalent
(Bottom Nozzle)					
B-19B (2 in.)	SB5I	182	12.4	52	4.2
	SB6I	130	18.5	↓	2.8
	SB8I	186	12.0	↓	4.3
	SB8Ø	95	<u>10.4</u>	52	<u>5.0</u>
			Avg <u><u>13.3</u></u>		Avg <u><u>3.9</u></u>
B-20B (4 in.)	SB5I	260	17.7	71	4.0
	SB8I	250	16.1	↓	4.4
	SB8Ø	90	<u>9.9</u>	71	<u>7.2</u>
			Avg <u><u>14.6</u></u>		Avg <u><u>4.9</u></u>
B-24	SB5I	300	20.5	52	2.5
	SB6I	140	20.0	↓	2.5
	SB8I	240	15.5	↓	3.2
	SB8Ø	125	<u>13.7</u>	52	<u>3.6</u>
			Avg <u><u>17.4</u></u>		Avg <u><u>3.0</u></u>
B-21	SB6I	250	35.6	75	2.1
(Middle Nozzle)					
B-22B (2 in.)	SB5I	100	6.8	16.0	2.4
	SB6I	40	5.7	↓	2.8
	SB8I	120	<u>7.7</u>	↓	<u>2.1</u>
			Avg <u><u>6.7</u></u>		Avg <u><u>2.4</u></u>
B-25 (4 in.)	SB5I	260	17.8	55	3.1
	SB6I	130	18.5	↓	3.0
	SB8I	325	<u>20.8</u>	↓	<u>2.6</u>
			Avg <u><u>19.0</u></u>		Avg <u><u>2.9</u></u>
(Top Nozzle)					
B-50 (2 in.) 2100 psi	SB6I	85	12.1	26	2.2
	SB8I	160	<u>10.3</u>	↓	<u>2.5</u>
			Avg <u><u>11.2</u></u>		Avg <u><u>2.4</u></u>
B-51 (4 in.) 1700 psi	SB8I	280	18.0	55	3.1
B-52 (6 in.) 1300 psi	SB8I	210	13.5	70	5.2

* See Sample Calculation in Appendix B

Conclusions

- A successful measurement of plate loading in an immersion situation was made with a nominal precision of $\pm 25\%$ in peak pressure loadings.
- Direct comparisons of the plate loading waveform and the predicted waveform are in substantial disagreement.
- Observations show less high-frequency component contribution than WHAM or WATERHAMMER predictions.
- Peak loadings on the plate are two to five times greater in the WHAM or WATERHAMMER run than in the observed data.
- Mechanical vibration responses predicted dynamic amplification and resonances in the structure which were not observed in 15 blowdowns at three nozzle locations.

SATURATED REGIME

The sieve plate had very little effect on the overall mass velocity of the blowdown during the saturated regime. The main effect of the sieve plate was on the liquid level history, the liquid level remaining following blowdown, and the method of applying FLASH2 to make predictions.

Liquid Level

Figure 5.25 shows a typical pattern of liquid level versus time for a blowdown in which the sieve plate was used (B-25). Also shown is the liquid level from another blowdown (B-84) which was made from the same nozzle with essentially the same initial conditions but with no sieve plate.

The characteristic effect of the sieve plate when blowdown was made through a nozzle below it was to show a sudden drop in level of the liquid. This drop is believed to be the result of a separate steam dome formed below the plate. When the level of the upper chamber reached the plate the sensor (which senses from the top of the vessel down) suddenly

FIGURE 5.25. Liquid Level Versus Time for a Blowdown in Which a Sieve Plate Was Used

"sees" the level in the lower chamber, which is registered as sudden drop to the new level.

Comparisons of FLASH2 Predictions and Experimental Data for Liquid Level and Vessel Pressure

a. Outlet Below Plate

The FLASH2 code⁽²⁾ was applied to five of the CSE blow-downs B-22B, B-23, B-25, B-26, and B-27B with the outlet below the plate. Table 5.5 contains a list of parameters used in applying the code to the CSE blowdowns. Comparisons were made between predicted and experimental liquid level and pressure histories.

The code was able to predict pressures well when the proper orifice coefficient was used. However, liquid level predictions were highly dependent on the geometry and the size of break. For very small breaks the sieve plate had no effect and the prediction using a single control volume gave the best results. For larger breaks, a two-volume model could be used successfully.

Figures 5.26 and 5.27 show observed liquid level histories and FLASH2 predictions. The experimental data is taken from a Time Domain Reflectometer (TDR)⁽³⁵⁾ probe which essentially gives the distance from the top of the vessel to an electronic impedance discontinuity caused by the upper surface of the liquid or foam. As long as liquid remains above the dummy core plate, the probe receives no information concerning liquid level in the lower volume. When the liquid level in the upper volume is gone, the indication suddenly collapses to the liquid level reading in the lower volume. The time and pattern of the collapse are used as a measure of the liquid level behavior. Some of the discrepancy between the predicted curve and the observed level data can be attributed to geometric differences between the FLASH2 model which is a right-circular

TABLE 5.5. FLASH2 Parameters

Run Number	No. of Control Volume	Nominal Size, in.	Break Diam, in.	Initial Vol, ft ³	Discharge Orifice Coefficients		Bubble ^(a) Rise Velocity, ft/sec	Quality Gradient Factor
					Low-Quality	High-Quality		
B-22B	1	2	1.689	149	0.80	1.00	2.0(b)	0.8
B-23	1	1	0.815	149	1.049	1.049	3.0	0.8
B-25	2	4	3.438	149'	0.664	0.89	2.0, 2.0 ^(b)	0.8, 0.4 ^(a)
B-26	1	2	1.689	113.6	0.80	1.00	2.0 ^(b)	0.8
B-26	2	2	1.689	113.6	0.80	1.00	3.0, 3.0	0.8, 0.8 ^(a)
B-27B	2	4	3.438	113.5	0.664	0.89	2.0, 2.0 ^(b)	0.8, 0.4 ^(a)

a. For two-volume cases, the first number designates the upper volume parameter, the second number the lower volume parameter.

b. Variable bubble rise model from Redfield, J. A., and Murphy, J. H., Void Fraction and Residual Water Predictions During Loss-of-Coolant, WAPD-T-2155, Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania, September 1968.

Neg 0693300-3

FIGURE 5.26. Level of Fluid Remaining in Vessel

Neg 0693300-2

FIGURE 5.27. Level of Fluid Remaining in Vessel (Run B-25 MN)

cylinder and the actual reactor simulator vessel which is a cylinder with hemispherical ends. If total volume remaining rather than liquid level were being compared, better agreement would be obtained.

The TDR data is known to contain a temperature drift for which no corrections have been made in the figures (see Figure 5.28). Corrections for this drift would make the level continue to decrease after the transition region (inflection point in pressure curve at which high quality blowdown begins) rather than stay constant as shown for most of the runs.

Figure 5.27 illustrates the results of two FLASH2 predictions for Run B-26, a small area break. The prediction made on the basis of a two-volume vessel was not as good in predicting level drop pattern as was the single volume prediction. The major level discrepancies are primarily due to inaccuracy of the initial fluid level and its effect on the level gage calibration. The shape remains similar in spite of this inaccuracy. The more detailed two-volume approximation, which includes the sieve-plate restriction, indicated a level drop at the time the level reached the sieve plate (level collapse). The FLASH2 model in this case predicts a steam volume will be trapped under the plate since the model does not allow for counter-current bubble rise between the two volumes. The experimental data indicated that there was little or no steam volume under the plate, and hence, there was counter-current bubble rise through the plate. Agreement of the single-volume model for B-26 was much better since it contained no plate restriction and allowed bubble rise to occur.

Further evidence indicating bubble rise through the plate for B-26 was found by comparing the pressure decay curves in Figure 5.29. The two-volume model predicted a change in slope in pressure decay before transition that did not appear in the experimental data.

Neg 0693300-4

FIGURE 5.28

Level of Fluid Remaining in Vessel

Comparisons of data and predictions for the remaining four runs indicated that counter-current bubble rise through the sieve plate occurred for the small break diameter blowdowns (1 and 2-in.) but not for the intermediate break size 4-in.). For B-22, a full vessel blowdown with a 2 in. break, the single volume FLASH2 prediction showed good agreement with both the pressure curve, Figure 5.29, and the liquid level history, Figure 5.27.

For B-23, a full vessel blowdown with a 1-in. break, the single-volume prediction again gave good agreement with the liquid level history as shown in Figure 5.26. However, for larger break size (4 in, nominal) runs, B-25 and B-27, shown in Figure 5.27, the two-volume model gave superior results. In these runs the bubble passage upward through the plate was being inhibited.

The level history for B-25, (Figure 5.27) showed a level collapse near the transition from low-quality flow. This indicates that a steam volume was trapped under the plate; therefore, bubble rise through the plate was inhibited. For B-27, (Figure 5.27) a 3/4-full vessel blowdown, the level history indicates the same level collapse as seen in the B-25 data.

In an effort to define the approximate value of the through-plate liquid velocity above which bubble rise is inhibited and below which bubbles rise freely through the plate, an investigation of the liquid level data from several sieve plate runs was made. Results are given in Table 5.6. For those blowdowns that exhibited total collapse to approximately the nozzle level, the nominal mixture velocity through the plate was well above 4.6 ft/sec. For those blowdowns that showed no level collapse, the nominal mixture velocity through the plate was below 4.6 ft/sec.

FIGURE 5.29. Pressure Decay in Vessel

TABLE 5.6. Nominal Mixture Velocities Through the Sieve Plate Orifices

<u>Run Number</u>	<u>Break Position</u>	<u>TDR Trace</u>	<u>Nominal Velocity, ft/sec</u>
B-19B	bottom	partial collapse	4.6
B-20B	bottom	total collapse	7.8
B-21	bottom	total collapse	15.9
B-22B	middle	smooth	2.6
B-23	middle	smooth	0.9
B-24	middle	total collapse	7.5
B-25	middle	total collapse	7.8
B-26	middle	smooth	3.1
B-27	middle	total collapse	8.5

In B-19B, a bottom nozzle blowdown, the liquid level (Figure 5.30) collapsed when it reached the plate; but the level did not drop to the exit nozzle level. In all other runs that indicated steam volumes under the plate, the level collapsed from the plate to about the elevation of the exit nozzle. Also, the slope of the level curve for B-19B does not change after the collapse through the plate. This fact indicated that the exit flow was still in the low-quality region (i.e. before transition). For all other cases that exhibited level collapse, the slope of the level curve changed after the level dropped, indicating that the flow regime changed from low-quality to high-quality near the time when the level dropped. A two-volume FLASH2 model predicted a level collapse to the exit nozzle for B-19B. RELAP2,⁽³⁾ another blowdown code, also predicted a level collapse to the exit nozzle. In view of the above, it appears that the mixture velocity of 4.6 ft/sec through the plate for B-19B is near the threshold where bubble transfer begins through the plate to the upper plenum. This conclusion precludes instabilities which might give riser and downcomer regions on the plate. This velocity represents a

Neg 0693300-6

FIGURE 5.30 Level of Fluid Remaining in Vessel

fluid velocity against which the bubbles cease to rise and is somewhat higher than the velocities used as parameters in bubble-rise-model blowdown calculations. This velocity represents a physically real value, however, and may be useful in further refinement of multiple volume blowdown codes.

For any situation during reactor blowdown which may result in downflow through such a plate or core, a steam dome could form. Geometrical arrangements such as bottom skirts, flow distributors, or jet pumps with diffusers below the bottom of the core could give rise to a steam region below the core. If flow reversal or reflooding should occur under this condition, the steam in the lower dome would pass up through the core giving lower heat transfer coefficients than liquid or two-phase mixture for a time until the liquid reached the core level.

b. Outlet Above Plate

The FLASH2 code⁽²⁾ predictions were compared with each of the CSE top nozzle (Nozzle A) blowdowns performed (see Table 5.1). The configuration of the apparatus is shown in Figure 4.6. A list of parameters used in applying the code to these blowdowns is shown in Table 5.7. Comparisons were made between predicted and experimental liquid level and pressure histories.

Figure 5.31 through 5.34 show observed liquid level histories and FLASH2 predictions. The experimental data was taken from the Time Domain Reflectometer (TDR) probe. As stated previously some of the discrepancy between the predicted curve and the observed level data can be attributed to geometric differences between the FLASH2 model, a right-circular cylinder, and the actual reactor simulator vessel, a cylinder with hemispherical ends. The TDR data is known to contain a temperature drift for which no corrections have been made in the figures. Corrections for this drift would cause the indicated liquid level to decrease more rapidly at times later in the run.

TABLE 5.7. FLASH2 Parameters

Run Number	No. of Control Volumes	Nominal Break Size, in.	Break Diam, in.	Initial Vol, ft ³	Discharge Orifice Coefficients		Bubble Rise Velocity, ft/sec	Quality Gradient Factor
					Low-Quality	High-Quality		
B-50	1	2	1.689	149	0.77	0.77	(a]	0.8
B-51	1	4	3.438	149	0.664	0.664		0.8
B-52	1	6	5.189	149	0.595	0.595		0.8
B-53B	1	2	1.689	84	0.77	0.77		0.8

a. Variable bubble rise model from edfield, J. A., and Murphy, J. H., Void Fraction and Residual Water Predictions Durin Loss-of-Coolant, WAPD-T-2155, Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania in 1968.

FIGURE 5.31. Level of Fluid Remaining in Vessel, Run B-50TN

FIGURE 5.32. Level of Fluid Remaining in Vessel, Run B-51TN

FIGURE 5.33 Level of Fluid Remaining in Vessel, Run B-52TN

FIGURE 5.34. Liquid Level of Fluid Remaining in Vessel, Run B53BTN

The liquid level data for the 4- and 6-in. break size runs show a plateau late in the run at the plate elevation. The indicated plateau in these larger break-area runs could be caused by liquid "hanging up" where the TDR probe passes through the core plate. The clearance at this point is small in order to achieve as effective a flow restriction as possible.

The FLASH2 predictions for all the runs in Figures 5.31 through 5.34, show a plateau in the liquid level history at the point where the foam level passes the blowdown nozzle. This is caused by the great difference in rates of critical massflow that exists between single-phase vapor and two-phase flow. When the predicted level drops below the nozzle (a mathematical plane of no height in FLASH2), gas flow begins. The gas flow allows rapid pressure decrease which in turn causes the foam to swell. Then two-phase flow starts at its greater rate, causing the foam level to decrease. The process is repeated until the predicted level no longer rises to the nozzle plane.

Actually, the nozzle has finite height and will draw fluid from both above and below the foam level. It can also be presumed that the rapid flow into the nozzle will be disturb the foam level so that the interface tilts up or down toward the nozzle. Both these effects will tend to smooth over the plateau which results from the mathematical assumption of a blowdown "plane" in FLASH2.

The conclusion is that the computer code will have to be modified to account for the above noted effects before adequate predictions of foam level will be obtained in the regions of the blowdown nozzle.

At later times, FLASH2 consistently predicts higher than observed foam levels. Presumably, this occurs because FLASH2

36. *F. J. Moody. Maximum Two-Phase Vessel Blowdown from Pipes, APED-4827. General Electric Company, Atomic Power Equipment Department, San Jose, California, 1965.*
37. *Quarterly Technical Report, LOFT Program Office, June-September 1968, IDO-17213. Phillips Petroleum Company, Idaho Falls, Idaho, January 1969.*
38. *A. R. Edwards. Conduction Controlled Flashing of a Fluid and the Prediction of Critical Flow Rates in a One-Dimensional System, AHSB(S)R-147. United Kingdom Atomic Energy Authority, Harwell, Berks, England, 1968.*

24. Nuclear Safety Quarterly Report, November, December, 1967, January 1968, BNWL-816. Battelle-Northwest, Richland, Washington, September 1968.
25. Nuclear Safety Quarterly Reports, November, December 1968, January 1969, BNWL-1009. Battelle-Northwest, Richland, Washington. March 1969.
26. R. J. Melosh, P. A. Diether, and M. Brennan. Structural Analysis and Matrix Interpretive System (SAMIS) Program Report, TM-33-307. Jet Propulsion Laboratory (NASA), Pasadena, California, September 1, 1966.
27. V. B. Watwood and R. A. Selby. Computer Code (RESPON) for Dynamic Response Calculations, BNWL-1493. (In Preparation)
28. Quarterly Technical Report, Step Project, January 1966-March 1966, IDO-17186, p. 38. Phillips Petroleum Company, Idaho, November 1966.
29. Nuclear Safety Quarterly Report, February, March, April 1968, BNWL-885. Battelle-Northwest, Richland, Washington, October 1968.
30. V. L. Streeter. Handbook of Fluid Dynamics. McGraw-Hill Book Company, New York, 1961.
31. G. H. Hanson. Subcooled-Blowdown LOFT - Quarterly Scale Experimental Pressures and Calculated Transients Using the WHAM Code. Presented June 18, 1969 at ANS Meeting, Seattle, Washington.
32. J. A. Redfield and J. H. Murphy. "Comparison of the FLASH2 Loss-of-Coolant Analysis Method with LOFT Semi-scale Tests Results," Trans. Am. Nucl. Soc., vol. 10, p. 701. November 1967.
33. Quarterly Technical Report, LOFT Program Office, October 1-December 31, 1968, IDO-17267, p. 27. Phillips Petroleum Company, Idaho Falls, Idaho, July 1969.
34. R. T. Allemann. "Dissolved Gas Influence on a PWR Design Basis Decompression," Trans. Am. Nucl. Soc., vol. 12, p. 2. 1969.
35. B. E. Dozer. "Liquid Level Measurement for Hostile Environment," Instrument Technology, p. 55. February 1967.

12. Nuclear Safety Quarterly Report, February, March, April 1969, BNWL-1084. Battelle-Northwest, Richland, Washington, July 1969.
13. R. P. Rose, G. H. Hanson, and G. A. Jayne. Hydrodynamics Describing Acoustic Phenomena During Reactor Coolant System BZowdown, IDO-17154. Phillips Petroleum Company, Idaho Falls, Idaho, July 1967.
14. S. Fabric. Early BZowdown Analysis for the Loss-of-Fluid Test Facility, Reference material Abstract 278. Argonne Code Center, June 1965.
15. S. Fabric. Computer Program WHAM for Calculation of Transients in Liquid Filled Piping Networks, Reference material Abstract 278. Argonne Code Center. November 1967.
16. B. M. Johnson. Containment Systems Experiment Part III - Mathematical Models of Pressure-Temperature Transients, BNW-233. Battelle-Northwest, Richland, Washington, May 1966.
17. E. V. Gallagher, T. A. Zaker, A. H. Wiedermann. Studies of Reactor Containment, Bimonthly Progress Report, IITRI-T6042-25. ITT Research Institute, Chicago, Illinois, November 1966.
18. W. A. Carbiener and P. A. Cudnik. "Similitude Considerations for Modeling Nuclear Reactor Blowdowns," Trans. Am. Nucl. Soc., vol. 12, no. 1, p. 253. June 1969.
19. F. J. Moody. "Maximum Flow Rate of a Single Component, Two-Phase Mixture," Trans. ASME, J. of Heat Transfer, vol. 87-C, p. 134. 1965.
20. H. K. Fauske. Contribution to the Theory of Two-phase One-Component Critical Flow, ANL-6633. Argonne National Laboratory, Argonne, Illinois, October 1962.
21. H. Karwat and K. Wolfert, "BRUCH-D A Digital Program for Pressurized Water Reactor BZowdown Investigations," Paper presented at CREST Specialist Meeting, Frankfurt a.M. June 1969. MRR 62.
22. H. Karwat. Studies Related to the Depressurization of Water Cooled Power Reactors. Contribution to 4th CREST Meeting in Paris, France, October 29-31, 1968.
23. H. Fujie et al. "Studies for the Safety Analysis of Loss-of-Coolant Accidents in Light-Water Power Reactors," J. Japan Soc. Mech. Engrs., vol. 69, no. 571, pp. 1068-1076. August 1966.

REFERENCES

1. R. T. Allemann et al. Experimental High-Enthalpy-Water Blowdown from a Simple Vessel Through a Bottom Outlet, BNWL-1411. Battelle-Northwest, Richland, Washington, June 1970.
2. J. A. Redfield, J. H. Murphy, and V. O. Davis. FLASH2: A FORTRAN Program for the Digital Simulation of a Multinode Reactor Plant During Loss-of-Coolant, WAPD-IM-666. Westinghouse Electric Corporation, Pittsburgh, Pennsylvania, April 1967.
3. K. V. Moore and W. H. Rettig. RELAP2: A Digital Program for Reactor Blowdown and Power Excursion Analysis, IDO-17263. Phillips Petroleum Company, Idaho Falls, Idaho, March 1968.
4. W. H. Rettig et al. RELAP3--A Computer Program for Reactor Blowdown Analysis, IN-1321. Idaho Nuclear Corporation, Idaho Falls, Idaho, June 1970.
5. N. P. Wilburn. Void Fraction Profile in a Nuclear Reactor Vessel During Coolant Blowdown, BNWL-1295. Battelle-Northwest, Richland, Washington, December 1969.
6. Emergency Core Cooling. Report of Advisory Task Force on Power Reactor: Emergency Cooling, USAEC, 1967.
7. C. E. Linderoth. Containment Systems Experiment Description of Experimental Facilities, BNWL-456. Battelle-Northwest, Richland, Washington, February 1970.
8. G. J. Rogers. Program for Containment Systems Experiment HW-83607. Available from Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, September 1964.
9. Nuclear Safety Quarterly Report, May, June, July 1969, BNWL-1187. Battelle-Northwest, Richland, Washington, September 1969.
10. Nuclear Safety Quarterly Report, August, September, October, 1969, BNWL-1266. Battelle-Northwest, Richland, Washington, December 1969.
11. Nuclear Safety Quarterly Report, November, December 1969, January 1970, BNWL-1315-1. Battelle-Northwest, Richland, Washington, March 1970.

FIGURE 5.43. Thrust Coefficient

Several calculated thrust coefficients with ranges is shown in Table 5.9 and in Figure 5.43. In these experiments the smallest orifice produced the largest specific thrust partly due to the higher mass velocity but also due to the diffuser effect (as mentioned above) beyond the orifice which gave additional thrust by virtue of continued flashing and acceleration of the fluid.

These results show that the shape of the end of a broken pipe may have an important effect on the amount of thrust produced even though the flow rate is limited by critical flow. For example, if the pipe bulges and forms a flared end upon breaking it would give more thrust than the simple sharp ended break.

TABLE 5.9. Thrust Coefficients

<u>Run Number</u>	<u>Nominal Size, in.</u>	<u>Thrust/Pressure × Area</u>
B19	2	1.76 - 1.64
19B	2	2.07 - 1.5
20B	4	1.9 - 1.85
21	6	1.94 - 1.64
22B	2	2.5 - 2.1
23	1	3.9 - 4.8
24	4	1.86 - 1.7
25	4	1.4 - 1.24
26	2	2.02 - 1.95
27B	4	0.92 - 0.7
28	6	1.3 - 1.4
29	4	1.68 - 1.25
40	4	1.28 - 1.21
50	2	
51	4	
52	6	
53B	2

FIGURE 5.42. CSE Blowdown (2 in. 2115, 603, 2) Cross-Plot of Vessel Pressure Versus Thrust Force from LC-3

Thrust

The force generated by the expulsion of a two-phase mixture was found to be approximately $2 PA$ where P is the vessel pressure and A is the break area. However, the shape of the pipe at the break and the coefficient of flow rate may result in higher or lower values.

One of the purposes of these tests was to measure the thrust force generated as a reaction to the ejection of the fluid from the vessel during the subcooled and the two-phase critical flow regimes of blowdown. Data were obtained for the saturated regime of blowdown but the subcooled regime was of too short a duration (a. t. 0.5 sec) for data to be obtained from the relatively slow response load cell-mass system.

The thrust was obtained from the output of two load cell sensors which were calibrated by hydraulic press loading along the axis of the blowdown nozzle used. The thrust data showed no regular trend and correlation was somewhat difficult. The method used here was to cross plot the thrust with the vessel pressure (Figure 5.42). Plots of this kind showed a fairly constant slope during the two-phase saturated portion of the blowdown. The slope could be termed a thrust coefficient C where $C = T/P \cdot A$. Note the drop in thrust at transition to single phase flow. This drop could be represented by an offset for the two-phase portion of the blowdown. The added thrust is probably produced by the additional flashing outside the orifice which acts on the orifice and flange faces producing an additional load on the thrust support load cells. This offset would probably not result from a free ended pipe, instead of the flanged pipe used in the experiments. The offset generally causes the coefficient to have a range of values during the course of the two-phase blowdown.

FIGURE 5.41. Outlet Test Section for Runs B-25 and B-40.

rate to its actual value without resorting to the use of an empirically determined flow coefficient constant for each size blowdown.

The effect of outlet nozzle length on the blowdown rate was examined in one test and found to be less pronounced than predicted. The use of a square edged orifice on blowdown runs does not correspond to the assumed condition of a full open break (the Design Basis Accident for nuclear reactors). This is attained on the CSE apparatus only with an 8 in. (nominal) break. However, previous work had shown that the mass velocity data for such a full open break fall in line with data obtained from square edge orifices of smaller size. This suggested that the critical flow mechanism and the coefficient was not a strong function of the outlet geometry. To prove this, two tests (Runs B-25 and B-40) were made starting from the same saturation temperature. One of the tests was made with no outlet pipe, the other with an extended outlet section. Figure 4.8 shows the outlet test section for these two runs. The B-40 run had an 45.5-in. insert in the exit nozzle. All the other tests were made without the insert. The L/D of the small diameter section was 1.02 for B-25 and 14.3 for B-40.

The table of run conditions shows that the transition time (time when high quality steam began to flow) for B-25 was 25.8 sec and for B-40 was 26.5. Thus, the average-mass-velocity changed on the order of only 3%. Mass velocity predictions by theories such as Moody's⁽¹⁹⁾ or Edwards⁽³⁸⁾ suggest that the decrease in flow for this L/D should have been on the order 75 and 45% respectively, caused mainly by flow friction effects. Since the decrease was much smaller than this, the earlier result confirmed that the configuration of the outlet pipe did not have a large effect on critical mass velocity. This result suggests caution in assuming pipe friction decreases in mass velocity when applying them to a reactor safety analysis.

FIGURE 5.40. Residual Water in Vessel After Blowdown of Full Vessel

CSE and other⁽³⁷⁾ experimental data of residual water following blowdown were compared in Figure 5.40. CSE data were reduced to the same nondimensional basis for comparison. Agreement in the low area ratio range is good; however, the CSE data, with a large vessel area, do not reach the "knee" shown by the LOFT data.

The blowdowns starting with a part full vessel (e.g. BWR conditions, saturated with a steam dome) gave less mass remaining but a higher fraction of the original mass than did the full vessel subcooled blowdowns.

Mass Velocities

All CSE data on blowdown rates have supported earlier findings to the effect that the average mass velocity decreases with break area, all other parameters being equal. For example, the average mass velocities for several blowdowns which had similar starting conditions [blowdowns B-21, B-22, B-23, B-25) are shown in Figure 5.41. To correct for this decrease, a flow coefficient was used in applying the FLASH code. The coefficients which gave the best fit to the pressure data are also shown. These coefficients decrease with the -0.156 power of the area. This decrease is similar to the decrease noted in the bottom nozzle empty vessel tests.⁽¹⁾ The mechanism that causes the decrease continues to function with the outlet at mid-heights and with a sieve plate just as with the bottom nozzle position previously studied. A mechanism proposed to explain this coefficient and its decrease was that of bubbles (or quality) induced into the outlet stream from those rising in the vessel. A special FLASH⁽³²⁾ formulation, which gives a bubble gradient, and a new code BURP⁽³²⁾ gives slight adjustments in the flow rate, but the vertical quality gradient in the vessel predicted by these codes was insufficient to correct the predicted flow

FIGURE 5.39. Residual Water in Vessel After Blowdown from Full Vessel

TABLE 5.8. Liquid Remaining After Blowdown

<u>Run Number</u>	<u>Nozzle Location</u>	<u>Liquid Level, f t</u>	<u>Water Remaining, lb_m</u>	<u>Fraction of Initial Mass</u>
22	2-B	1.8	590	0.079
22B	2-B	1.7	540	0.073
23	1-B	1.95	660	0.089
24	4-B			
25	4-B	1.0	240	0.032
26	2-B	1.45	415	0.075
27	4-B	0.62	505	0.088
27B	4-B	0.95	208	0.037
28	6-B	0.51	87	0.016
29	4-B	1.1	260	0.36
40	4-B	1.15	282	0.0387
50	2-A	4.95	2220	0.3
51	4-A	3.45	1460	0.197
52	6-A	1.8	585	0.079
53B	2-A	3.4	1420	0.418
53	2-A	3.7	1575	0.42

The differences between prediction and experiment (Figures 5.39 and 5.40) may be due to the entrained fluid discharged from the vessel during blowdown. Entrainment is not considered in FLASH2; however, with the fluid velocities (choked exit flow) at transition and the violent fluid motion even immediately after transition entrainment is believed to be significant. Residual pool vaporization has been considered and does not account for the difference because sufficient heat is not transferred from the wetted region of the vessel to the fluid. Detailed radiant heat transfer calculations were not made because of the relatively low differential temperature and hence, the low radiant energy transfer.

Liquid Remaining

Increasing the orifice size decreased the amount of liquid remaining after blowdown when the nozzle used was not at the very bottom.

The largest blowdowns (6 in.) made, generally left less than 10% of the original liquid after the blowdown. It is expected that if more complex internal parts were included or if the break were full scale to a reactor, the liquid remaining after blowdown would be even less.

Some residual water remained in the blowdown vessel after blowdowns whenever the outlet was either nozzle A or B (i.e. not the bottom).

Shortly after each blowdown (10 to 20 min), a sight glass on the side of the blowdown vessel was valved in and the liquid remaining was measured. This measurement was used as a TDR (level gage) calibration point and it was used with the vessel volume curve to give the mass of liquid remaining. The data is shown in Table 5.8. Some data are plotted in Figure 5.39 showing the decrease in mass remaining as nozzle size is increased. The calculated values from predictions made with FLASH2 are also shown. These predictions are all high and therefore non-conservative with respect to core cooling requirements, but the percentage error based on the initial mass is not large. These predictions were made with a discharge coefficient chosen to provide agreement between vessel pressure, and mass velocity during the blowdown. The observed discharge rate is 50 to 80% of that in the Moody^(19,36) flow model. The Moody discharge rate would provide somewhat better agreement on residual mass predictions.

FIGURE 5.38. Pressure Decay in Vessel Run B53BTN

FIGURE 5.37. Pressure Decay in Vessel, Run B-52TN

FIGURE 5.36. Pressure Decay in Vessel, Run B-51TN

FIGURE 5.35. Pressure Decay in Vessel, Run B-50TN

uses a dynamic material balance on the gas in the foam to determine the average void fraction, $\bar{\alpha}$.⁽¹⁾ $\bar{\alpha}$ in turn is used to estimate the gas phase disengagement rate, $\dot{m}_g$.

$$\dot{m}_g = \frac{U_B A_v \bar{\alpha}}{v_g}$$

where U_B is the bubble rise velocity, A_v the fluid area in the vessel, and v_g the gas phase specific volume. Actually, the void fraction right at the interface α_H should be used in place of $(\bar{\alpha})$ in the expression for $\dot{m}_g$. In general, α_H is always greater than $\bar{\alpha}$ and hence $\dot{m}_g$ would be greater. The result is that because the gas disengages faster if α_H is used, the foam level would be lower. Again, the conclusion is that FLASH2 will have to be modified if adequate predictions of foam levels are to be obtained at later times during the blowdown.

The pressure histories for runs B-50 through B-53 are compared with the FLASH2 predictions in Figures 5.35 through 5.38. As has been demonstrated before, FLASH2 does an adequate job of predicting the pressure history during blowdown if the correct nozzle coefficient is selected. The method by which this coefficient should be selected is not known, and this is exemplified here in that the coefficients necessary for a good prediction are different from those determined previously in bottom and middle nozzle blowdowns. (9,12)

The modifications required to make FLASH2 fit the data for these top nozzle blowdowns will be empirical corrections to the code for this case. Further tests must be made to test the applicability of these corrections to other cases, particularly for more complex geometrics involving cores, baffles, barrels, jet pumps, and multiple loops and breaks.

APPENDIX A

HIGH SPEED PRESSURE DATA WITH WHAM CALCULATIONS

APPENDIX A

HIGH SPEED PRESSURE DATA WITH WHAM CALCULATIONS

<u>Figure Number</u>	<u>Run</u>	<u>Orifice P-8 P-10</u>	<u>Pipe P-4</u>	<u>Plate Lug</u>	<u>Inst Ring</u>	<u>Radial Probe</u>	<u>Nozzle</u>					
							<u>Q</u>	<u>H</u>	<u>J</u>	<u>R</u>	<u>L</u>	<u>C</u>
A.1-1	B19B	X*										
A.1-2				X								
A.1-3								X				
A.1-4									X			
A.2-1	B20B	X										
A.2-2			X									
A.2-3					X							
A.2-4								X				
A.2-5										X		
A.2-6											X	
A.3-1	B21	X										
A.3-2			X									
A.3-3				X								
A.3-4					X							
A.3-5								X				
A.3-6									X			
A.3-7											X	
A.3-8							X					
A.4-1	B22	X										
A.4-2			X									
A.4-3				X								
A.4-4					X							
A.4-5								X				
A.4-6									X			
A.4-7							X					
A.5-1	B23	X										
A.5-2			X									
A.5-3				X								
A.5-4					X							
A.5-5								X				
A.5-6							X					
A.5-7											X	

NOTE: Each of these curves has a solid line data curve and a dotted line calculated (WHAM) curve.

* No WHAM curve

Figure Number	Run	Orifice	Pipe P-4	Plate Lug	Inst Ring	Radial Probe	Nozzle					
		P-8 P-10					<u>Q</u>	<u>H</u>	<u>J</u>	<u>R</u>	<u>L</u>	<u>C</u>
A.6-1	B24	X										
A.6-2			X									
A.6-3				X								
A.6-4					X							
A.6-5								X				
A.6-6									X			
A.7-1	B-25	X										
A.7-2				X								
A.7-3*					X							
A.7-4**						X						
A.8-1	B27	X										
A.8-2				X								
A.8-3					X							
A.9-1	B-28B	X										
A.9-2						X						
A.9-3												
A.9-4				X								
A.9-5					X							
A.9-6								X				
A.10-1	B40	X										
A.10-2				X								
A.10-3					X							
A.10-4								X				
A.10-5						X						
A.10-6												X
A.10-7		Pressure above plate.										
A.11-1	B-50	X										
A.11-2			X									
A.11-3				X								
A.11-4					X							
A.11-5								X				
A.11-6												X
A.11-7		Pressure below plate P21.										

NOTE: Each of these curves has a solid line data curve and a dotted line calculated (WHAM) curve.

* 2 data curve
** 2 data only

Figure Number	Run	Orifice	Pipe P-4	Plate Lug	Inst Ring	Radial Probe	Nozzle					
		P-8 P-10					Q	H	J	R	L	C
A.12-1	B52	X										
A.12-2			X									
A.12-3				X								
A.12-4					X							
A.12-5								X				
A.12-6												
A.12-7		Pressure 20.75 in from exit P17.										X

NOTE: Each of these curves has a solid line data curve and a dotted line calculated (WHAM) curve.

10¹
250.00

FIGURE A.11-1

WHRM B-5Q-01
NODE 2 P-8 1.375 IN FROM EXIT

10¹
250.00

FIGURE A.11-1

RUN B-50MN
CSE BLOWDOWN (2IN,2100,500,211)
HS PRESS. (P-8) .125FT FROM EXIT

APPENDIX B

SELECTED LOW SPEED DATA

1911-1912

1911-1912

1911-1912

APPENDIX B

SELECTED LOW SPEED DATA

The following are selected computer plots of typical raw data taken during this work. The data for thrust, liquid level remaining, and mass remaining have not been zero adjusted, but the slopes are believed to be correct. Also available, but not given here, are other pressure and temperature histories of the fluid and the data of temperatures and strain in the bottom head of the vessel.

<u>Figure Number</u>	<u>Run</u>	<u>Pressure Vessel</u>	<u>Pressure Orifice</u>	<u>Temp. Vessel</u>	<u>Temp. Test Section</u>	<u>Liquid Level</u>	<u>Weight of Water</u>	<u>Thrust</u>
B.1-1	B19	X						
B.1-2			X					
B.1-3				X				
B.1-4					X			
B.1-5						X		
B.2-1	B-19B	X						
B.2-2			X					
B.2-3				X				
B.2-4					X			
B.2-5						X		
B.2-6							X	
B.2-7								X
B.3-1	B20	X						
B.3-2			X					
B.3-3				X				
B.3-4					X			
B.3-5								
B.4-1	B-20B	X						
B.4-2			X					
B.4-3				X				
B.4-4					X			
B.4-5						X		
B.4-6							X	
B.4-7								X
B.5-1	B21	X						
B.5-2			X					
B.5-3				X				
B.5-4					X			
B.5-5						X		
B.6-1	B22B	X						
B.6-2			X					
B.6-3				X				
B.6-4					X			
B.6-5						X		
B.6-6							X	
B.6-7								X
B.7-1	B-23	X						
B.7-2			X					
B.7-3								
B.7-4					X			
B.7-5						X		
B.7-6							X	
B.8-1	B24	X						
B.8-2			X					
B.8-3				X				
B.8-4					X			
B.8-5						X		
B.8-6							X	
B.8-7								X
B.9-1	B25	X						
B.9-2			X					
B.9-3				X				
B.9-4					X			
B.9-5						X		
B.9-6								X

<u>Figure Number</u>	<u>Run</u>	<u>Pressure Vessel</u>	<u>Pressure Orifice</u>	<u>Temp. Vessel</u>	<u>Temp. Test Section</u>	<u>Liquid Level</u>	<u>Weight of Water</u>	<u>Thrust</u>
B.10-1 B.10-2 B.10-3 B.10-4 B.10-5 B.10-6 B.10-7	B-26	X	X	X	X	X	X	X
B.11-1 B.11-2 B.11-3 B.11-4 B.11-5 B.11-6	B-27B	X	X	X	X	X		X
B.12-1 B.12-2 B.12-3 B.12-4 B.12-5	B-28	X	X	X	X	X		
B.13-1 B.13-2 B.13-3 B.13-4 B.13-5 B.13-6 B.13-7	B-29	X	X	X	X	X	X	X
B.14-1 B.14-2 B.14-3 B.14-4 B.14-5	B40	X	X	X			X	X
B.15-1 B.15-2 B.15-3 B.15-4 B.15-5	B50	X	X	X			X	
B.16-1 B.16-2 B.16-3 B.16-4 B.16-5 B.16-6 B.16-7	B51	X	X	X	X	X	X	X
B.17-1 B.17-2 B.17-3 B.17-4 B.17-5 B.17-6	B52	X	X	X	X	X	X	
B.18-1 B.18-2 B.18-3 B.18-4 B.18-5 B.18-6 B.18-7	B53B	X	X	X	X	X	X	X

FIGURE B.2-5

RUN B-19B
 CSE BLOWDOWN (2IN,2150,600, 8)
 LEVEL OF FLUID REMAINING IN VESSEL

FIGURE B.2-6

RUN B-19B
 CSE BLOWDOWN (2IN,2150,600, 5F1.0)
 WEIGHT OF WATER IN VESSEL

FIGURE B.4-5

FIGURE B.4-6

*10¹
120.00
100.00
80.00
60.00
40.00
20.00
0.00

FIGURE B.5-1

RUN B-21
CSE BLOWDOWN (6IN,1000,500,010)
PRESSURE NOZZLE H (P 7 I)

*1
120.00
100.00
80.00
60.00
40.00
20.00
0.00

FIGURE B.5-2

RUN 6-21
CSE BLOWDOWN (6IN,1000,500,011)
PRESSURE .0104FT FROM EXIT (P-10)

$\times 10^1$
100.00
120.00

FIGURE B.6-1

RUN B228MN
CSE BLOWDOWN (2IN,1286,500,012)
PRESSURE INSTRUMENT RING (P-15)

$\times 10^1$
100.00
120.00
90.00

FIGURE B.6-2

RUN B228MN
CSE BLOWDOWN (2IN,1286,500,022)
PRESS. (P-8) .125 FT FROM EXIT

FIGURE B.7-1

RUN B-23MN
CSE BLOWDOWN (1IN,2137,500,009)
PRESSURE NOZZLE 4 (P-6 I

FIGURE B.7-2

RUN B-23MN
CSE BLOWDOWN (1IN,2137,500,011)
PRESSURE .0104FT FRBM EXIT (P-101

FIGURE B.7-5

RUN B-23MN
CSE BLOWDOWN (11N,2137,500, 5F2.0)
WEIGHT OF WATER IN VESSEL

LC-1

FIGURE B.7-6

FIGURE B.8-5

RUN B-24
 CSE BLOWDOWN (4IN. 809,500. 8)
 LEVEL OF FLUID REMAINING IN VESSEL

FIGURE B.8-6

RUN 8-24
 CSE BLOWDOWN (4 IN. 809,500. 5F1.0)
 WEIGHT OF WATER IN VESSEL

FIGURE B.10-6

RUN 8-25MN
OSE BLOWDOWN (2IN.1000,545, 5F2.0)
WEIGHT OF WATER IN VESSEL

23 JUL 69

AJMCCLFRESH2758720

515246

UB132

FIGURE B.13-5

RUN 8-29MN
CSE BLOWDOWN 14IN.1302.500. SF2.1
WEIGHT OF WATER IN VESSEL

① LC-1

FIGURE B.13-6

RUN-- B-40MN
 CSE BLOWDOWN (4IN,854,500.. 5F2.1)
 WEIGHT OF WATER IN VESSEL

○ LC-1

FIGURE B.14-4

FIGURE B.16-6

*C
60.00

FIGURE B.17-1

RUN B-52TN
CSE BLOWDOWN (6IN,1290,500,012)
PRESSURE INSTRUMENT RING (P-15)

*10'
120.00
100.00
80.00

FIGURE B.17-2

RUN B-52TN
CSE BLOWDOWN (6IN,1290,500,011)
PRESSURE .0104FT FROM EXIT (P-101)

PSIG
60.00PRESSURE
40.00
20.00
0.00

TIME AFTER RUPTURE (SEC)

FIGURE B.17-7

RUN B-521N
CSE BLOWDOWN (tin, 1290.500, 5F2.2)
WEIGHT OF WATER IN VESSEL

○ LC-1

DISTRIBUTIONNo. of
CopiesOFFSITE

1	<u>AEC Chicago Operations Office</u> D. M. Gardiner
1	<u>AEC Chicago Patent Group</u> G. H. Lee
2	<u>AEC Division of Naval Reactors</u> R. S. Brodsky
25	<u>AEC Division of Reactor Development and Technology</u> Assistant Director, Project Management Chief, Water Projects Branch Chief, Gas Cooled Projects Branch (2) Chief, Liquid Metal Projects Branch Assistant Director, Reactor Technology Assistant Director, Plant Engineering Assistant Director, Reactor Engineering Assistant Director, Nuclear Safety (5) Chief, Research and Development Branch H. L. Hamester R. R. Newton (5) Environmental and Sanitary Engineering Branch I. C. Roberts Assistant Director, Engineering Standards Assistant Director, Program Analysis Assistant Director, Army Reactors
16	<u>AEC Division of Reactor Standards</u> M. Bolotsky G. Burley E. G. Case (10) A. B. Holt R. Impara P. Norien R. Waterfield
215	<u>AEC Division of Technical Information Extension</u>

No. of
Copies

- 5 AEC Library, Washington
 Advisory Committee on Reactor Safeguards
 F. R. Fraley
 Division of Compliance
 L. Kornblith, Jr.
 J. W. Flora, Region IV
 Division of Operational Safety
 H. Gilbert
 Division of Production
 G. B. Pleat
- 1 AEG - Telefunken
 E-213
 6 Frankfort/Main 70
 AEG - Hochhaus Süd
 Germany
 Dieter Ewers
- 1 Aerojet-General
 Idaho Falls, Idaho
 W. E. Nyer
- 1 Aerojet-General
 Sacramento, California
 F. L. Climent
- 1 American Electric Power Company
 2 Broadway
 New York, N.Y. 10004
 Stephen J. Milioti
- 10 Argonne National Laboratory
 C. E. Dickerman
 S. Fistedis
 R. O. Ivins
 P. Lottes
 H. O. Monson
 D. Okrent
 R. C. Vogel
 P. G. Shewmon
 LMFBR Program Office
 A. Amorosi
 L. Baker

No. of
Copies

- 2 Atomics International
 H. Morewitz
 Liquid Metals Engr. Center
 R. W. Dickinson
- 1 Auburn University
 School of Engineering and Engineering
 Experiment Station
 G. H. Nix
- 4 Babcock & Wilcox Company
 Virginia
 S. Delicate
 D. A. Nitti
 R. Wascher
 Washington
 L. R. Weissert
- 6 Battelle Memorial Institute
 A. R. Duffy
 D. L. Morrison/D. L. Ritzman
 S. Paprocki (2)
 D. N. Sunderman (2)
- 1 Battelle Memorial Institute
 Frankfurt, Germany
 G. Leistner/K. J. Kober
- 2 Bechtel Corporation
 R. F. Griffin
 W. P. Neuendorf
- 1 Bettis Atomic Power Laboratory
 P. O. Box 79
 West Mifflin, Pa. 15122
 Dr. J. A. Redfield
- 2 Brookhaven National Laboratory
 A. W. Castleman
 J. M. Hendri
- 1 Canoga Park Area Office
 R. L. Morgan

No. of
Copies

1	<u>Chalk River Nuclear Laboratories</u> Chalk River, Ontario, Canada Station 3 G. Hake
1	<u>Combustion Engineering</u> M. F. Valerino
1	<u>Consolidated Edison Company</u> J. J. Grob
1	<u>du Pont Company, Aiken (AEC)</u> A. H. Peters
1	<u>du Pont Company, Wilmington (AEC)</u> F. P. Allen <u>for</u> Lombard Squires
1	H. Etherington 84 Lighthouse Drive Jupiter, Florida 33458
1	W. L. Faith 2540 Huntington Drive San Marino, California 91108
3	<u>General Atomic Division (AEC)</u> A. J. Goodjohn (2) R. H. Ball
1	<u>General Electric Company</u> 621 S. W. Alder Street Portland, Oregon 97223 J. E. Grund
8	<u>General Electric Company</u> 175 Curtner Ave. San Jose, California 95125 Fred Moody S. Vandenberg G. E. Wade E. Zebroski P. Bray M. Siegler W. A. Sutherland D. A. Rockwell

No. of
Copies

- 1 General Electric Company, Cincinnati (AEC)
 J. F. White
- 9 Idaho Nuclear Corporation
 G. O. Bright
 G. F. Brockett
 J. A. Buckham
 S. Forbes (2)
 C. Haire
 G. B. Matheny
 C. M. Slansky
 N. K. Sowards
- 2 Idaho Operations Office (AEC)
 D. Williams
- 2 IIT Research Institute
 E. V. Gallagher
 T. A. Zaker
- 1 Institute für Reactorsicherheit
 5 Köln, Lukasstrasse
 Germany
 Heinz G. Seipel
- 1 Japan Atomic Energy Research Institute
 Tokai Laboratory, Tokai Ibaragi, Japan
 Masayoshi Shiba
- 2 Los Alamos Scientific Laboratory
 J. H. Russel
 W. R. Stratton
- 1 H. G. Mangelsdorf
 78 Knollwood Road
 Short Hills, New Jersey 07078

No. of
Copies

1	<u>MPR Associates, Inc.</u> T. Rockwell, III
1	<u>National Bureau of Standards</u> C. Muehlhause
1	<u>Naval Ordnance Laboratory</u> J. Proctor
1	<u>North American Carbon, Inc.</u> P. O. Box 19737 Columbus, Ohio 43219 J. Louis Kovach
1	<u>North Carolina State University</u> M. N. Ozisik
1	<u>Nuclear Fuels Service</u> R. P. Wischow
14	<u>Oak Ridge National Laboratory</u> R. E. Adams R. Blanco J. Buchanan W. B. Cottrell (4) D. Ferguson C. E. Miller G. W. Parker L. F. Parsley P. Rittenhouse D. B. Trauger (2)
4	<u>Oak Ridge Operations Office (AEC)</u> D. Cope (2) E. Delaney W. L. Smalley
1	A. A. L*Kelly 2421 West Rowland Avenue Littleton, Colorado 80120

No. of
Copies

- 1 Ontario Water Resources Commission
Water Quality Surveys Branch
Division of Sanitary Engineering
135 St. Clair Avenue West
Toronto 7, Ontario, Canada
W. A. Steggles
- 1 Oregon State University
James G. Knudsen
- 1 The Pennsylvania State University
College of Engineering
101 Hammond Building
University Park, Pennsylvania
N. J. Palladino
- 2 San Francisco Operations Office
Atomic Energy Commission
Lt. Col. J. B. Radcliffe
C. F. Backlund
- 1 Sargent & Lundy
Engineers
140 South Dearborn Street
Chicago, Illinois. 60603
O. A. Hrynewych
- 2 Southern Nuclear Engineering, Inc.
P. O. Box 10
Dunedin, Florida 35528
G. Brown
K. E. Roach
- 1 Stone and Webster Engineering Corp., Boston
L. P. Deackoff
- 2 TRW Incorporated
TRW Systems Group
D. B. Langmuir
S. M. Zivi

No. of
Copies

- 1 United Engineers & Constructors, Inc.
1401 Arch Street
Philadelphia, Pennsylvania 19105
A. T. Molin
- 1 United Kingdom Atomic Energy Authority
Authority Health and Safety Branch
Risely Warrington, Lancs
England
A. R. Edwards
- 2 University of California, Berkeley
Institute of Engineering Research
H. A. Johnson
V. E. Schrock
- 1 University of Houston
Cullen Boulevard
Houston, Texas 77004
C. W. Zabel, Dir. of Research
- 1 University of Illinois
Department of Civil Engineering
3129 Civil Engineering Building
Urbana, Illinois 61801
C. P. Siess
- 1 University of Minnesota
Department of Chemical Engineering
Minneapolis, Minnesota 55455
H. S. Isbin
- 1 University of Tennessee
606 Dougherty Hall
Knoxville, Tennessee 37916
S. H. Hanauer
- 1 University of Tokyo
Mechanical Engineering Section
Tokyo, Bunkyo-Ku,
Tokyo, Japan
Prof. Hidao, Uchida

No. of
Copies

- 2 University of Washington
 Prof. Wells Moulton
 Prof. K. L. Garlid
- 1 USAEC Scientific Representative
 c/o Atomic Energy of Canada, Ltd.
 Chalk River, Ontario, Canada
 H. J. Reynolds
- 9 Westinghouse Electric Corporation (AEC)
 (APD)
 E. Beckjord
 S. Fabic
 D. Fletcher
 H. Graves
 F. M. Heck
 A. S. Neuls
 W. D. Townend
 R. A. Wieseemann
 (HTD)
 A. Lohmeier
- 1 Yankee Atomic Electric Company
 441 Stuart St.
 Boston, Massachusetts
 John DeVincentis

ONSITE-HANFORD

- 1 AEC Chicago Patent Group
 R. K. Sharp (Richland)
- 2 RDT Assistant Director for Pacific Northwest Programs
- 3 AEC Richland Operations Office
 A. Brunstad
 W. E. Lotz
 M. R. Schneller
- 2 Atlantic Richfield Hanford Company
 G. R. Kiel
 ARCHO Files

No. of
Copies

9	<u>Douglas United Nuclear</u> J. E. Mecca N. R. Miller W. F. Nechodom R. W. Reid J. W. Riches D. L. Renberger J. R. Spink R. H. Shoemaker DUN Files
1	<u>Vitro/HES</u> A. J. McElfresh
14	<u>WADCO Corporation</u> J. 3. Cadwell T. T. Claudson R. L. Junkins R. D. Leggett D. P. O'Keefe H. N. Pederson G. J. Rogers D. E. Simpson J. C. Spanner N. P. Wilburn (2) M. E. Witherspoon J. A. Williams WADCO Document Control

No. of
Copies

53

Battelle-Northwest

F. W. Albaugh	H. V. Larson
R. T. Allemann (10)	J. M. Nielson
J. M. Batch	R. E. Nightingale
S. H. Bush	H. M. Parker
L. A. Carter	D. W. Pearce
D. L. Condotta	L. T. Pedersen
G. J. Dau	A. M. Platt
F. G. Dawson	D. L. Reid
D. R. de Halas	R. L. Richardson
R. F. Foster	W. D. Richmond
J. C. Fox	L. C. Schwendiman
J. J. Fuquay	A. M. Sutey
W. A. Haney	E. E. Voiland
H. Harty	R. G. Wheeler
M. M. Hendrickson	N. G. Wittenbrock
J. F. Honstead	F. R. Zaloudek
P. A. Hutton	Technical Information
R. T. Jaske	Files (5)
B. M. Johnson (2)	Technical Publications (3)