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EXPERIMENTAL HIGH ENTHALPY
WATER BLOWDOWN FROM A SIMPLE VESSEL
THROUGH A BOTTOM OUTLET

June 1970

AEC RESEARCH &
DEVELOPMENT REPORT

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FROM A SIMPLE VESSEL THROUGH A BOTTOM OUTLET

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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 with orifice diameters of 1.5 to 6.8 in. from a bottom nozzle.

Internal pressure and temperature, liquid level, thrust reaction forces, weight of fluid in the vessel, void fraction of the fluid in the exit duct were measured during the blowdowns. Void fraction increased and mass velocity decreased with orifice size.

Anomalous subcooled pressure behavior was thought to be caused by nitrogen dissolved in the water. Liquid level decreased nonlinearly with time, whereas mass loss rate was nearly constant for most of the blowdown.

Comparisons with theoretical treatments showed the need for empirical coefficients to adjust predictions to the observed results.

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NOMENCLATURE

A_B	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_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^{**}	Dimensionalized time with coefficient
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

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SUMMARY AND CONCLUSIONS

Twenty blowdowns, simulating PWR and BWR loss-of-coolant accidents, were made from a bottom outlet of a ft^3 , 17 ft high pressure vessel through a circular pipe of 0.253 ft^2 with a final square edge orifice, ranging from 0.0156 to 0.253 ft^2 in area. The blowdowns were started with a full vessel of 6800 to 7000 lbs of water at pressures ranging from saturated to subcooled (600 - 2500 psi), and temperatures ranging from ambient to 600 °F. Subcooled water conditions were produced by pressurizing with nitrogen. A double-rupture-disk was broken to simulate a pipe break and start the blowdown. Data were obtained on pressure, temperature, liquid level, mass flow rate, void fraction, and thrust by analog and digital recording of sensor output.

Comparison of the data with theoretical predictions was made. The mass flow rates were less than predicted for all but the smallest orifices, and were shown to be proportional to orifice area raised to the -0.165 power. The subcooled blowdown data gathered here and elsewhere using gas (such as nitrogen) pressurization without special precautions will not be directly applicable to a typical reactor loss-of-coolant design basis accident because of the pronounced effect demonstrated by nitrogen solubility on blowdown in the subcooled regime.

- Allowing for gas solubility, the temperature-pressure history in the vessel followed the saturation curve after subcooled depressurization was complete.
- Pressure and liquid level predictions could be made using the FLASH computer code if appropriate discharge (or area) coefficients were applied to the leak rate values in FLASH.
- The void fraction of the exiting fluid increases with orifice size and initial fluid temperature.
- Liquid level in the simple vessel went down not linearly with time, but approximately with the square of time during the saturated blowdown regime.
- The liquid level history was a function of the discharge coefficient but the coefficient was not a strong function of the void fraction in the vessel.
- The thrust force during the saturated portion of blowdown was proportional to vessel pressure and to the discharge coefficient.
- Significant advances in the development and use of instruments for measuring void fraction and liquid level were achieved.

INTRODUCTION

PURPOSE AND SCOPE

This report describes the experiments made with the Containment System Experiment (CSE) reactor simulator vessel in the course of developing techniques and operational experience, and qualifying a digital data logging system. The tests were made with a simple vessel (no internal parts), and blowdown experiments were conducted from a bottom outlet as an initial and most simple check of blowdown theory versus the data from the apparatus. The reduced data are presented and compared with theoretical predictions. Some discussion of techniques and of problems encountered is included. The number of tests was greater than originally intended because of instrumentation

and operational problems, and because discrepancies between simple theory and the data were found. The runs were terminated at conclusion of the largest test of the planned group because of a structural support failure. This report describes only the bottom outlet blowdowns, inasmuch as the rest of the simple vessel tests, conducted with other nozzle locations, were postponed. Subsequent reports will cover this later work.

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 blow-down, i.e. 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 so numerous as 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.

This type of accident, while extremely unlikely, has been postulated and used as a means of assessing the safety of a reactor.

Importance of Blowdown Calculations in Licensing

Blowdown theory has influenced many aspects of the licensing procedure, the preparation of the safety analysis report, and 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 (FLASH,⁽²⁷⁾ RELAPSE⁽¹¹⁾). 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 evaluation 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 on Power Reactor Emergency Cooling,⁽²⁶⁾ 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; and
- 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 under way to perform them."

CONTAINMENT SYSTEM EXPERIMENT BLOWDOWN PROGRAM

Containment System Experiment⁽²⁹⁾

The Containment System Experiment (CSE) of Battelle-Northwest is 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 is 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.

- To determine 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.
- To determine 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.
- To evaluate 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.
- To determine the amount of leakage of fission product activity from containment under a range of postaccident conditions and to compare these values with those calculated from both low and high temperature air leakage rate tests and fission product concentration in the containment vessel.

- To determine, 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 will 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. (20-25)

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 include primarily the hydraulic resistance effects of the core structure and of 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. For example 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 spray**.

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 process 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.

Finally, important effects occur external to the reactor. 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. All must be evaluated. Data needed for evaluating all of these effects can be obtained during blowdown transient tests utilizing a series of unheated dummy cores. The initial tests discussed in this report were conducted without dummy core parts in order to check publically available blowdown theories in a simple configuration and to provide a check of the test instrumentation and data processing methods now being developed.

Purpose of CSE Blowdown Tests

CSE blowdown tests are conducted to:

- Provide experimental data with which to check modeling assumptions and calculations, so that verified models 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.

- Develop improved models where existing models are shown to be inadequate for predicting results of experiments.
- Run 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 predict accurately the blowdown times expected in the combined tests with the CSE containment vessel and the reactor simulator.
- 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, eventually, this knowledge will allow the codifying 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 such calculations can only come through comparisons with experiments.

REVIEW OF PREDICTIVE METHODS FOR DESIGN BASIS ACCIDENT

The design basis accident has three regimes as defined in Reference 3. 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,⁽⁵⁾ BANLOG,⁽²³⁾ WATER HAMMER,⁽⁶⁾ WHAM,⁽⁷⁾ and the method of characteristics⁽¹⁰⁾ 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 using initial velocities and 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. BANLOG is an analog computer system which solves the equations using an analog current for flow, voltage for pressure, and time constants determined by the velocities of propagation of the decompression wave. The method of characteristics utilizes 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. Consideration of other paths would require the use of a bookkeeping code such as WHAM.

Several proprietary codes, e.g. SHEILA and SATAN, developed by reactor manufacturers are not available to other than the manufacturers.

Because of its availability and general ease of use, the subcooled data obtained here was compared mainly with WATER HAMMER⁽⁶⁾ or with its more recently modified form, WHAM.⁽⁷⁾

TWO-PHASE TRANSITION REGIME

When subcooled decompression has reduced the pressure of the system sufficiently, and 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 occurrence is dependent 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 two-phase regime allows pressure differences between regions to exist for longer periods. However, these pressure differences are controlled more by temperature differences and flow rates, i.e. 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. Calculations utilizing variations to the subcooled calculation approach may consider time delay for bubble formation, or 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.

A second approach, starting from consideration of the saturated regime discussed in the following section utilizes the simple lumped saturated blowdown solution 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, from those covering single phase (i.e. subcooled) 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 fluid condition can be considered saturated and thus will 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 affects the blowdown rate and the liquid remaining after blowdown, the level swell, and the steam blanketing of the core.

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, (12)

and work at IITRI,⁽¹⁰⁾ and BMI⁽⁴⁾ consider the distribution of steam in the fluid in the vessel to be uniform. This model is termed "homogeneous." Manufacturers have their proprietary codes, e.g. General Electric's RIP and LAMB, Westinghouse's SATAN, Combustion Engineering's BARF, which divide the vessel into from 3 to 10 nodes. These codes are also generally "homogeneous" in any single node. In both the LOFT developed code RELAPSE⁽¹⁸⁾ and its similar predecessor (the generally available code FLASH2),⁽²⁷⁾ 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 is dependent on parameters called "bubble rise velocity," and void distribution coefficients 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. Formulas predicting this flow developed by Moody⁽¹⁶⁾ or Fauske⁽⁸⁾ are most generally used in this country whereas, in Germany⁽¹³⁾ or Japan,⁽⁹⁾ 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 bypass control rod cooling path and the core element cooling paths can be treated. Pressure drop along a flow path is generally calculated by using a two-phase friction multiplier. Usually this involves extrapolation to the velocities at blowdown. Treatments thus far have been verified by comparison with only simple-vessel blowdown data.

EXPERIMENTAL FACILITY AND EQUIPMENTCSE BLOWDOWN FACILITY⁽²⁹⁾Description

The full description of the CSE facility is contained in Reference 20. The CSE reactor simulator vessel was fabricated and accepted in accordance with Section III of the ASME Pressure Vessel (Figure 1) and Boiler Code. Design temperature and pressure are 650 °F and 2750 psig, respectively, and volume is 150 ft³.

The reactor simulator vessel was mounted within a supporting frame (Figure 2). The weight of the vessel and simulator support tower are supported by the vertical load cell. Thrust forces generated during the blowdown experiment are restrained by a thrust support system which includes upper and lower thrust support members and load cells. The thrust reaction forces at the upper and lower support locations were originally transmitted through the vessel trunnions. Later, saddles were added to take compressive loading. Sufficient adjustment was provided to align the axial centerline 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 force.

Operation

A blowdown experiment was started by filling the vessel with demineralized (250,000 ohms/cm) 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 conditions. During the heat-up stage, the pressure in the cavity between the rupture disks (each rated at greater than 50% of the run pressure) was maintained at one-half of the

FIGURE 1. Setting Plan for Reactor Simulator Vessel

FIGURE 2. Reactor Simulator Vessel in Blowdown Framework

vessel pressure. After the desired conditions were established, the vessel was isolated (by valving off the circulation loop) and the rupture disks were broken. Pressure between the disks was increased by injecting nitrogen in the cavity between them 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 test started. Nitrogen injection into the rupture disk cavity and data logging were controlled by the computer. Triggering of the 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 3 shows the volume calibration of the blowdown vessel with equivalent right cylindrical vessel elevations.

■ 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 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 the general difficulties associated with basic correlations for two-phase flow. The nozzle extension detail is shown in Figure 4, and associated instrumentation for the simulator vessel in Figure 5. The function of the framework was previously described. Tables 1 and 2 summarize the instrumentation types, the intended measurements and locations, and list of the manufacturers.

FIGURE 3. Vessel Volume Calibration

BNWL-1411

NOTE: FRACTIONAL DIMENSIONS ON RD ASSEMBLY VARY ACCORDING TO ASSEMBLY USED AND COMPRESSION OF GASKETS.

NOTE:

NOMINAL DIAMETER	ID	AREA, ft^2	ORIFICE LENGTH
1 in.	0.815	0.00362	3 9/16 in.
2 in.	1.689	0.0156	
4 in.	3.438	0.0643	
6 in.	5.189	0.1467	
8 in.	6.8	0.253	

FIGURE 4. Nozzle Extension Test Section for Blowdowns, B-12 to B-18

FIGURE 5. Instrumentation Layout for CSE Simulator Vessel

TABLE 1. List of Instrumentation

Sensor Designation	Manufacturer*	Type	Intended Measurement	Location
TDR	1	Time Domain Reflector	Liquid Level During Blowdown	Down Axis of Vessel Through Top Nozzle
LC1	2	Strain Gage Load Cell	Weight of vessel, Cage and Contents Reaction Forces on Vessel Supports as a result of Klowdown	Coupling blain Frame and Support Cage; Attached to Simulator Vessel in Pairs at Two Heights, Coupled With blain Frame
LC2	3			
LC3				
LC4				
LC5				
P-2	4	Water Cooled Flush Diaphragm Pressure Sensors	Pressure State of Fluid During Decompression Transient and Subsequent Blowdown	Nozzle J
P-3				Blowdown Nozzle Extension Piece
P-4				Klowdown Nozzle Extension Piece
P-6				Nozzle R
P-7				Nozzle H
P-8				Rupture Disk Assembly
P-10				Stagnation Wing Assembly
P-12				Stagnation Wing Assembly
P-15				Instrument Ring
T-2		Chromel-Constantan Thermocouples	Temperature State of Fluid During Blowdown	Nozzle J
T-3				Klowdown Nozzle Extension Piece
T-6				Nozzle R
T-7				Nozzle H
T-8				In Instrument Ring
T-9				Nozzle Insert Heat Transfer Assembly
T-10				
S-3		Weldable Strain Gage	Stress in Critical Joint, Klowdown Nozzle Hoop Stress, Simulator Vessel	Top of Weld Junction, Blowdown
S-4	6			Nozzle Midway Between Thrust Support Arms on Vessel
D-1	7	Proportional Neutron Detector	Void Fraction in Blowdown Pipe During Discharge	Around Circumference of Discharge Pipe
D-2				
D-4				

* See Table 2

TABLE 2. Manufacturers, Models, and Nominal Specifications of Instrumentation

	Manufacturer and Model	No.	Description	Range	Static Accuracy % Full Scale
1	Hewlett-Packard 14A with 1415A Module	(1)	Sampling Oscilloscope Coupled with Time Domain Reflectometer	N/A	N/A
2	Toroid Model 35-132 DDG	(1)	Strain Gage Load Cell	0-100,000 lb	0.1
3	Strainert Model FLV-50SF2.5	(2)	Strain Gage Load Cell	0-50,000 lb	0.1
	Strainert Model FLV-100SG2.5	(2)	Strain Gage Load Cell	0-100,000 lb	
4	Standard Controls-Norwood Model 110-2-3000G	(8)	Water Cooled Strain Gage Pressure Sensor	0-3000 psig	0.1
5	NANMAC Models A and G	(7)	Chromel-Constantan Thermocouple Probes	0-600 °F	1.0
6	Microdot Model SG 122	(2)	Quarter Bridge Weldable Strain Gage	0-6000 microstrain	5.0
7	Hamner Model NA-15	(2)	Amplifier/Discriminator	N/A	N/A
	Hamner Model NC-11	(1)	Discriminator		
	Harshaw Model B10-4A	(3)	Boron Lined Proportional Neutron Detector	N/A	Sensitivity: $1 \frac{\text{count}}{\text{sec} \left(\frac{n}{\text{cm}^2 \cdot \text{sec}} \right)}$

INSTRUMENTATION DEVELOPMENTTime Domain Reflectometer (TDR) Liquid Level Probe(5)

A liquid level probe based on the principle of time domain reflectometry (TDR) was successfully used in CSE blowdown experiments at temperatures as high as 600 °F. A simple stainless steel probe, which has no transmitter or transducer mounted in the severe conditions of the vessel water, is used to represent an extension of a coaxial cable with a "traveling discontinuity." This discontinuity is actually a short circuit caused by the water between the coaxial probe legs. A practical static calibration resolution of 2 in. in 230 in. of liquid level has been achieved with the CSE configuration.

The system consists of three components, the stainless steel probe shown in Figure 6, a 150 kHz pulser, and a commercial sampling oscilloscope. The observer sees a trace of the square pulse "chopped" from right to left on the time scale by reflection from the impedance discontinuity of the changing liquid level. Insulation washers on the probe body (Figure 7) serve as reference or calibration points on the trace itself, and to reduce severity of bumps on the trace.

In addition to this visual display, a converter has been attached to the oscilloscope vertical output and internal scan to give an analog voltage output for a recorder or computer scanning. The response time of this converter over the range of vessel full-to-empty condition is less than 100 msec.

The device accurately measures the falling liquid level during cold blowdowns as well as the subcooled portion of other blowdowns under conditions as severe as 600 °F and 2485 psig. The device also gives an indication of foam level during saturated blowdowns. No calibrations have been

FIGURE 6. CSE Simulator Vessel with TDR Probe Installed

FIGURE 7. Ceramic Insulators Separate Probe Sections

fraction of the high pressure water-steam mixture in a thick walled steel duct during movement of the mixture toward an outlet or simulated pipe break.

The densitometer utilizes moderation and/or absorption of fast neutrons by the steam-water mixture. The measurement of the resulting thermal neutron flux in a region outside the duct is used to determine the void fraction. A commercial fast neutron generator, serving as a relatively compact neutron source, can be turned on conveniently from the control room during the measurement period.

The installation of this complex laboratory machine required rugged and protective mounting fixtures. The generator at full power supplies about 1×10^{11} n/sec at an energy of 14.7 MeV. The count rate circuits were designed to be compatible with the digital multiplexed data logging system. The minimum thermal-neutron count rate of 14,000 counts/sec assures a statistical accuracy of about 2.5% at the 95% confidence limits. The flux from the neutron generator allows achievement of this statistical accuracy with a response time of 100 msec. Other instrumentation and system errors reduce the overall accuracy to 3%.

The calibration of the unit was achieved by inserting various patterns of water-filled aluminum tubes into the test section and measuring the relative intensity of thermal neutron flux. Figure 8 shows a typical arrangement of the generator and detectors. The level of slow neutron flux, where the void fraction is uniformly distributed, was found to be a function of the void fraction (empty aluminum tube fraction).

Since calibration was done at ambient temperature and atmospheric pressure, the readings taken during a blowdown required reduction from the values at high temperatures and pressures. Neutrons are moderated to a different energy by hot water than by cold, and the relatively high density

made with foam to determine what liquid fraction is actually required for sensitivity. But measurements correlated well with other foam level indications such as audible noise changes.

Some sample outputs of this device are compared in a subsequent section to the liquid level calculated from the weight load cell data. The load cell weighs the vessel and contents during blowdowns. The TDR signal was found to correlate well with stop-watch and tape-recorded records of the end of water exhaustion at the blowdown nozzle. For example in Figure 27, page 64, a change in the sound of the blowdown was heard and a higher quality jet is seen at 12 sec. Also at about this time, a considerable discrepancy between the TDR and load cell was noted. This discrepancy has been partially attributed to a component of thrust detected by the weight load cell, but is still an unresolved inaccuracy.

Another plot of TDR liquid level and a liquid level calculated from the weight load cell, and assuming that saturated liquid remains in the vessel, is also presented in the next section. (Figure 24, page 58) In this case, a tape recording indicates a sound transition at about 27 sec, the time when the blowdown enters a final high quality regime. During this phase, the temperature begins to drop sharply along with the pressure. This rapid temperature-pressure change is believed to result in the upward drift of the TDR probe reading after transition. A subsequent data readout system has used this temperature drift effect to account for the smaller changes in temperature during the two-phase portion of the blowdown.

Neutron Densitometer

A method⁽²⁾ was developed and tested during the course of these bottom blowdown experiments for measuring the void

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FIGURE 8. Steady State Densitometer Response as a Function of Water Fraction

steam at high pressures also contributes a moderating effect. The calculation of these effects as well as the normalization of the detector output to that of the generator is done by a computer code developed for the purpose. The code has not been applied to the early data because these data were taken on chart recorders rather than digitally. Calculation of the quality of the flow is made from the void fraction using the homogeneous assumption and the continuity equation.

$$x = \frac{W_g}{W_g + W_l} = \frac{\alpha U_g / v_g}{\alpha U_g / v_g + (1 - \alpha) \frac{U_l}{v_l}},$$

where:

W = Weight flow rate

x = quality

a = void fraction

U = velocity

v = specific volume

l = liquid

g = gas.

For no slip, ($U_g = U_l$), so

$$x = \frac{\alpha}{\alpha + (1 - \alpha) \frac{v_g}{v_l}}$$

In using the densitometer, two thermal neutron detector channels provide output signals that increase in a single valued manner with water fraction over a full 0 to 100% range. These signals exhibiting some fine structure, will require additional investigation to determine more about the water-steam flow characteristics.

A third neutron detector channel, located below the spool piece and further from the generator, operates on the principle

of neutron beam attenuation. The signal from this detector is double-valued over part of the range and additional investigation of the geometry will be required to obtain a signal that decreases in a single-valued manner. This detector, located on the opposite side of the spool piece from the neutron generator, is sensitive to the full water path distance across the diameter of the pipe.

A fourth detector provides a measure of fast neutron output from the generator. It is located about 5 ft from the source, and its signal output is recorded and used for data normalization.

Under transient test conditions with attendant vibration and changing fluid geometry, the neutron generator provided a relatively constant neutron output as measured by Detector No. 4. The generator was operated at about 1×10^{10} n/sec, 1/10 of its maximum output, in order to provide longer target life by reducing target burnup.

Attempt to Measure Jet Impact Pressure

An attempt was made to measure the impact pressure and pressure profile of the blowdown jet by mounting six high-speed, water cooled pressure transducers across the axis of the fluid jet. The attempt was unsuccessful. Impact pressures as high as the vessel pressure were seen only at the first instant of jet impact. Immediately thereafter the transducer output begins to drift (even though the sensors were water-cooled and shrouded) nonlinearly and nonreproducibly, probably because of the transient heating effects of the hot impacting fluid.

DATA LOGGING SYSTEM

The large amount of physical and radiochemical experimental data resulting from experiments in CSE dictated the

need for electronic data processing. A digital computer was selected to collect and store the data on magnetic tape.

A PDP-7 computer, manufactured by the Digital Equipment Corporation, was purchased for the data logging purpose. The machine, basically the standard system supplied by this company, has a high-speed optical paper-tape reader and is also capable of punching the paper-tape. The central processing unit has the "normal" arithmetic option and is supplied with an 8,192-word core of 18 bits per word. Two teletypes, Model 33 KSR, were supplied with the machine. A switch was installed to allow one teletype unit to operate near the computer, and a second teletype unit to be located approximately 70 ft from the computer in the radiochemical analysis counting room. Four magnetic tape units, the DECTAPE transports, were also included.

The machine is also equipped with a relay buffer consisting of an 8-bit relay register and filters to reduce noise from contact bounce. Under program control, the flip-flop register can be set to correspond to the contents of the accumulator and can be cleared. Each bit of the flip-flop registered in the binary 1 condition energizes an associated relay in the relay register.

The computer is interfaced to both a low-speed and high-speed multiplexer. These electronic switches required in the blowdown experiments are for the data acquisition. The low-speed multiplexer consists of relay and solid-state switches, and an analogue-to-digital converter. The overall gross scanning rate for this multiplexer system, approximately 2000 points/sec, is sufficient for monitoring most of the signals during a typical CSE blowdown experiment.

The high-speed multiplexer is necessary to monitor very fast transients such as acoustical waves occurring in the primary vessel during a blowdown. This multiplexer has an

overall gross scanning rate of 240,000 points/sec. The main components of this system are three analogue-to-digital converters, three DEC Type 139 E multiplexers with 24 DEC Type A103 solid-state switches, and 24 amplifiers, one for each of the 24 monitored 25 points. The operation of this multiplexer is triggered when a ground connection to a rupture disk on the blowdown nozzle is broken. The break is caused by disk rupture and signals the start of a blowdown.

While immediate retrieval of the collected data is possible, the data are in a raw form and would require excessive man-hours to reduce and correlate. Therefore, programs have been so written that tapes of the raw data can be taken to the site central data processing facility for processing and for printouts in desired formats. Some typical formats include pressure, temperature, liquid level, and thrust loads versus time graphs for the blowdown studies.

The development of the data logging system was carried on simultaneously with the blowdown program described in this report. For this reason many of the early blowdown tests were not recorded on magnetic tape but with oscilloscopes and chart recorders. Switch over to digital data logging was not accomplished until Blowdown B-14B. It has been used since on all runs, with increasing utility.

RESULTS AND DISCUSSION

COLD BLOWDOWNS

The initial conditions for all blowdowns are shown in Table 4 (page 69). Most figures refer to a run number which can be found in the table to obtain the run conditions. Blowdown tests in the CSE reactor simulator vessel were conducted initially with cold water, driven by a 50 ft³ dome of nitrogen in the upper part of the vessel. The purpose of the tests was to train personnel and to evaluate the

instrumentation. The conditions for the run and the run data are given in the Appendix.

The recorded sensor output showed the instrumentation to be working well and general agreement (ca. 2%) was found between the measurements and theory based on nonideal gas, adiabatic expansion of the nitrogen driver gas, and the incompressible flow formula for water:

$$Q = A_b C_d \left(\frac{2g_c \Delta P}{\rho} \right)^{1/2}$$

The mass and thrust data also agreed with the theory. Thrust = $(C_d^2 2PA_b)$. The coefficient, C_d , was found to have a value of about 0.65 - 0.7. Discrepancies were seen in the transition-to-air flow (indicating essentially no water left), and the weight load cell indication of from 200 to 500 lb of water. The water level at this time was indicated to be about one foot above the outlet. This anomaly was never resolved, i.e. whether it was caused by an instrumentation error or by a special flow pattern such as level dipping or vortex formation.

SATURATED BLOWDOWNS

A series of initially saturated blowdown runs were made. The run conditions are shown in Table 4 (page 69) and data are shown in the Appendix. An example of the results of one of these runs is shown in Figures 9, 10, and 11, and are compared with predictions using B. M. Johnson's⁽¹²⁾ CSEBAC (CSE Blowdown And Containment) codes. Figure 12 is compared with FLASH⁽²⁷⁾ predictions. The prediction method of Johnson⁽¹²⁾ was modified slightly to separate some input constants and to leave out the containment vessel response. Adjustment of two parameters was required to get agreement with the blowdown data from Run B-7.

One of these parameters allows for the degree of subcooled versus flashing flow which may occur during blowdown depending on the degree of equilibration and phase separation that has

FIGURE 9. Pressure Decay in CSE Simulator Vessel-Saturated Blowdown

FIGURE 10. Weight of Water in CSE Simulator Vessel

FIGURE 11. Temperature Versus Time in CSE Simulator Vessel-Saturated Blowdown B-7

Neg 0684137-3

FIGURE 12. CSE Blowdown Pressure History, Run B-10, $D_B = 1.689$

time to take place in the reactor vessel. The relative break size to tank volume has an effect on this time. For the 4-in. nominal break diameter of Run B-7, a full volume equilibrium layer was found to give the best agreement with experimental data (Figures 9, 10, and 11). Indeed, the variation of the equilibrium-layer-depth parameter suggests that more accurate predictions would result from an even greater volume equilibrium layer. This approach, however, is simplified and greater accuracy of prediction may result from the more complicated consideration of bubble rise and vapor-liquid action in the vessel. A few points based on a uniform bubble rise model were calculated by hand and are shown in Figures 9 and 10.

FLASH-2 is a code that has a detailed, built-in bubble rise treatment. In it the bubble rise velocity and quality distribution factor act as parameters to account for pressure decay profile, liquid remaining, and time of transition. Example predictions using this code are shown in Figures 12, 13, and 14.

Both the computer codes described use the Moody⁽¹⁶⁾ maximum flow rate equation to calculate the leak rate during the saturated regime. The figures show that the additional parameter needed to give the correct pressure decays and mass fluxes is the leak discharge coefficient or flow coefficient. The theoretical prediction of pressure agrees within experimental error of about 50 psi when the proper flow coefficient is used.

A series of blowdowns Runs B-9, B-10, and B-11, (see page 69) were made starting at pressures near saturation in order to check vessel blowdown predictions given by Moody.⁽¹⁵⁾ The pressure versus time data follow the predictions for a liquid blowdown. These predictions, based on the Moody maximum flow model, depend on type of flow, a pipe friction term ($fL/D \approx 0$ in this case), and a mass and energy balance in the vessel. The zero value friction term is used because the friction factor f for Reynolds number in the range of 10^6 is about 0.01 and

Neg 0684137-2

FIGURE 13. CSE Blowdown Pressure History. Run B-13, $D_B = 6.803$

Neg 0684137-5

FIGURE 14. CSE Blowdown Pressure History, Run B-15, $D_B = 3.438$

the L/D of the outlet pipe of the CSE reactor simulator vessel is only seven. Pressure versus reduced time and reduced mass for these runs is plotted in Figures 15 and 16, respectively. The same data for these 1250 psi runs are replotted in Figures 17 and 18, with the pressure also nondimensionalized. Data from runs started at subcooled conditions could be included in these figures by using the saturation-pressure, -time, and -mass as characteristic factors in forming nondimensional parameters.

The pressure versus nondimensionalized time plots (Figures 15 and 17) show little difference between the three modes of discharge. The data indicate somewhat slower pressure drop than predicted. Figures 16 and 18, in a sense, represent an equation of state for the fluid left in the vessel during blowdown. The data points are in agreement with the pressures predicted by a mixture blowdown.

Mass Velocity - Saturated Blowdown

The agreement of the pressure in the vessel with various theories has often been used as an argument for the correctness of the theory. This work shows fair agreement with pressure predictions, but the calculated mass velocities are generally lower than those predicted by two-phase critical flow theory.

The experimental technique for obtaining mass velocity with the CSE apparatus is to measure the weight of the vessel versus time by a load cell from which the vessel hangs. During, blowdown, the spring-mass system of the load cell-supported vessel oscillates at 5 Hz. After averaging the maximum and minimum of the oscillations, the weight is obtained from initial and final load-cell output readings and a calibration curve. Some disagreement was found between the load cell weight value and the calculated weight value at the time of transition from liquid to steam flow from the blowdown nozzle. The result of this unresolved discrepancy is a spread in mass velocity values derived from the weight-loss curves.

Neg 0674103-4

FIGURE 15. Comparison of 1250 psi Saturated Blowdown Tests with Moody Predictions

Neg 0674103-5

FIGURE 16. Comparison of 1250
with Moody Predicti

Saturated Blowdown Results

Neg 0674103-6

FIGURE 17. Pressure Versus Time for Saturated Vessel Blowdown

Neg 0674103-7

FIGURE 18. Moody Prediction Pressure Versus Weight Saturated Vessel Blowdown

The mass velocity values obtained for saturated blowdowns have been plotted along with data from other sites and from some theoretical predictions shown in Figure 19. Vessel pressure at time of mass velocity measurement is the parameter. It can be seen that mass velocity is dependent on the orifice or opening size through which blowdown is taking place. Believing the variation to be a function of opening and of vessel areas, we have plotted the mass velocity data versus the ratio (Orifice areas/Vessel area*). The data from Hitachi Ltd. are most complete and suggest a relatively sharp drop in mass velocity as the area ratio passes 0.01. The addition of the CSE and G.E. test data fail to indicate this sharp drop, and that the correlation can be extended beyond an area ratio of 0.01.

The addition of points from LOFT⁽²⁹⁾ was made by estimating the flow rate required to empty the flask in the reported time after initial flow was subcooled to the saturation pressure. The IITRI datum point in Figure 19, although for a different pressure than any of the others, indicates leveling off of the decrease at full breaks.

A widely used blowdown mass velocity prediction, (Moody's)⁽¹⁶⁾ has no area dependent term except for minor pipe friction. Some mass velocities predicted by his code are shown on the left of Figure 19. The fact that agreement between prediction and experiment occurs at different orifice diameters, depending on the pressure, suggests the use of an adjustable flow coefficient in vessel blowdown predictions, or that more detailed calculations should be carried out to evaluate the fluid conditions at the nozzle in terms of enthalpy, pressure, and quality.

* Denotes inside cross-sectional area of the vessel in a horizontal plane.

FIGURE 19. Average Mass Velocity Versus Orifice-to-Vessel Area Ratio
(Data from Various Sites)

One of the advantages of Moody's critical flow model is that he has given mass velocity on the basis of the conditions in the vessel rather than at the critical plane. Using a technique similar to his, a computer program was assembled to calculate the vessel conditions for critical flow based on the homogeneous critical flow model. The results for a limited range of pressures are shown in Figure 20. These results are also shown in Figure 19 for a few pressures.

The finding that lower rates predicted by the homogeneous model are closer to measured values at larger orifice sizes than are those of the Moody slip model suggests, perhaps, that less slip is occurring in these cases. The deviation between theory and these experiments is in a normally conservative direction, at least for the nozzle sizes usually found on reactor loops, since lower than predicted flow rates will mean slower containment pressurization and less rapid coolant loss from the reactor.

The FLASH2 code^(27,28) was applied to three CSE bottom blowdown cases, Test Runs B-10, B-15, and B-13, (Figures 12, 13, 14) with different orifice sizes in order to correlate the effective flow coefficients for predictions of mass flow rates.

It was shown that the mass flow velocity predicted by the Moody equilibrium-slip-flow model can, by use of a nozzle discharge coefficient, be adjusted to give a good fit to the data of the pressure in the vessel. Also as previously described, the mass velocity and, consequently, the coefficient decreases with increased nozzle size. An empirical expression for the saturated blowdown coefficient, based on the ratio of outlet (break) area to vessel cross-sectional area, was developed. The expression is,

$$C_{CSEM} = 0.287 R^{-0.165}$$

FIGURE 20. Homogeneous-Critical-Flow-Model Mass Velocity Versus Vessel Conditions

where :

$$C_{\text{CSEM}} = \text{flow coefficient to be applied to the Moody}^{(13)} \\ \text{model of mass velocity based on CSE data.}$$

$$R = \frac{\text{Area of Break}}{\text{Area of Vessel}}$$

This coefficient expression, shown in Figure 19, approximates reasonably well the break area effect measured at CSE, and obtained by other experimenters.

Best estimates of effective orifice coefficients and single-phase orifice coefficients at the pipe exit are shown in Table 3 for the three cases. A reversed trend in the change of effective orifice coefficient with a change in break size was observed when the effective values were compared with the corresponding single-phase values.

TABLE 3. Orifice Coefficients

<u>Nominal Break Size, in.</u>	<u>Orifice Pipe Diameter</u>	<u>Single-Phase Orifice Coefficient</u>	<u>Effective FLASH2 Coefficient, Two-phase</u>
2 (1.689)	0.248	0.61 ^(a)	0.82
4 (3.438)	0.513	0.648 ^(b)	0.69
8 (6.813)	1.00	1.0 ^(c)	0.54

-
- a. *Estimated. See Perry. Chemical Engineers Handbook, 3rd ed., McGraw-Hill, 1950, p. 405.*
- b. *Calculated from pressure-time and also from mass flow rate-time data from an ambient temperature blowdown 4 in. in diameter.*
- c. *The considerable exit pipe entrance losses, would give an effective coefficient of 0.61 to 0.70, are neglected.*

The FLASH2 code used for the simulations is a multinode, digital model of a nuclear power plant coolant loop during the loss-of-coolant accident. The code is sufficiently flexible to be applied to the tests of a single leak blowdown for a simple

vessel with no internal structure. Some of the important input parameters for the cases are vessel dimensions, initial temperature and pressure, bubble rise velocity, quality gradient factor, and orifice coefficient. The code uses Moody's two-phase critical flow model of flow through a nozzle for the leak rate calculations.

The CSE blowdown with different nozzle sizes and initial pressures were calculated using a single node to represent the vessel. The vessel was approximated by a right-circular cylinder of 9.35 ft^2 in cross sectional area and 16.25 ft high. Comparison of the theory with the data are shown in Figures 12, 13, and 14. Various adjustments of the input parameters can be used.

In the case of Run B-15 (Figure 14), a two-volume approximation was tried using the same conditions as the single volume case, but with the addition of a 6-ft^3 pressurizer. The pressurizer was initially one-third full and the fluid was at saturated conditions. This case was added in an attempt to simulate the small gas volume in the vessel at the start of the experimental run. (Later work suggests that there may have been dissolved nitrogen in the water not a real bubble.)

The results indicated the pressurizer volume to have little effect, but the quality gradient factor and the increased bubble rise velocity improved the prediction considerably by shifting the elbow in the pressure curve. The premature cut-off in the third approximation was caused by a calculation instability.

By comparing for each blowdown case the best FLASH2 simulation using the single-phase orifice coefficient with the experimental results, and by referring to the best effective orifice coefficients listed in Table 3, a major problem in predicting the proper orifice coefficient can be recognized. The single-phase coefficient increased with orifice size. The best

effective coefficient for the FLASH2 simulations, however, showed an inverse trend. Orifice coefficients are generally available from hydraulics tests for single-phase flow. The use of a single-phase coefficient in a two-phase situation was, however, questionable.

A possible contributing cause to the problem of defining the proper orifice coefficient was the apparent inability of FLASH2 to handle a blowdown calculation with a length of pipe extending from the vessel exit. All FLASH2 results presented herein used a vessel leak calculation in which exit pipe losses were neglected. The physical situation closely matched the FLASH2 model for the 2 in. break, since the mass velocity in the exit pipe was low compared to that at the orifice. Frictional losses in the pipe were, therefore, low. However, for the 8-in. break, the entrance and friction losses were small but not negligible. Two-volume FLASH2 simulations of the CSE vessel were attempted by using the exit pipe as the second volume but, due to the small relative volume of the pipe, computational instabilities resulting in error terminations were encountered. It should be noted, however, that results of the single-volume 2-in. break size simulation using the single-phase coefficients were not too close to the experimental results despite the apparent suitability of the model to the physical situation.

The changes in bubble rise velocity and quality gradient factor had a small effect on the results in the ranges considered. For the smaller breaks, a bubble rise velocity of 3 ft/sec and a quality gradient factor of 0.8 gave the best agreement to the experimental data when combined with the best coefficient. However, for the 8-in. break, a homogeneous steam distribution in the liquid ($C_x = 0$) and a bubble rise velocity of 2 ft/sec gave a closer approximation to the pressure curve shape (Figure 13), although the total blowdown time was about the same.

The prediction of the best effective orifice coefficient was, then, the primary problem associated with the use of FLASH2 for describing CSE blowdowns. The results using single-phase orifice coefficients were, however, as accurate as previously reported FLASH2 simulations of simple blowdowns. (28)

Weight of Liquid in Vessel

As described in the preceding section, the liquid weight in the vessel is determined from a load cell supporting the entire vessel. Because of the high level of vibration, filtering and smoothing of the data is required. The results, therefore, do not show much change from the average rate of mass loss and only a small decrease weight loss rate with time. The data have been normalized in different ways and are shown in Figures 21, 22, and 23. These plots show the flow rate to be fairly steady to the time of transition to steam flow, with only a moderate change in rate as pressure is reduced.

A cross-plot of weight fraction versus vessel pressure (Figure 23) shows the liquid in the vessel to follow a thermodynamic path more dependent on temperature than on nozzle size.

Liquid Level During Blowdown

A time-domain reflectometer was used in the CSE vessel bottom blowdown experiments to gather data on the liquid level in the vessel during the expulsion of the fluid. Figure 24 shows a typical plot of this data. The liquid level as indicated by the TDR shows a relative "s ell" compared to the level calculated from fluid weight, and from specific volume derived from steam tables. Figure 25 shows the liquid level fraction for several blowdowns as a function of a dimensional-time parameter used to correct for outlet area and initial mass differences.

That the larger nozzle size is shown in this figure to have a relatively slower rate of level decrease, is partly the

FIGURE 21. Weight Fraction Versus Fraction of Time to Transition

FIGURE 22 Weight Fraction Versus Dimensionalized Time

FIGURE 23 Weight Fraction Versus Vessel Pressure

FIGURE 24. Liquid Level Versus Time

FIGURE 25. Liquid Level (Y_L/H) Versus Dimensional Time $\left(\frac{A_B}{M_0} t \right)$

result of the lower mass velocity (mass flow rate per unit area) of the larger areas discussed in the preceding section.

Moody⁽¹⁷⁾ has made some preliminary calculations of the liquid level in a partly full reactor vessel during a bottom break blowdown. His results, although not directly applicable because they were calculated for a simple vessel initially only 75% full of liquid, indicate that a steam dome may have an important effect since his prediction shows the level initially dropping nearly linearly with time and then surging back upwards. The CSE blowdowns were done with the vessel essentially full (0.25 vol% nitrogen pressurization dome and some dissolved nitrogen), and no level surges were observed. The initial decrease rate was proportional to the square of the time. This is shown in Figure 26, a dimensionalized plot of the normalized liquid level. Several liquid level data are plotted and are seen to be straight lines as a function of $(t^*)^2$. Further work is required to account for the slopes of these data, but the linearity has been shown by bubble rise model correlations such as FLASH⁽²⁷⁾ and BURP.⁽¹¹⁾

The nitrogen pressurization used in the CSE experiments should not have strongly influenced the liquid level decrease. Although the nitrogen prevented an immediate reduction of pressure to saturation that should occur without the gas, subcooled flow should allow the level to drop faster than the saturated flow where no nitrogen-steam bubbles have formed in the liquid. Since this condition was not observed, the nitrogen in solution was apparently coming out as bubbles to give an initial level profile similar to the saturated case where steam bubbles are formed. Slightly higher level swells indicated for higher temperature runs may be caused by increased solubility of nitrogen, or by the lower rate of level decrease generally caused by the lower (exit-choking) flow rate at higher enthalpies. It has been observed that nitrogen, although

FIGURE 26. Liquid Level Versus Dimensionalized Time

causing a slightly higher swell initially than the saturated liquid, will produce a faster level decrease after about half the liquid is gone. Thus, the level reaches the bottom blow-down level faster with nitrogen, than without it.

Some of the level data, normalized in Figure 27 have taken into account the previously cited flow coefficient. It is seen that liquid level data still differentiates itself into groups depending on the break size. The relatively slower rate of decrease in level for the larger breaks, shown in Figure 25, is only partly accounted for by the decreased mass velocity of the larger breaks. This rate might be explained by the shorter time available for vapor disengagement in the larger, shorter blowdown. It might be caused by a difference in bubble rise velocity resulting from formation of a larger number of small bubbles in the case of rapid blowdown, versus formation of a fewer number of larger, faster rising bubbles during the smaller break blowdown. Since the flow coefficient was taken from comparisons with the FLASH code,⁽²⁷⁾ which assumes a constant bubble rise velocity, the coefficient is probably not independent of this assumption (use of a variable bubble rise velocity would result in a different flow coefficient). However, a more detailed study of the bubble rise assumption⁽³¹⁾ indicates the liquid level, not the flow coefficient, to be a strong function of the bubble rise assumption.

The liquid level in general is initially a function of the square of time after blowdown. However, in a case such as Run B-12 (Figure 28), in which a large initial steam-nitrogen dome had formed at the top of the vessel at the beginning of the Slowdown, little or no liquid swell occurred and the level dropped linearly with time and in accordance with the weight load cell readings. This decrease was similar to that exhibited by the cold, nitrogen-pressurized blowdowns, and therefore suggests that bubble formation under the liquid surface was almost completely inhibited.

FIGURE 27. Corrected Liquid Level Decrease During Bottom, Saturated Blowdown

FIGURE 28. Liquid Level Versus Time

Fluid Quality in Exit Duct

Because of the developmental nature of the densitometer used in obtaining the void fraction data in the outlet duct, only tentative data so far have been available. A correction for temperature was needed in the use of the data necessitated by cold temperature in the stagnant blowdown pipe just prior to blowdown. As a result, doubt exists as to whether the initial increase in void fraction and quality given by the data is real or whether it is the result of the sudden rise in temperature as the water begins to exhaust. In spite of this possible systematic error in the absolute magnitude, some relative trends are shown.

The density data for several runs have been reduced to quality on the basis of homogeneous zero-slip flow, and are shown in Figure 29. Although the void fraction was constant or slightly increasing with time during the saturated portion of the blowdown, the calculated quality shows a decrease because of the correction for pressure change. Part of any possible increase in the void fraction is caused by expansion of the steam, and if little void fraction increase is seen, then the expansion corrections serve to decrease the measured quality.

The major trend observable in Figure 29 is an increase in quality as the orifice size is increased and as the initial temperature is increased. Some of these data are plotted roughly in Figure 30 to show the mass velocity trend with quality. The general trend in the data are predicted by the theories of Moody,⁽¹⁶⁾ Henry,⁽¹¹⁾ and others. The Fauske⁽⁸⁾ prediction is not shown because it is close to that of Moody and was not conveniently obtainable in terms of the inlet quality. The CSE data for the quality, although uncertain, do appear to group somewhat in terms of pressure and quality level. The lower-than-predicted mass velocity is evident in

FIGURE 29. Quality Versus Time, Outlet Pipe

FIGURE 30. Effect of Quality on Mass Velocity

Figure 30. Also evident is the decrease in mass velocity with quality which is as predicted by theory. Since mass velocity decrease is also associated with an increase in orifice size, perhaps a mechanistic relation could be developed between orifice size and exit quality without resorting to empirical correlations. Only preliminary work has been done in this regard, pending more accurate data. Further work is required to determine the quality values more accurately and to predict the critical section inlet conditions from the liquid-vapor action in the vessel.

SUBCOOLED REGIME

Mass Velocity

Truly subcooled decompression periods did not accompany most of the blowdowns described in this report because nitrogen, dissolved in the hot water during the heatup period, would escape from the solution during decompression before true saturation could occur. This result can be seen in Table 4 for runs such as B-14B, B-15, or B-17, in which "subcooled" periods lasted from 5 to 14 sec after start of blowdown. A plot of the pressure and temperature showed the fluid to be subcooled relative to pure water for at least this amount of time before coming to saturation conditions, within the experimental error. Subsequent studies⁽¹⁾ showed this effect to be the result of nitrogen dissolved in the water. Sample measurements showed the amount of nitrogen dissolved in the water to be on the order of 80% of the saturation value. The pressure of nitrogen in the water casts some doubt on the use of this early CSE data in the subcooled region as representative of subcooled mass velocity. It was shown by later experiments that large amounts of dissolved gas came out of solution very quickly during the initial stage of fluid decompression. With the initial formation of bubbles the nitrogen coming out of solution in the vessel may maintain "subcooled" entrance conditions at the orifice. However, at the rapid reduction of pressure

TABLE 4. Summary of Blowdown Run Data

Run No.	Date, 1967	Pressure, psig	Approximate Initial Temperature, (a) °F	Nominal Circular Orifice Size, (c) in.	Initial Water Volume, ft ³	Initial Water Mass, lb	Estimated Initial Steam-Nitrogen Volume, ft ³	Approximate Saturation Time, sec	Water Exhaustion Time, sec
B-3	3/10	600	Ambient	3	100	6250	52.5	N/A	21.0
B-4	2/29	600	Ambient	4	100	6250	52.5	N/A	11.8
B-5	4/03	1550	Ambient	4	100	6250	52.5	N/A	7.0
B-6A	6/02	1550	Ambient	6	100	6250	52.5	N/A	3.1
B-6B	8/18		Ambient	8	100	6250	52.5	N/A	2.5
B-7 ^(b)	6/22	656	490	4	147.5	7300	0.5	N/A	27.0
B-8 ^(b)	6/29	1565	495	8	145	7100	7.5	N/A	8.0
B-9 ^(b)	9/01	1610	570	8	151.8	6750	0.7	1.9	5.8
B-10 ^(b)	9/06	1400	575	2	152	6750	0.5	N/A	54.0
B-11 ^(b)	9/08	1435	575	4	152	6700	0.5	N/A	16.0
B-12A ^(b)	7/06	1565	400	4	122	6600	30.0	>12.0	12.0
B-12B ^(b)	9/12	1650	600	4	152	6500	0.5	3.0	14.0
B-13 ^(b)	9/14	1600	590	8	135	5800	17.5	N/A	3.9
B-14A	10/17	2160	500	4	150.6	7400	1.9	10	21.0
B-14B	10/25	2160	492	4	150.6	7275	0	14.0	20.3
B-15	10/23	2185	560	4	140.8	6500	0	5	14.0
B-16A	10/24	2384	583	4	138.8	6000	0	6	13.7
B-16B	11/07	2385	577	4	143.6	6330	9.3	3.6	15.0
B-17	10/26	2375	589	2	150	6450	2.4	9.4	49.6
B-18	11/10	2400	600	8	146.8	5350	0	2.0	7.0

a. Temperature gradient in vessel as much as 20 to 30 °F from bottom to top and, 100 to 125 °F in bottom outlet pipe.

b. Run was made with initial conditions in vessel as close as possible to saturation values.

c. Nominal Orifice Size, in.

ID	Area, ft ²
2	1.689 0.0156
4	3.438 0.0643
6	5.189 0.146
8	6.813 0.253

occurring near the critical flow orifice, the nitrogen might be relatively slow in coming out of solution because of a limited diffusion rate. If so, although proof is lacking, the critical flow would be governed by the flashing of the hot water just as in classical saturated or subcooled flashing critical flow. With these considerations in mind, some mass velocity data obtained from these runs are shown in Figure 31, and are compared with the subcooled formula suggested by Zaloudek. (32,33) The data for Runs B-12 and B-14B (Figure 31) with "subcooled" periods of >12 and 14 sec, respectively, agree fairly well with the Zaloudek formula. However, the mass velocities measured for Runs B-16B and 13-17 (Figure 32) which had shorter "subcooled" periods of 3.6 and 9.4 sec, respectively, showed higher mass velocities than predicted by the subcooled empirical formula. The implication is that these shorter subcooled periods were actually operating at close to a saturated condition near the critical orifice and, as a result, do not show much agreement with the Zaloudek subcooled formula. The data for the shorter subcooled runs might indicate, in this case, the upstream choking phenomenon observed by Zaloudek in which a flow coefficient of 0.95 was used to correlate the data. The results from these tests are probably strongly influenced by the dissolved nitrogen and therefore detailed experiments would be needed to isolate the effect of the nitrogen evolution on the choking phenomenon. Although nitrogen evolution would be expected to change the specific volume less than water flashing there is no assurance that the rates of these two mechanisms are independent or that one or the other is controlling.

Subcooled Decompression

During the course of the experiments, the capability was acquired to do successful logging of high speed data (high speed needed to follow the rapid pressure transients of subcooled decompression) from the pressure transducers.

FIGURE 31. Mass Velocity Versus Pressure Drop

FIGURE 32. Mass Velocity Versus Vessel Pressure Minus Saturation Pressure

In the early runs, the transducer output of some pressure transducers was logged on memoscope and the trace photographed after the blowdown. Appendix Figure A-9-2 shows a typical example of this type of data for pressure probes at the outlet orifice, the outlet pipe, and the vessel.

Computer logging of the high speed data was used on Blowdown B-14B et seq. These data, which show far more detail than the memoscope traces, are also shown in the appendix (Figures A-21-13 to -19, A-24-17 to -24, A-25-19 to -23, and A-26-9 to -14).

Not all runs were successful. Malfunction of the data logging trigger (such as B-18) or transducer failure occurred occasionally and resulted in poor or no plots. When three data loggers were used, they gave some slightly mismatched overlaps of the data which can be seen occasionally on the plots as, for example, in Figure A-25-19. The offsets can be adjusted visually by reference to the shape.

These runs were all done with nitrogen overpressurization to give subcooled conditions, but its use gave anomolous decompression patterns because the technique allowed some of the nitrogen to dissolve in the water. A later experiment⁽¹⁾ showed the nitrogen to be dissolved at about 80% of its saturation value. Saturated blowdown would not have been strongly influenced by the nitrogen. It is difficult to make inferences from these data because of the unknown effect of the nitrogen. Nevertheless, the data for several runs are given in this report and may be used for later comparison with blowdowns without nitrogen.

The history of the measured pressure at the orifice showed an influence of the orifice size, taking longer to begin to recover for the 4-in. Run B-7 than for the full open break B-8. The pattern of the pressure at the break indicates that, in absence of vena contracta effects (full area break),

nucleation and recovery to saturation begins to occur within 30 msec of the break, although this delay could be the result of the initial low temperature in the leg. The recovery to a pressure near the saturation value in an outlet pipe occurs more rapidly when the break is smaller than the pipe (see Figures A-9B, A-17A, A-21-13, and A-24-17) than with a full open break (see Figures A-11 and A-19A). Although recovery in pressure began before any indication of temperature rise in the outlet pipe, the thermocouple response time of 300 to 400 msec is too long to pick up the flow of hot water which should reach the pipe in 10 to 20 msec for a typical 8-in. break and 40 to 80 msec for a 4-in. break. Pressure recovery in the orifice began typically at 30 to 50 msec. It appears, then, that the pressure recovery pattern at the orifice is most strongly affected by the temperature of the water arriving there. At typical blowdown velocities, the arrival time of the hot water would be from 15 to 200 msec, depending on orifice size. Therefore, these data of pressure history at the orifice should not be used to infer metastability effects in actual blowdown cases in which a fully-hot, fluid-filled-pipe break occurs.

The vessel pressure decreased in a step-wise fashion (see Figure A-21-16) with a time scale of ca. 10 msec per step. Based on one-dimensional harmonic modes⁽¹⁹⁾ this decrease gives a pipe length for the fundamental of $p c/4 = 7$ and 12.4 ft for hot and cold water, respectively, and $p c/2 = 3.5$ and 6.2 ft for the 2nd harmonic. The outlet pipe is 5.5 ft long.

Berta,⁽³⁾ at LOFT, used step periods corresponding to the 4th harmonic ($p = L/c$) of the outlet pipe in making predictions of the rate of pressure relaxation in the vessel. His method reproduced the overall rate of pressure decrease but the major steps of the LOFT data corresponded more closely to ($p = 2L/c$), the second harmonic for a full open break. For a partly open

break, the period of the steps was longer, corresponding to the fundamental ($p = 4L/c$) or longer periods. These increases probably result from partial reflection of acoustic signals from the inside surface of the orifice restriction.

The CSE results also indicate that 2nd harmonic should be used for rough estimates of the decompression step periods. Less effect of nozzle size was seen in the CSE data than in the LOFT data since a 25% pipe break at CSE also gave the 2nd harmonic while, in LOFT, the 30% break produced a period close to the fundamental. The results also show that the frequency of pressure oscillation is governed by the temperatures (which vary the acoustic velocity) in the break leg.

The actual measured pressure differences of the steps involved do not lend themselves to analysis or interpretation because of the unknown effect of dissolved nitrogen in the water used in these tests.

A higher frequency pulsation was found to ride on top of, and to almost obscure, the main steps of the depressurization (Figure A-24-24). This pulsation is believed to be caused by the nozzles on the vessel and two-dimensional oscillation modes in the vessel itself. An anomaly occurred at the pressure gage 1.41 ft from the exit orifice (Figure A-24-19). It exhibited large pressure fluctuations within a period of 6 msec, whereas the gages, half a foot on each side of it, did not (see Figure A-24-19). The type and range of all three of these gages was the same, but the anomalous gage did have a longer tube connecting it to the test section than did the others. Although no reason was found in two tests for the anomalous indications at this gage position, it is reasonable to assume that a systematic error in the logging or printout might be responsible.

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APPENDIX A
BLOWDOWN DATA

FIGURE A.1. Combined Weight and Pressure Versus Time (Run B-3)

FIGURE A.2. Combined Weight and Pressure Versus Time (Run B-4)

FIGURE A.3. Thrust Force Versus Time (B-4)

A.4

FIGURE A.4. Combined Plot - Weight and Pressure Versus Time (B-5)

BNM-1001

FIGURE A.5. Force and Liquid Level Versus Time (B-5)

A.6

FIGURE A.6. Unified Force, Liquid Level, Pressure, Weight, and Volume Versus Time (B-6A)

A.7

FIGURE A.7. Pressure, Weight, and Liquid Level Versus Time (B-6B)

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FIGURE A.8. Combined Plot of Data Versus Time (B-7)

FIGURE A.9. Memoscope Pressure Histories. Blowdown B-7,
100 psi/div 5 ms/div

FIGURE A.10. Combined Plot of Data Versus Time (B-8)

A. Pressure at Orifice

B. Pressure in Nozzle Extension

FIGURE A.11. Memoscope Pressure History. Blowdown B-8,
100 psi/div 5 ms/div

FIGURE A.12. Combined Plot of Data Versus Time (B-9)

FIGURE A.13. Combined Plot of Data Versus Time (B-10)

FIGURE A.14. Combined Plot of Data Versus Time (B-11)

A.15

FIGURE A.15. Combined Plot of Data Versus Time (B-12A)

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FIGURE A.16. Combined Plot of Data Versus Time (B-12B)

A. Pressure in Nozzle Extension
5 ms/div 250 psi/div

B. Pressure at Nozzle J

FIGURE A.17. High-Speed Memoscope Pressure Histories (B-12B)

FIGURE A.18 Combined Plot of Data Versus Time (B-13)

A. Pressure in Nozzle Extension Pipe
5ms/div 250 psi/div

B. Pressure in Vessel Nozzle J

FIGURE A.19. High-Speed Memoscope Pressure Histories (B-13)

FIGURE A.20-1. Pressure at Instrument Ring (B-14A)

FIGURE A.20-2. Pressure at Nozzle H (B-14A)

FIGURE A.20-3. Pressure at Nozzle J (B-14A)

FIGURE A.20-4. Pressure at 2.08 ft from Exit (B-14A)

FIGURE A.20-5. Pressure at 1.08 ft from Exit (B-14A)

FIGURE A.20-6. Temperature Instrument Ring (B-14A)

FIGURE A.20-7. Temperature Nozzle J (B-14A)

FIGURE A.20-8. Temperature 1.25 ft from Exit (B-14A)

FIGURE A.20-9. Weight of Fluid in Vessel (B-14A)

FIGURE A.20-10. Nozzle Thrust Force (B-14A)

FIGURE A.21-1. Pressure at Nozzle R (B-14B)

FIGURE A.21-2. Pressure at Nozzle H (B-14B)

FIGURE A.21-3. Pressure at Nozzle J (B-14B)

FIGURE A.21-4. Pressure at 2.08 ft from Exit (B-14B)

FIGURE A.21-5. Pressure at 1.41 ft from Exit (B-14B)

FIGURE A.21-6. Pressure at 0.125 ft from Exit (B-14B)

FIGURE A.21-7. Temperature Instrument Ring (B-14B)

FIGURE A.21-8. Temperature Nozzle J (B-14B)

FIGURE A.21-9. Temperature 1.25 ft from Exit (B-14B)

FIGURE A.21-10. Weight of Fluid in Vessel (B-14B)

FIGURE A.21-11. Nozzle Thrust Force from LC-2, LC-4 (B-14B)

FIGURE A.21-12. Water Level in Vessel (B-14B)

18 DEC 69

FIGURE A.21-13. High-Speed Pressure Response at Orifice (B-14B)

A.43

18 088 69

FIGURE A.21-14. High-Speed Pressure Response 1.41 ft from Exit (B-14B)

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FIGURE A.21-15. High-Speed Pressure Response 2.08 ft from Exit

A.45

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FIGURE A.21-16. High-Speed Pressure Response at Nozzle J

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FIGURE A.21-17. High-Speed Pressure Response at Nozzle H

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A.47

FIGURE A.21-18. High-Speed Pressure Response at Nozzle R

BNWL-1411

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FIGURE A.21-19. High-Speed Pressure Response at Instrument Ring

FIGURE A.22-1. Pressure at Instrument Ring (B-15)

FIGURE A.22-2. Pressure at Nozzle R (B-15)

FIGURE A.22-3. Pressure at Nozzle H (B-15)

FIGURE A.22-4. Pressure at Nozzle J (B-15)

FIGURE A.22-5. Pressure at 2.08 ft from Exit (B-15)

FIGURE A.22-6. Pressure at 1.41 ft from Exit (B-15)

FIGURE A.22-7. Pressure at 1.08 ft from Exit (B-15)

FIGURE A.22-8. Pressure at 0.125 ft from Exit (B-15)

FIGURE A.22-9. Temperature at Instrument Ring (B-15)

FIGURE A.22-10. Temperature at Nozzle R (B-15)

FIGURE A.22-11. Temperature at Nozzle H (B-15)

FIGURE A.22-12. Temperature at Nozzle J (B-15)

FIGURE A.22-13. Temperature at 1.25 ft from Exit (B-15)

FIGURE A. 22-14. Weight Fluid in Vessel (Data Filtered) (B-15)

FIGURE A.22-15. Thrust Forces (B-15)

A.64

FIGURE A. 22-16. Water Level in Vessel (Data Filtered) (B-15)

3NW1-1111

FIGURE A.22-17. Void Fraction and Quality (B-15)

FIGURE A.23-1. Pressure at Instrument Ring (B-16A)

FIGURE A.23-2. Pressure at Nozzle R (B-16A)

FIGURE A.23-3. Pressure at Nozzle H (B-16A)

FIGURE A.23-4. Pressure at Nozzle J (B-16A)

A.70

FIGURE A.23-5. Pressure at 2.08 ft from Exit (B-16A)

FIGURE A.23-6. Pressure at 1.41 ft from Exit (B-16A)

FIGURE A.23-7. Pressure at 1.08 ft from Exit (B-16A)

FIGURE A.23-8. Pressure at 0.125 ft from Exit (B-16A)

FIGURE A.23-9. Temperature at Instrument Ring (B-16A)

A.75

FIGURE A.23-10. Temperature at Nozzle R (B-16A)

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FIGURE A.23-11. Temperature at Nozzle H (B-16A)

FIGURE A.23-12. Temperature at Nozzle J (B-16A)

FIGURE A.23-13. Temperature at 1.25 ft from Exit (B-16A)

FIGURE A.23-14. Weight of Fluid in Vessel (B-16A)

FIGURE A.23-15. Nozzle Thrust Force from LC-2, LC-4 (B-16A)

FIGURE A.23-16. Water Level in Vessel (B-16A)

FIGURE A.24-1. Pressure at Instrument Ring (B-16B)

FIGURE A.24-2. Pressure at Nozzle R (B-16B)

FIGURE A.24-3. Pressure at Nozzle H (B-16B)

FIGURE A.24-4. Pressure at Nozzle J (B-16B)

FIGURE A.24-5. Pressure at 2.08 ft from Exit (B-16B)

FIGURE A.24-6. Pressure at 1.41 ft from Exit (B-16B)

FIGURE A.24-7. Pressure at 1.08 ft from Exit (B-16B)

FIGURE A.24-8. Pressure at 0.125 ft from Exit (B-16B)

FIGURE A.24-9. Temperature at Instrument Ring (B-16B)

FIGURE A.24-10. Temperature at Nozzle R (B-16B)

FIGURE A.24-11. Temperature at Nozzle H (B-16B)

FIGURE A.24-12. Weight of Fluid in Vessel (B-16B)

FIGURE A.24-13. Nozzle Thrust Force from LC-2, LC-4 (B-16B)

FIGURE A.24-14. Water Level in Vessel (B-16B)

FIGURES A.24-15. High-Speed Pressure 0.125 ft from Exit (B-16B)

A.97

FIGURE A.24-16. High-Speed Pressure 1.08 ft from Exit (B-16B)

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FIGURE A.24-17. High-Speed Pressure 1.41 ft from Exit (B-16B)

66.V

FIGURE A.24-18. High-Speed Pressure 2.08 ft from Exit (B-16B)

WL-1411

A.100

FIGURE A.24-19. High-Speed Pressure at Nozzle J Exit (B-16B)

BNWL-1411

A.101

FIGURE A.24-20. High-Speed Pressure at Nozzle H Exit (B-16B)

BNWL-1411

A.102

FIGURE A.24-21. High-Speed Pressure at Nozzle R Exit (B-16B)

BNWL-1411

A.103

FIGURE A.24-22. High-Speed Pressure at Instrument Ring (B-16B)

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FIGURE A.25-1. Pressure at Instrument Ring (B-17)

FIGURE A.25-2. Pressure at Nozzle R (B-17)

FIGURE A.25-3. Pressure at Nozzle H (B-17)

FIGURE A.25-4. Pressure at Nozzle J (B-17)

FIGURE A.25-5. Pressure at 2.08 ft from Exit (B-17)

FIGURE A.25-6. Pressure at 1.41 ft from Exit (B-17)

FIGURE A.25-7. Pressure at 1.08 ft from Exit (B-17)

FIGURE A.25-8. Pressure at 0.125 ft from Exit (B-17)

FIGURE A.25-9. Temperature Instrument Ring (B-17)

FIGURE A.25-10. Temperature at Nozzle R (B-17)

FIGURE A.25-11. Temperature at Nozzle H (B-17)

FIGURE A.25-12. Temperature at Nozzle J (B-17)

FIGURE A.25-13. Temperature at 1.25 ft from Exit (B-17)

FIGURE A.25-14. Weight of Fluid in Vessel (B-17)

FIGURE A.25-15. Nozzle Thrust Force from LC-2, LC-4 (B-17)

FIGURE A.25-16. Water Level in Vessel (B-17)

FIGURE A.25-17. Densitometer Sensor Output

FIGURE A.25-18. Void Fraction and Quality (B-17)

A.122

FIGURE A.25-19. High-Speed Pressure at 1.08 ft from Exit (B-17)

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A.123

FIGURE A.25-20. High-Speed Pressure at 1.41 ft from Exit (B-17)

FIGURE A.25-21. High-Speed Pressure at 2.08 ft from Exit (B-17)

A.125

FIGURE A.25-22. High-Speed Pressure at Nozzle J (B-17)

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FIGURE A. 25-23. High-Speed Pressure at Nozzle H (B-17)

A.127

FIGURE A.25-24. High-Speed Pressure at Nozzle R (B-17)

BNWL-1411

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FIGURE A.25-25. High-Speed Pressure at Instrument Ring (B-17)

FIGURE A.26-1. Pressure at Instrument Ring (B-18)

FIGURE A.26-2. Pressure at Nozzle H (B-18)

FIGURE A.26-3. Pressure at Nozzle J (B-18)

FIGURE A.26-4. Pressure at 2.08 ft from Exit (B-18)

FIGURE A.26-5. Pressure at 1.08 ft from Exit (B-18)

FIGURE A.26-6. Temperature at Instrument Ring (B-18)

FIGURE A.26-7. Temperature at Nozzle H (B-18)

FIGURE A.26-8. Temperature at Nozzle J (B-18)

A.137

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FIGURE A.26-9. High-Speed Pressure at Orifice (B-18)

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A.138

18 DEC 69

FIGURE A.26-10. High-Speed Pressure at 1.08 ft from Exit (B-18)

NWL-1411

18 DEC 69

FIGURE A.26-11. High-Speed Pressure at 2.08 ft from Exit (B-18)

FIGURE A.26-12. High-Speed Pressure Response at Nozzle J (E-18)

FIGURE A.26-13. High-Speed Pressure Response at Nozzle H (B-18)

FIGURE A.26-14. High-speed Pressure at Nozzle R (B-18)

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