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HIGH-ENTHALPY-WATER BLOWDOWN TESTS
FROM A SIMPLE VESSEL
THROUGH A SIDE OUTLET

February 1971

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ABSTRACT

Safety studies concerning the design basis loss-of-coolant accident of a water cooled nuclear power reactor were carried out with a 150 ft³ reactor simulator vessel by performing tests of blowdown through a 1.5 to 6.8 in. diameter orificed side nozzle.

Liquid level and weight, vessel pressure and temperature, exit duct void fraction, and reaction thrust were measured during blowdown, and high speed movies were taken of the fluid in the exit duct.

Comparisons were made with theory and with earlier results. Previous saturated flow rate results were confirmed, and a decrease in mass velocity with nozzle size was associated with increased void fraction. However, since no bubbles could be seen for large break sizes, it was inferred that the bubbles are extremely small (less than 1/64 in. diameter). Liquid remaining in the vessel after blowdown was 2 to 6% of initial mass.

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NOMENCLATURE

A_b	area of break, ft^2
C	coefficient
C_D	discharge coefficient
C_x	quality gradient coefficient
C_T	thrust coefficient, ratio of measured to incompressible ideal thrust
g_c	dimensional constant, $37.2 \frac{\text{lb}_m}{\text{lb}_f} \text{ft/sec}^2$
G	mass velocity, $\text{lb}_m/\text{ft}^2 \text{ sec}$
M_o	initial mass of fluid in vessel, lb_m
P	local pressure
P_v	vapor pressure
ΔS	surface element, ft^2
T	thrust, lb_f
t	time, seconds
t^*	dimensioned time = $\frac{A}{M_o} t$
u	bubble rise velocity (Moody)
V	specific volume
V_D	bubble rise velocity parameter (FLASH2)
α	void fraction
ρ	density, lb_m/ft^3
a	cavitation number

Subscripts

c	critical section	m	relative to Moody prediction
ct	calculated, thrust	T	thrust
f	fluid	v	vessel
g	vapor or gas		

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HIGH- ENTHALPY- WATER BLOWDOWN TESTS
FROM A SIMPLE VESSEL THROUGH A SIDE OUTLET

INTRODUCTION

CSE DESCRIPTION

A reactor simulator vessel with a volume of 150 ft⁵ and designed for operation at 600 °F and 2750 psig was used in experiments to study loss-of-coolant accidents of water cooled power reactors. The objectives of the experiments included testing the validity of mathematical models used for predicting the consequences of a loss-of-coolant reactor accident. The vessel was mounted in a steel framework with the discharge nozzles directed horizontally. The blowdown apparatus was instrumented to measure internal pressures, temperatures, liquid level, void fraction of the fluid in the exit duct, mass of fluid remaining in vessel, thrust reaction forces, shell stresses, and forces on reactor dummy core structures.

These blowdown experiments were done as a continuation of a series done with the bottom nozzle of the same vessel. These experiments were reported in BNWL-1411,⁽¹⁾ and a series with a sieve plate septum in the vessel reported in BNWL-1463⁽²⁾

SUMMARY

A series of eight high pressure, 500 °F water blowdown tests were made with a 150 ft³ instrumented vessel. The tests indicated that bubble separation theories applied to the fluid in the vessel are inadequate to explain the observed flow rates. The observed reduction of mass velocity with nozzle size appears to be associated with the void fraction or quality in the exit duct which are in turn determined by the flow conditions. Liquid level versus time can be predicted reasonably well but the final amount remaining is less than predicted. This would normally be somewhat unconservative for reactor safety in cases where the water remaining and injected water are relied upon for post-accident cooling of the core.

CONCLUSIONS

1. The two-phase critical flow orifice coefficients required to give the correct pressure-time history with the FLASH2 prediction code were substantially the same as those required for the bottom outlet tests.
2. The use of a bubble-rise model code to predict the void fraction in the vessel at the exit level and thereby give the correct flow rate was insufficient to eliminate the need for an empirical orifice flow coefficient.
3. The void fraction and quality in the exit pipe was roughly proportional to the orifice area.
4. High speed movies of the exiting fluid during the early stages of blowdown showed visible bubbles (1/32 to 1/16 in. diameter) only for the smallest orifice area tested.
5. When bubbles were seen, there was an associated superheat condition of about 2 °F.
6. Movies of large area blowdowns showed "fogging" suggesting that very tiny bubbles were formed.
7. Liquid remaining after blowdown was about 50% of that predicted by FLASH2, and due to the low elevation of the exit nozzle, it amounted to less than 10% of the original liquid.
8. Subcooled decompression histories recorded by most pressure sensors were predicted well by a one-dimensional acoustic wave code (WHAM) if the correct outlet pressure history was used as the boundary condition.
9. The measured thrust, flow rates, and pressures indicated that the saturated two-phase flow is not at equilibrium in the actual flow orifice.

DISCUSSION

EXPERIMENTAL CONDITIONS

The initial conditions used for the side nozzle simple vessel blowdown tests are shown in Table 1. The series was designed to explore two types of water cooled reactor: the pressurized water reactor (PWR) which contains hot subcooled water only, and the boiling water reactor (BWR) which contains saturated water surmounted by a vapor region of essentially pure steam. The ultimate temperatures and pressures which were used were dictated by the operating limitations of the apparatus in its configuration at the time of the tests. Several of the runs were made from initial temperatures and pressures below typical reactor conditions. They were made to provide a range of conditions so that the effects could be compared with various blowdown theories. The effects can be extrapolated to conditions beyond the safe capabilities of this equipment.

EXPERIMENTAL APPARATUS AND EQUIPMENT

CSE Blowdown Facility

Description

The full description of the CSE facility is contained in Reference 3. The CSE reactor simulator vessel (Figure 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 supporting frame (Figure 2). The weight of the vessel and simulator support frame were supported by a vertical load cell. Thrust forces generated during the blowdown experiment were restrained by a thrust support system which included upper and lower

TABLE 1. Initial Conditions - Simple Vessel Series
(Side Nozzle B)

<u>Run No.</u>	<u>Date</u>	<u>Orif Size</u>	<u>Loc</u>	<u>Press, psig</u>	<u>Temp, °F</u>	<u>Weight of Water, lb</u>	<u>Transition Time, sec</u>	<u>Comments</u>
B-80	12-11-69	8	B	985	509	7400	6.9-7.2	Full Vessel (PWR type)
B-85	12-17-69	2	B	983	487	7400	74	<div>↓</div> <div>↓</div> <div>↓</div>
B-84	12-23-69	4	B	984	495	7400	22.8-23.0	
B-83	1-2-70	6	B	980	506	7400	10.5	
B-82	1-9-70	6	B	1086	530	4700	4-4.5	Steam Dome (BWR type) (60% liquid)
B-81	1-14-70	8	B	984	542	4400	2.7-3.1	<div>↓</div> <div>↓</div> <div>↓</div>
B-86	1-22-70	4	B	665	498	4700	10.3-10.8	

<u>Orifice Nominal Size, in.</u>	<u>Description Actual D, in.</u>	<u>Square Edge Area, ft²</u>
2	1.687	0.01552
4	3.438	0.06447
6	5.187	0.1467
8	6.8	0.253

FIGURE 1. As-Built Drawing of Reactor Simulator Vessel

FIGURE 2. Reactor Simulator Vessel
in Blowdown Framework

thrust support members and load cells (Figure 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 prevented major damage in case of failure of the restraint system used for measurement or in case the defected bottom head⁽⁴⁾ should fail.

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.

Neg. No. PNL-0690250

FIGURE 3. CSE Reactor Simulator Vessel and Primary Restraint System

BNWL-1470

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

MEASUREMENT APPARATUS AND INSTRUMENTATION

The reactor simulator vessel was instrumented (Figure 5) with pressure and temperature sensors in each of the nozzles, temperature sensors attached to the liquid level probe at intervals along the axis of the vessel, and two pressure sensors mounted through a nozzle to reach the main vessel volume on a special assembly intended to give pressure measurements at the centerline and at the wall of the vessel simultaneously during blowdown transients. As reported in earlier experiments, the vessel is also equipped with thrust measuring load cells,⁽²⁾ a load cell to give weight of vessel contents,⁽¹⁾ a special liquid level measuring device,⁽¹⁾ and a neutron densitometer,⁽¹⁾ which are described in the indicated references.

A special photographic assembly for obtaining pictures of bubble formation during the blowdown transient included a nozzle extension assembly with viewports (Figure 6) for a high intensity light source and a high-speed camera (Figure 7).

Information related to the instrumentation used is consolidated in Tables 2 and 3. Figures 3 and 4 show the location of the sensors on the vessel and a detail of the nozzle extension section.

The general performance of the instrumentation was good. The one exception was ~~the~~ special dual pressure probe mounted through a nozzle. Because of mechanical seal problems, the probe did not give good results on both sensors simultaneously until a subsequent blowdown series. Successful measurements were made of liquid level and state and, on some runs, the discharge void fraction and bubbles in the nozzle.

FIGURE 5. Instrumentation for the Empty Vessel Blowdowns

Neg. No. PNL-701424-2

FIGURE 6. Blowdown Nozzle Extension - Test Section

FIGURE 7. Camera Arrangement

TABLE 2. List of Instrumentation

Sensor Designation	Mfgr. Table VR 2	Type	Intended Measurement	Location
TDR	1	Time Domain Reflectometer	Liquid Level During Blowdown	Down Axis of Vessel Through Top Nozzle
LC1	2	Strain Gage Load Cell	Weight of Vessel, Gage and Contents	Coupling Main Frame and Support Cable
LC2	3	Strain Gage Load Cell	Reaction Forces on Vessel Supports as a result of Blowdown	Attached to Simulator Vessel at Two Heights, Coupled with Main Frame
LC4		Strain Gage Load Cell	Reaction Forces on Vessel Supports as a result of Blowdown	Attached to Simulator Vessel at Two Heights, Coupled with Main Frame
P-1	4	Water Cooled Flush Diaphragm Pressure Sensors	Pressure State of Fluid During Decompression Transient and Subsequent Blowdown	Nozzle A
P-4				Nozzle B, Test Section (Extension)
P-6				Nozzle B, Test Section (Extension)
P-7				Nozzle R'
P-8				Nozzle H
P-10				Rupture Disc Assembly
P-12				Rupture Disc Assembly
P-13				Nozzle C Elbow
P-14				Nozzle S Special Pressure Probe
P-15				Nozzle S Special Pressure Probe
P-17	9	Uncooled High Temp Pressure Sensors		Instrument Ring
P-18	9	Uncooled High Temp Pressure Sensors		Nozzle B, Test Section (Extension)
T-3	5	Chromel-Constantan Thermocouples	Temperature State of Fluid During Blowdown	Nozzle B, Test Section (Extension)
T-6				Nozzle Q
T-7				Nozzle H
T-12				Nozzle C Ell
T-15				In Instrument Ring
T-9				Nozzle Insert Heat Transfer Assembly
T-10				
T-11				
T-20				
T-21				
D-1	7	Proportional Neutron Detector	Void Fraction in Blowdown Test Section During Discharge	Arms on Vessel around Circumference of Discharge Pipe
D-2				
D-4				
Camera	8			
	FASTAX	400 ft Model, 16 mm Full Frame	Fluid Condition in Outlet	Through Window on Test Section
	WF/4			Light at Right Angles to Camera View

TABLE 3 Manufacturers, Models, and Nominal Specifications of Instrumentation

	Manufacturer and Model	No	Description	Range	Static Accuracy
1	Hewlett-Packard 14DA with 1415AM models	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% FS
3	Strainert Model FLY-50SF2.5 Strainert Model FLY-100SG2.5	2 2	Strain Gage Load Cell Strain Gage Load Cell	0-50,000 lb 0-100,000 lb	0.1% FS
4	American Cyanamid-Norwood Model 1102-3000G	8	Water Cooled Strain Gage Pressure Sensor	0-3000 psig	0.1% FS
5	NANMAC Models A and G	7	Chromel-Constantan Thermocouple Probes	0-600 °F	1.0% FS
6	Microdot Model SG 122	2	Quarter Bridge Weldable Strain Gage	0-6000 microstrain	5.0% FS
7	Hamner Model NA-15 Hamner Model NC-11 Harshaw Model B10-4A	2 1 3	Amplifier/Discriminator Discriminator Boron Lined Proportional Neutron Detector	N/A N/A	N/A Sensitivity: $1 \frac{\text{count}}{\text{sec}} / \frac{n}{\text{cm}^2 \text{ sec}}$
8	FASTAX Camera		2000 ± 000 Frames/sec	400 ft/film	millisecond timer
9	Standard Controls Model 420		Uncooled High Temperature Strain Gage Pressure Sensor	0-3000 psig	0.1% FS

RESULTS

'Pressure History

The basic pressure histories of the simple vessel blow-downs were predicted by WHAM for the subcooled regime and by FLASH2 for the saturated regime. As discussed in a previous report⁽²⁾ the success at predicting the subcooled history was most dependent on the correct choice of the pressure history at the orifice. The back pressure at the orifice was found to drop close to zero shortly after the break and to build back to a critical flow value. This type of behavior was observed on the BWR (saturated) blowdowns also but the initial drop was to about half the saturation value. (See Appendix A, Figure A-10.)

Subcooled Regime

The sudden break of an element in a pressurized water loop results in a rapid decompression of the water to a pressure at which the water flashes to steam. This sudden drop in pressure involves large, rapidly moving pressure waves which pass through the medium in the coolant loop. These pressure waves can conceivably cause damage to a reactor system because of the large forces that they may impose. Consequently, the prediction of such pressure waves and of their results is important to the safety assessment of a reactor.

One predictive method in wide use is a computer code called WHAM,⁽⁵⁾ which treats the behavior of these waves in a one-dimensional system. A primary purpose of these tests was to obtain data on a system which was obviously not one dimensional and to assess the applicability of codes such as WHAM to some multi-dimensional cases.

Figure 8 shows typical high-speed pressure data from pressure probe P4 and the prediction given by WHAM when using

FIGURE 8. High Speed Pressure at P4 - B-80

a simple ramp increase in area at the break requiring 0.56 msec. Also included are calculations using a break opening pressure function typical of the total two-step break opening pressure history observed at the critical flow orifice (Figure 9).

Figure 8 shows that a slightly improved prediction was obtained with the longer break time. Later results⁽²⁾ showed that much improved results were obtained with WHAM if an exit function of the pressure history for the first tens of milliseconds was taken from the sensor at the exit and not from an assumed rupture time. Attempts to improve simple exit function results by using nonlinear opening rates and special pipe friction factors were not effective in improving the WHAM predictions. Other work⁽²⁾ showed that a complete profile of exit pressure including the two steps rather than a simple ramp opening gives the best results.

WHAM predictions of results for stations within the vessel were reasonably good for this simple vessel case. Results of a WHAM prediction (3 msec break) are compared with measurements in Figure 10 for a point on a vessel nozzle and in Figure 11 for a point in the vessel interior. Although the computed data is short and the predicted pressure drop is somewhat steeper than observed, the initial agreement is considered to be good. The WHAM model appears to handle adequately subcooled decompression through a side nozzle of an empty vessel despite the limitation of being a one-dimensional code.

Saturated Regime

The FLASH2 blowdown code uses several parameters to give a prediction of the pressure history and liquid level in a simple vessel during a saturated blowdown, i.e. when the steam water mixture in the vessel is substantially on the saturation line of the phase diagram. The parameters used, shown in

FIGURE 9. High Speed Pressure at Orifice B-80

FIGURE 10. High Speed Pressure history: Nozzle, B-80

Table 4, are the quality gradient slope, C_x , the bubble rise velocity, V_b , and the orifice coefficient, C_D . C_x is essentially an arbitrary number which attempts to give a range of quality in the vertical direction in the vessel (or control volume) such that the quality at any level may be described with reference to the average quality and the level. V_b is another arbitrary coefficient which, by representing how fast steam rises in the liquid, determines not only the rate of disengagement of the rising steam bubbles into the steam dome but also the liquid water-steam mixture level in the control volume. The discharge coefficient, C_D , is used to adjust the maximum theoretical blowdown rate (obtained in the code from the local outlet conditions by using Moody's⁽⁶⁾ theoretical maximum flow rate results) to the flow rates actually seen in the experiment. C_D is also arbitrary, and for this work, rough values have been obtained generally from previous CSE experiments.⁽²⁾ Final values are determined by the best fit of FLASH2 results to the data. The results of all the predictions made are not shown but typical results for Run B-82 are shown in Figures 12, 13, and 14.

In general, the pressure results could be made to agree by making a correct choice of flow coefficients, but the mixture level predictions always showed a holdup at the nozzle level. The resultant mass loss rates show fair agreement (Figure 13). The entrainment effects do not seem to be properly handled by FLASH since the final liquid level was far below that predicted.

TABLE 4. Parameters Used in **FLASH2** Predictions

<u>Blowdown</u>	<u>C_x</u>	<u>V_b</u>	<u>C_D</u>
B-80	0.0	2.0	0.54
B-81	0.0	2.0	0.54
B-82	0.0	2.0	0.59
B-83	0.0	2.0	0.59
B-84	0.8	2.0	0.664
B-85	0.8	2.0	0.77
B-86	0.8	2.0	0.66

FIGURE 12. Pressure Versus Time - Run B-82

FIGURE 13. Weight of Water Remaining - Run B-82

FIGURE 14. Liquid Level Versus Time - B-82

Liquid Level

The liquid level behavior for an initially, partly full vessel (saturated, BWR conditions) showed a nonlinear decrease with time. The level dropped to well below the outlet nozzle.

The time domain reflectometer probe was used to measure the liquid level versus time for most blowdowns. Several of the blowdowns (B-81, 82 and 86) were done with a steam dome and saturated fluid conditions. The objective was to duplicate conditions of a BWR and to bracket the conditions used for liquid level prediction given by Moody.⁽⁶⁾ (APED-5177) His prediction indicated an initial decrease followed by a swell of the liquid level during the blowdown.

Figure 15 shows examples of his calculated liquid level curves.⁽⁵⁾ Shown also are the results for the three blowdowns with their respective parameters. The bubble rise velocity parameter has not been included as a listed parameter, but typical values used range from 1 to 2 ft/sec for this model. These values would not change the size of the A/A_v parameter very much. It seems that early in these blowdown tests there is more bubble entrainment into the exit stream than is predicted by the Moody model, as evidenced by the nonlinear level decrease. The results showed a hint of, but no actual, swell predicted by Moody. The level appears to fall faster in actual time than predicted by the Moody level model. For the saturated blowdown regime, the FLASH2 prediction required an empirical orifice coefficient to predict the correct pressure history. Figure 14 shows examples of FLASH predictions of liquid level versus the data.

Liquid Level Remaining

Less liquid remains after blowdown as the break size is increased. Extrapolation of the data to a scaled break representative of a full scale reactor at the height used in these simple vessel experiments would leave essentially no liquid remaining in the vessel.

FIGURE 15. Liquid Level Behavior - BWR Steam Dome Conditions

Table 5 shows liquid-remaining results which are plotted in Figure 16. The liquid fraction remaining was obtained by sight glass reading after each blowdown test. Shown also are previously reported Battelle-Northwest results when a sieve plate was in the vessel. The sieve plate apparently has the effect of reducing the amount of liquid which remains. Predictions from FLASH2, using orifice discharge coefficients to give the correct pressure history, show higher fractions of water remaining than were measured. However, the absolute error is about 5% of the initial mass. This error may vary depending on the absolute height of the discharge. The middle nozzle used in these tests was about 4 ft from the bottom. However, earlier top nozzle break (height 12.8 ft with sieve plate) show absolute errors of about the same amount (2 to 6%).

TABLE 5. Residual Liquid Following Blowdown
(Side Nozzle B)

<u>Run No.</u>	<u>Orifice Size</u>	<u>Press, psig</u>	<u>Temp, °F</u>	<u>Weight of Water, lb</u>	<u>Liquid Height After Blowdown, in.</u>
B-85	2	983	487	7400	21
B-86	4	665	498	4700	14
B-84	4	984	495	7400	14
B-83	6	980	506	7400	9
B-82	6	1086	630	4700	6.3
B-80	8	985	509	7400	7
B-81	8	984	542	4400	6

The amount of liquid remaining is a strong function of the height of break and the size of break. The data plotted in Figure 16 as a function of area ratio show that as the break size increased, a large but lessening decrease in the mass fraction of liquid remain. By extrapolation to breaks scaled to full size at a 4 ft level, one would estimate that essentially no liquid would remain.

FIGURE 16. Residual Water in Vessel After Blowdown - Middle Nozzle B

Void Fraction

The neutron densitometer did not operate satisfactorily. It is a delicate device, consisting of an evacuated tube in which deuterium is accelerated into a tritium target to produce neutrons, and often the shock of the blowdown initiation would cause it to shut off. As a result, only two blowdowns of this series resulted in usable void fraction data.

The data agreed basically with previous results⁽¹⁾ and showed an increase in void fraction with orifice size. This increase in void fraction and associated quality is in the correct range to explain the decrease in mass velocity with nozzle size, but the reason for the higher quality is not as well understood. An early theory suggested that bubbles were formed in the vessel and induced into the flow somewhat proportionally to the flow rate. However, the increase in quality is not sufficiently explained by considerations of bubble rise and separation within the vessel. Typical codes which consider bubble rise phenomena (FLASH2,⁽⁷⁾ BURP,⁽⁸⁾ RELAPSE⁽⁹⁾) still require a coefficient to give a reasonable prediction for this vessel configuration.

The test series included two runs in which the void fraction in the test section (Figures 5 and 6) was measured with a neutron densitometer. In this device, neutron moderation is used as a measure of the amount of liquid in the pipe. The neutron detector data were converted to quality values by the code DENPRØ developed for the purpose. Example of these quality data are shown in Figures 17 and 18. The data are scattered because the digitized recording technique transmits occasional values that represent physically unrealistic situations which introduce instability in the detector output-to-quality conversion equations. However, the overall values and trends are obvious. The low quality portion of the run early in the blowdown is followed by a rapid transition to high quality flow.

FIGURE 17. Quality in Test Section,
Blowdown B-82

FIGURE 18. Quality in Test Section,
Blowdown B-85

The low quality region is characteristic of the saturated flow regime of blowdown. The value of the quality during the saturated flow regime is about 1.5×10^{-2} for a 6 in. (nominal) break and 2×10^{-3} for a 2 in. (nominal) diameter break. Although the blowdowns were started at 530 and 487 °F respectively, the predicted (on the basis of isentropic expansion) values of quality in the pipe are 1.7×10^{-2} and 1.4×10^{-2} respectively. Hence the small break had a much lower quality flow than expected, and much lower than for the larger orifice blowdown test. Earlier data taken with the neutron densitometer had also shown that the mass velocity decrease was associated with orifice size decrease.⁽¹⁾ These data also showed a mass velocity decrease with quality, as predicted by most two-phase critical flow theories.

The experiments of Lienhard and Stephenson,⁽¹⁰⁾ which involved flashing and cavitation in jet flow, show the same effect of size as do these experiments. In their studies they found the cavitation number

$$\sigma = \frac{2\rho(P - P_v)}{G^2}$$

is proportional to orifice area to the -0.33 power. Thus one can conclude that $G_{crit.}$ should be proportional to (Area of orifice)^{-0.166}. This relationship is close to that which has been found by direct experiment in previous work at CSE and other sites.⁽¹⁾

The implication is that the larger break allows higher flow rates which result in more turbulence and a lower cavitation number; hence more bubble nuclei are triggered to form bubbles. The larger number of bubbles gives a higher quality which limits the mass velocity to a lower value than with smaller breaks. Photographs taken of the fluid in the test section do not contradict this theory.

High-Speed Motion Pictures of Fluid in the Test Section

High speed motion pictures taken through the window of the test section (Figures 6 and 7) using cross illumination showed individual bubbles moving at measurable rates (Figure 19) for small (0.0155 ft^2) breaks.

In larger breaks no individual bubbles were seen in spite of a higher quality registered by the neutron densitometer. However, early in the blowdown for a large orifice (0.253 ft^2), a milky cloud was seen moving rapidly with the fluid. Hence, it appears that much smaller but more numerous bubbles are formed as the break size is increased. For small breaks fewer bubbles are formed which are able to grow to visible size in the time available.

The test B-85 was made from subcooled initial conditions shown in Table 1. In addition to the normal pressure and temperature sensors, this run included a special outlet test section consisting of a nominal 8 in. pipe with the glass windows capable of withstanding the initial pressure temperature (Figure 6). High speed (2000 to 8800 frames/sec) motion pictures were taken of the fluid in the test section by lighting at 90° (from view) a narrow, flat channel ($2 \times 2 \times 1/4 \text{ in.}$) on which the camera was focussed (Figure 7). A stainless steel shim stock "flag" with fiducial marks was placed in the pipe in the light beam and was used to show when blowdown began by its movement out of the pipe and to give a calibration of the film for measuring the bubble diameter. The system was moderately successful in that bubble size and velocity could be measured. Not many bubbles were seen, however.

Based on the viewed and illuminated volume and the bubbles seen on each frame, the number of bubbles per unit volume was calculated and results are shown in Figure 20.

FIGURE 19. Film Strip

FIGURE 20. Motion Picture and Pressure History
in Outlet Test Section

The pressure and saturation pressure (obtained from the temperature) in the test section are also shown during this period of high-speed motion picture, lasting about 2 sec. Although pressure errors of ± 10 psi may be present, there appears to be a correlation between the bubbles seen and the supersaturation value. The bubbles appeared in two groups; the first corresponding to an underpressure of 20 psi. The second group showed more bubbles and appeared to be continuing as the film ended.

The bubble diameter was in the range $1/32$ to $1/16 \pm 1/64$ in. well into the skin cooling controlled region of bubble growth (growth limited by heat transfer). The velocity along the flow direction obtained from five bubbles which stayed in the illuminated region for 10 frames or more ranged from 6.8 to 8.6 ft/sec (8 ft/sec average). Calculations made with the bubble information gave a bubble rise velocity of 0.6 to 0.75 ft/sec in a 1 g potential field. This rise velocity is slower than ordinarily used in such codes as FLASH2. Possibly the bubble sampling was poor because of the small volume observed and because the low flow rate induces few bubbles into the outlet stream. Further tests with larger illuminated fields did not increase the bubble observations. The mass flow rate obtained from the bubble velocity was 85 to 105 lb/sec which corresponds to the data of the liquid level probe of 91 lb_m/sec (assuming few bubbles), and the weight load cell data of ~ 100 lb_m/sec. The mass flow rate predicted by the Moody⁽¹¹⁾ model at these conditions is also about 97 lb_m/sec so that the flow coefficient as applied to Moody's flow rate based on most observed bubble velocities would be about one. The low end of bubble velocity measured came within the range of the other data. A possible cause of the high bubble velocity is the presence of a velocity profile in the test section; the velocity was highest in the center where the camera views.

The profile could be the result of wall friction or the velocity potential field caused by the contraction of flow area from the test section to the orifice. The best correlation of FLASH2, which uses the Moody flow rates, is given when an overall coefficient of 0.77 to 0.80 is used for the run conditions of B-85. The quality obtained for 10^5 bubbles per ft^3 is 7×10^{-3} for 1/16 in. bubbles and 7.6×10^{-4} for 1/32 in. bubbles. This compares with 2 to 8×10^{-3} obtained nearby with the neutron densitometer void fraction detector.

For larger blowdowns no individual bubbles could be seen. Special precautions were taken with each succeeding large blowdown to insure that the camera was working. A floodlight system was installed for illumination instead of the 1/8 in. thick light beam, and a small monitor light was used to show that the lens system of the camera was not obscured. In spite of this, the only thing that would be seen on the films for blowdown orifice sizes greater than 2 in. in diameter was a milky cloud, which was quite visible at first formation, but which thinned later. Its movement could be seen. The total length of the camera running was about 2 sec so transition to steam flow could not be observed. Examples of the film results are shown in Figure 19;

It appears that the higher void fraction measured by the densitometer for larger breaks is associated with smaller, not quite visible bubbles. These bubbles give the void fraction which is measured (quality) and which causes the observed reduction in mass velocity.

To apply this conclusion to reactor pipe failures one must assume that for the large breaks sufficient turbulence and nucleation sites exist for bubbles to be formed and for the flow rate to be limited by quality effects. As a result, small breaks may behave as though they were even smaller, giving lower mass loss rates than in these tests, because initial turbulence and nucleation sites present in a flowing loop give a higher quality

at the break than in the stagnant CSE tests. However, since the quality of the flow is highly dependent on the temperature-pressure at the outlet, relative to that in other parts of the system, the determination of the fluid condition should be carefully done. For example, cold emergency core cooling water, if mixed with a blowdown flow, could increase the flow rate through the break by an amount greater than the coolant addition rate. Hence, the fluid loss would be faster than without the emergency coolant addition.

Thrust

The thrust force generated by the blowdown was measured by calibrated load cells. Relatively low thrust values were observed which indicate that the critical flow through the orifice is "metastable," or that the flow has a large slip ratio.

Plots have been made of the measured thrust versus the vessel pressure for several blowdown runs of this series, as in Figure 21. Since the classical value of thrust resulting from incompressible flow through a contracting orifice is $2 P_v A_b$, (obtained by mass, momentum and mechanical energy balance), a thrust coefficient which indicates the amount of thrust obtained relative to the incompressible value

$$C_T = \frac{\text{Thrust}}{2 P_v A_b}$$

was determined from the slope of these curves. The results are shown in Table 6 for several blowdown experiments. It is seen that the thrust is generally less than the incompressible value.

The thrust generated by the expulsion of a fluid is equal to the momentum flux through the boundary plus the sum of the

FIGURE 21. Thrust Versus Vessel Pressure - B-84

pressure acting on the vessel envelope. This results from the second law of motion and by considering only surface forces on the envelope and may be expressed as

$$\bar{F} = \iint_S \rho \bar{u} \cdot \bar{u} \cdot d\bar{s} + \iint_S P \cdot d\bar{s} . \quad (1)$$

Over most of the vessel surface the flux is zero and the ambient pressure is balanced in any direction. Only at the nozzle do the

two terms in the equation have any important effects, and at this location a one-dimensional treatment may be used. The aforementioned equation becomes

$$\text{Thrust} = \frac{G_c^2}{g_c} A_b v_c + P_c A_b = T_{CT} \quad (2)$$

with the assumption that there is no pressure above atmospheric acting on the outside of the vessel except at the orifice.

The specific volume is given by

$$v_c = x_c v_{gc} + [(1 - x_c) v_{fc}] \quad (3)$$

for a zero slip case.

Using Equation 2 the thrust can be calculated on the basis of the Moody flow (mass velocity) and the measured coefficient and the observed back pressure.

An empirical expression for the saturated Moody mass velocity⁽¹¹⁾ is given by

$$G_m = 4550 + 3.23 P_v \quad (12) \quad (4)$$

The actual flow rate can be obtained from the coefficients used as the input to FLASH2 for these tests which are also shown in Table 6.

TABLE 6. Thrust Coefficients

Run No./Size	Thrust Coefficient, $C_T = \frac{\text{Thrust}}{2 P_v A_b}$	Flow Coefficient (FLASH2), $C_M = \frac{G_{\text{measured}}}{G_{\text{Moody}}}$	Calculated Thrust Coefficient, $C_{CT}(\text{@ } 550 \text{ psig})$	Ratio, $\frac{C_T}{C_{CT}}$
B-85/2 in.	1.255	0.77	3.53	0.36
B-84/4 in.	0.70	0.664	2.46	0.29
B-83/6 in.	0.82	0.59	2.24	0.36
B-80/8 in.	0.68-7.5	0.54	1.96	0.36

This coefficient is

$$C_m = \frac{\text{Average Mass Velocity Measured}}{G_m}$$

Thus, the actual flow rate is,

$$G = C_m G_m . \quad (5)$$

The term P_c in Equation 2 can also be obtained from measurement or from empirical correlation with the vessel pressure taken from Figure 22.

By substitution of the measured flow and pressure values by using Equations 2 and 3 and Figure 22 plus a typical equilibrium critical flow void fraction of 0.6, the ratio

$$C_{CT} - \frac{T_{CT}}{2 P_c A_b} \text{ was calculated.}$$

The calculated values of C_T are shown in Table 6. This calculated thrust coefficient shows a decrease with increasing orifice size. The direct measured thrust can be compared with the values calculated from the pressures and flows in the following way.

$$\text{Since} \quad 2 P_c A_b = \frac{T_{CT}}{C_{CT}} = \frac{T_m}{C_T} ,$$

$$\frac{T_m}{T_{CT}} = \frac{C_T}{C_{CT}} \approx 0.3 - 0.36 \text{ (Table 6).}$$

Hence, the thrust measured is less than predicted from the momentum fluxes and pressures measured. This result is probably caused by the assumption of equilibrium void fraction in the momentum Equation (2).

Hence, the flow must be metastable, (still a low void fraction) or have high slip ratio which gives slow liquid flow. Either explanation can account for the low thrust values measured.

FIGURE 22. Relationship of Orifice Pressure to Vessel Pressure

The above analysis is very rough and is only a preliminary attempt to illustrate some thrust effects. The thrust is larger than that for purely incompressible or nonflashing flow. This results partially from back pressure that acts on the outside of the orifice plate and the pipe end flange. It is this back pressure, though small in some configurations, which gives larger than simple theoretical thrusts and points up the requirement for proper definition of the broken pipe configuration to obtain a true value of thrust. The jet could expand in such a way as to contribute more total force than that based on the critical flow area (by virtue of back pressure on an expanding or flared pipe break).

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APPENDIX

DATA PLOTS

These plots are representative data taken from the blowdown series. They represent a good profile of the results. More data were taken but they were largely redundant or inaccurate. Complete data may be obtained from BNW.

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