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HEDL-TC-537

LMFBR SOURCE TERM IODINE ATTENUATION

TEST OF BUBBLE BREAKUP/COALESCENCE IN LMFBR OUTLET PLENUM FOLLOWING LARGE FISSION GAS RELEASE

Hanford Engineering Development Laboratory

Operated by the **Westinghouse Hanford Company**

A Subsidiary of Westinghouse Electric Corporation

for the United States Energy Research and Development Administration Contract No EY-76-C-14-2170

DISCLAIMER

PRELIMINARY REPORT

This report contains information of a preliminary nature prepared in the course of work under Energy Research and Development Administration Contract E (45–1)2170. This information is subject to correction or modification upon the collection and evaluation of additional data.

NOTICE

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BY

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1.0 OBJECTIVE

The purpose of these tests was to qualitatively determine the behavior of fission gas released from LMFBR fuel subassemblies following a hypothetical loss of cladding integrity accident. Information on bubble size and on coalescence and/or breakup of gas bubbles as they rise through chimney and outlet plenum are required to permit estimation of removal of iodine from the fission gas by the sodium.

2.0 INTRODUCTION

In the highly unlikely event of a LMFBR accident releasing fission products to outside the reactor containment, the behavior of iodine is of particular importance. If released to the environs, ^{131}I is likely to be one of the critical isotopes making a major contribution to public health hazard. If the iodine is retained, the health hazard of such an accident is greatly reduced. Fortunately, iodine reacts rapidly and completely with sodium to form sodium iodide which is soluble in sodium. Therefore, if fission gas released from failed fuel elements makes good contact with the sodium in rising through the outlet plenum (i.e., is broken up into sufficiently small bubbles), the iodine may be removed from it and not released to the atmosphere.

A determination of the degree of iodine removal by sodium from fission gas released from fuel subassemblies following a hypothetical sudden loss of cladding integrity is the objective of two parallel complementary test programs:

- Water testing at HEDL of bubble behavior and determination of bubble diameter following simulated fission gas release in a model of significant CRBR components. This report describes this test and its results.
- Measurements by Atomics International of iodine removal from single bubbles of fission gas rising through a column of sodium as a function of bubble diameter. These tests are the subject of a separate report by Atomics International.

3.0 SUMMARY AND CONCLUSIONS

Tests were performed with water in a 0.51-scale model to determine the bubble sizes and degree of contact of liquid and gas in the CRBR outlet plenum following a hypothetical large sudden release of fission gas from the fuel.

The test assembly modeled the tops of six fuel subassemblies surrounding a control rod, the chimney above these, and the free space in the outlet plenum up to the suppressor plate. A known volume of gas was introduced rapidly by opening a valve from a pressurized storage reservoir.

Proper modeling of bubble behavior in sodium by a water test requires simultaneous matching of the Froude and Weber numbers of the model to those of the prototype. The 0.51-scale used in this test permits close, although not exact, adherence to this criterion.

Test parameters studied were liquid flow rate (modeling 0, 10 and 50 percent CRBR flow); number of fuel subassemblies with gas release (1 and 6); volume of gas released (modeling 40 and 100 percent of end-of-life gas inventory); and speed of gas release (less than 1 sec and 8 sec). Data were obtained by direct visual observation and by high-speed color motion pictures.

Effective breakup of the gas released into small bubbles was noted for all conditions tested. In the region between the fuel outlets and the bottom of the chimney, the gas was dispersed as a cloud of bubbles with typical diameter of about 1/4-inch. As the bubbles passed up the chimney they became concentrated into a dense cloud, froth, or in some cases a continuous cylinder of gas. The gas passed out of the top of the chimney as a column of either heavily concentrated bubbles or pure gas, often with strong pulsations which produced large surges or bubbles with diameter somewhat larger than that of the chimney. These were in all cases broken up again within about 1 foot of the top of the chimney, and the gas rose through the rest of the outlet plenum as a spreading cloud of bubbles with typical diameter of 1/4-inch. A very few larger bubbles (1/2- to 1-inch diameter) were observed in the upper part of the outlet plenum near the end of the gas surge.

The bubble sizes observed in this test should be scaled up by a factor of 2 to apply to sodium in CRBR. Thus it may be expected that nearly all the fission gas released in CRBR under the conditions tested would pass through the sodium pool in bubbles of about 1/2-inch diameter or smaller. Final conclusions as to the fraction of iodine which would be removed under these conditions must await completion of concurrent tests by Atomics International to measure removal of iodine from single bubbles in sodium as a function of bubble size. Preliminary results of these tests indicate a high degree of iodine removal from 1/2-inch bubbles.*

4.0 TEST FACILITY

4.1 General

Tests were conducted with air bubbles in water in a reduced-scale model of significant CRBR features.

4.2 Test Assembly

The test assembly built for these tests is shown in Figures 1 and 2. The following features of the CRBR were modeled at a nominal scale of 0.512:

- The top ends of six fuel subassemblies surrounding a control element.
- Free space (12-in. high in model) above top of fuel subassemblies.
- Bottom plate of Upper Internals Structure (UIS) above the fuel positions.
- Chimney centered over control position. This was made of lucite to permit observation of gas flow within it.
- Free space in outlet plenum above top of chimney.
- Suppressor plate at top of plenum.
- Control rod shroud extending from core through center of chimney to suppressor plate.

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*R. P. Johnson, Atomics International, personal communication.

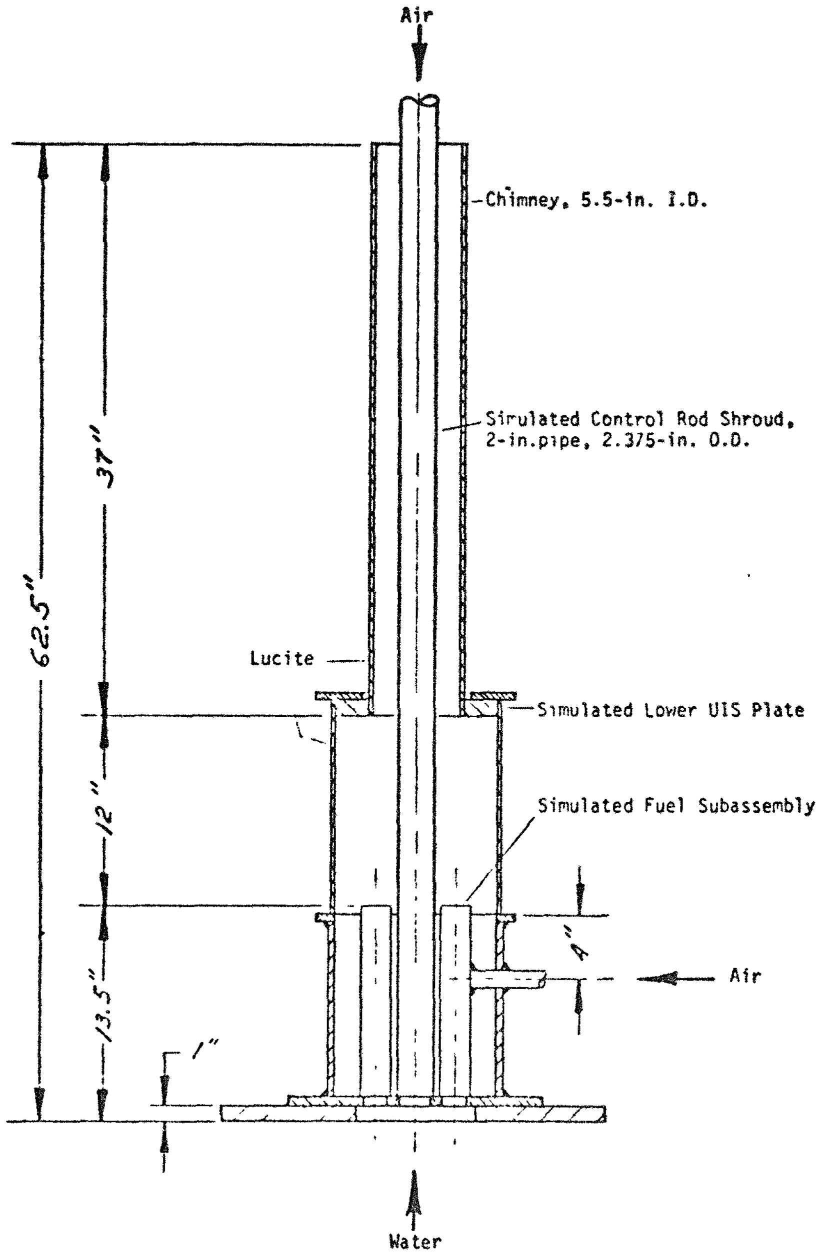

FIGURE 1. Test Assembly for Bubble Breakup/Coalescence Tests.

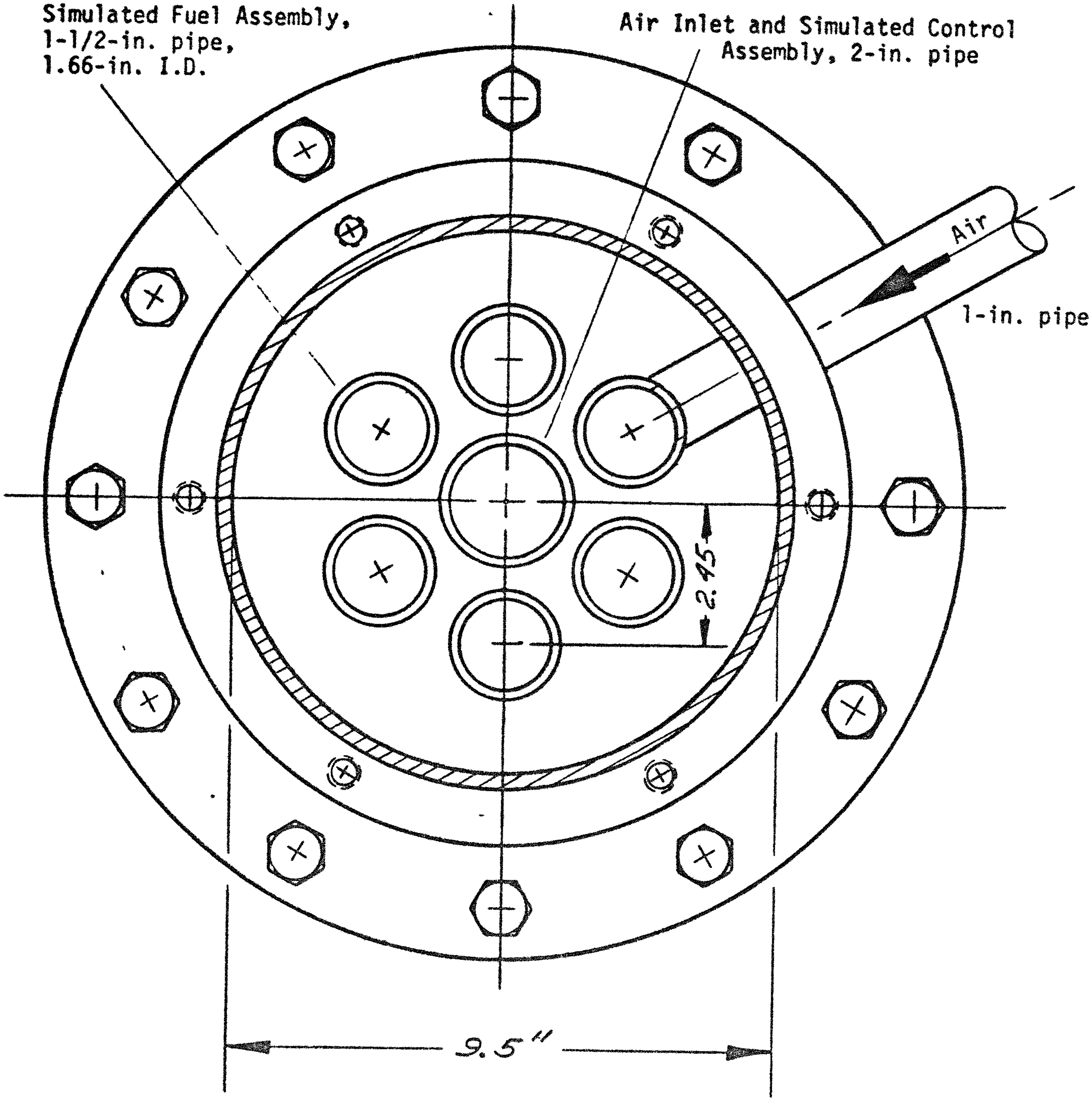

FIGURE 2. Plan View of Test Assembly.

A partition (made of lucite to permit visibility) was provided to surround the region between the simulated fuel subassemblies and the bottom plate of the UIS. This forced all water and air flow through the chimney. The facility thus modeled the worst case of simultaneous gas release over a large area of the core where the gas flow in each chimney would approximately equal that released below it. (Localized gas releases might tend to become distributed among two or more chimneys which would promote better contact with the liquid.)

Each CRBR inner chimney is fed from eight equivalent fuel subassemblies, i.e., the six immediately surrounding a control rod and one-third of the flow from each of six others. Gas release from these outer six was not modeled in these tests.

4.3 Vessel

This test assembly was installed in the old Outlet Feature Model (OFM) in 321B Building at HEDL.* This facility was chosen because it provided a tank of suitable size and shape with many windows to permit observation and the ability to introduce water flow. The OFM vessel with test assembly installed in shown in Figures 3, 5 and 6.

A measured and controlled flow of water was introduced at the bottom of the test assembly. All this flow passed through the six simulated fuel subassemblies and thence through the chimney. Flow in adjacent chimneys, which would affect outlet plenum velocities, was not modeled. Control assembly flow was not modeled.

4.4 Gas Supply

Provision was made to introduce a known quantity of air into the simulated fuel subassemblies. This system is shown in Figure 4. To model release from a single fuel subassembly, air was introduced through a 1-in. pipe into the top of one of the six simulated fuel ducts. To model simultaneous release from all six fuel subassemblies, the air was introduced through the

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*The OFM was originally built as a 0.268-scale model of the FFTF outlet plenum. All FFTF plenum hardware was removed for this test.

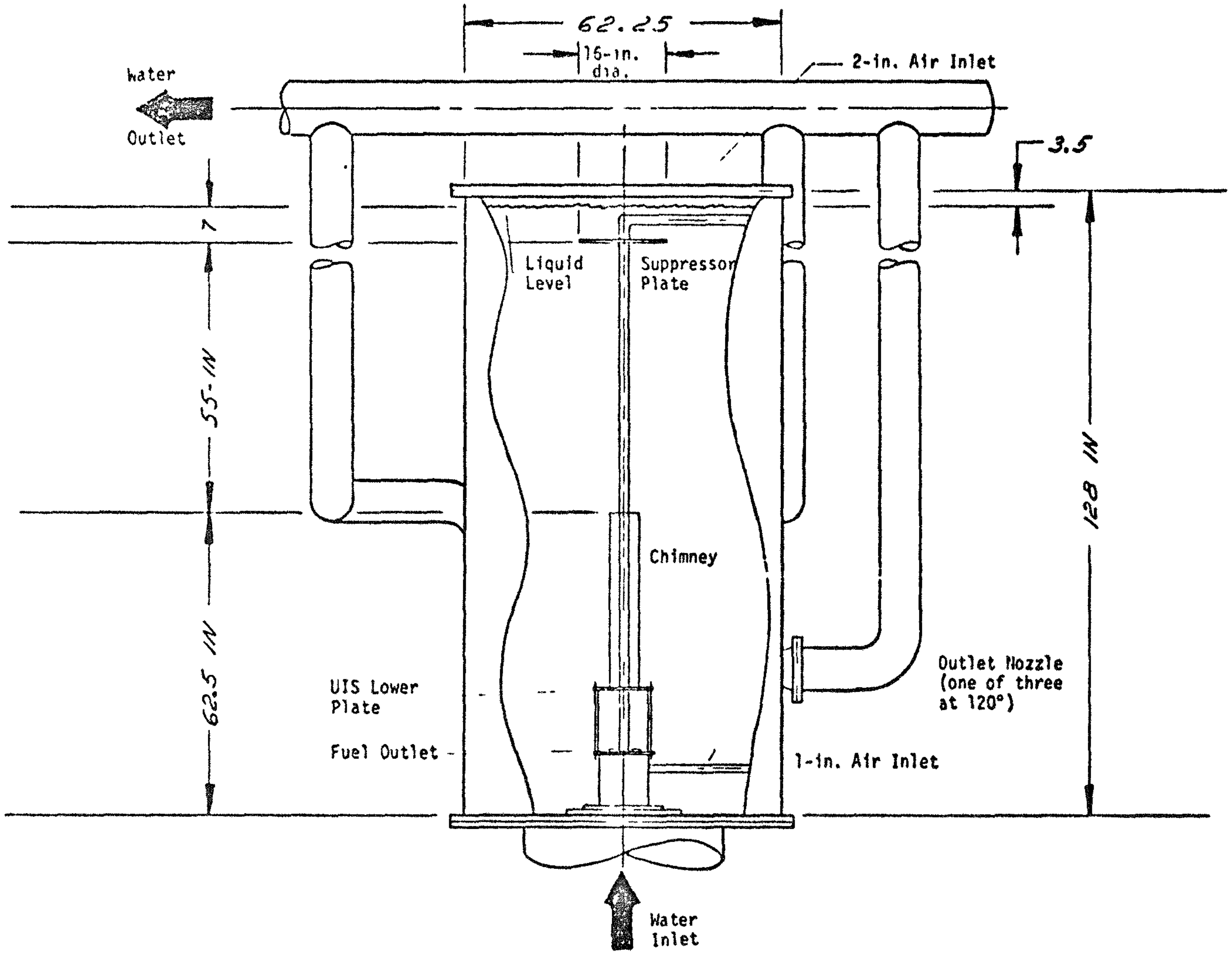

FIGURE 3. Test Assembly Installed in OFM Vessel.

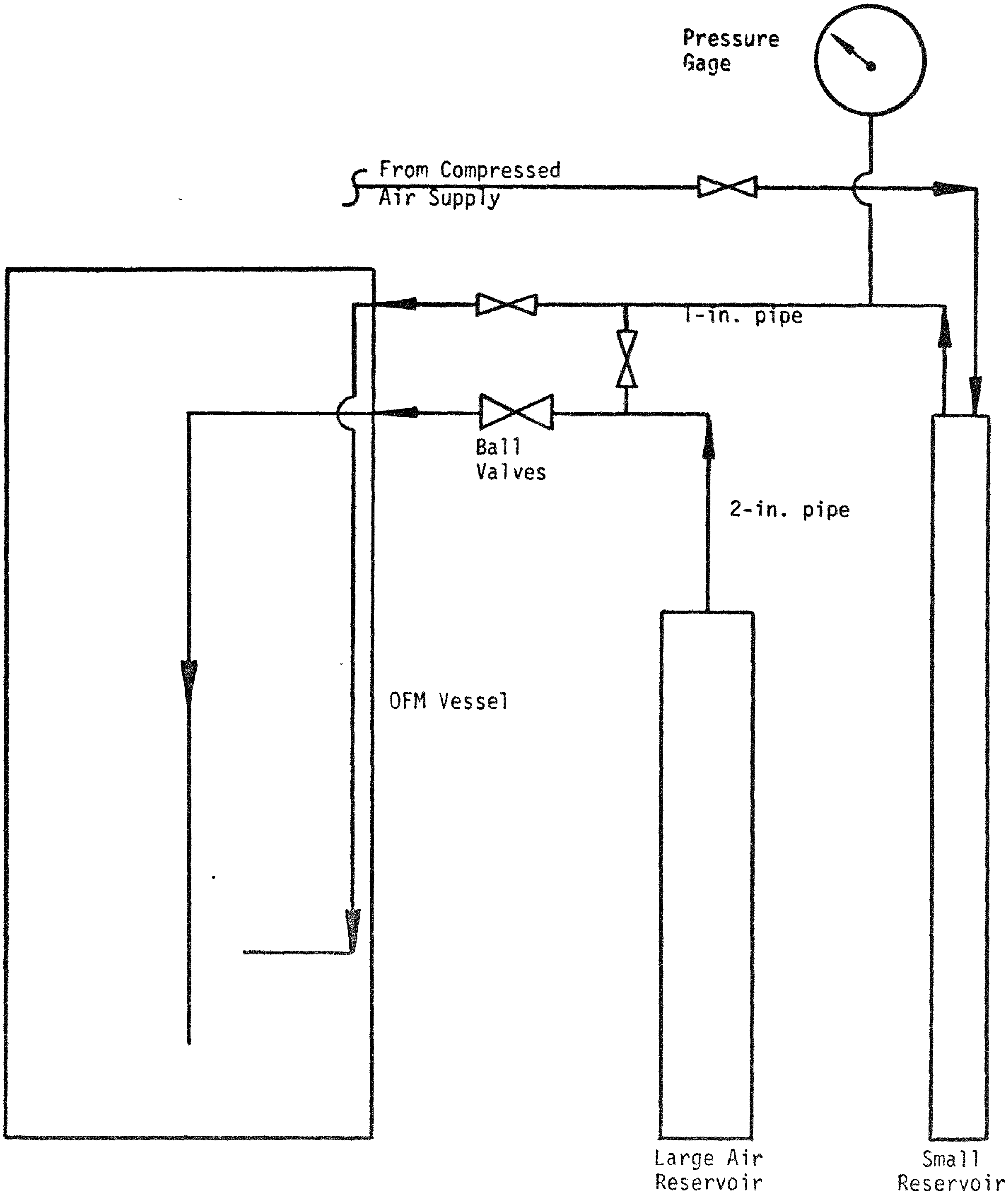

FIGURE 4. Gas Release System.

2-in. pipe used to model the control rod shroud and released into the bottoms of the six simulated fuel ducts. Two air reservoirs were provided. The smaller one had a volume up to the shut-off valve of 1.11 ft^3 and was used for releases from the single fuel assembly. Both reservoirs together, with a total volume of 6.85 ft^3 up to the shut-off valve, were used to release air to six fuel positions simultaneously.

4.5 Operation

A test run was performed in the following manner:

- The desired water flow rate was established. The 62 gpm flow was supplied from a 80 psig sanitary water line; the 310 gpm from a storage tank by a 200 psi recirculating pump.
- The pressure at the outlet of the fuel subassemblies was measured using the 1-in. pipe filled with air as a pressure tap. This pressure was typically 5 psig.
- One or both reservoirs were filled with air to a pressure (typically 19 psig) which would, upon isothermal expansion, introduce the desired volume of gas at the fuel subassembly outlet. (Air was introduced at relatively low pressure to avoid possibility of damage to the lucite by high pressure surges.)
- The test was initiated by rapidly opening a ball valve on the pipe between the reservoir and test assembly.

5.0 MODELING

Particular attention must be given to modeling laws and criteria to assure that test data obtained for gas bubbles in water can be applied reliably to predict behavior in sodium.

Several dimensionless groups containing the independent parameters of the test are significant in determining the behavior of gas rising through a liquid:

- Froude number. $Fr = V^2/gL$ (ratio of kinetic to gravitational forces)

- Weber number. $We = \rho V^2 L/\sigma$ (ratio of kinetic to surface tension forces)
- Reynolds number. $Re = LV\rho/\mu$ (ratio of kinetic to viscous forces)
- Ratios of linear dimensions. (geometric similarity).

In the above,

V = liquid velocity
L = reference length (e.g., chimney diameter)
g = gravitational acceleration
ρ = liquid density
σ = surface tension
μ = liquid viscosity.

Both gravity and surface tension are important in determining bubble breakup, size, shape and terminal velocity, and must be modeled. The effect of viscosity, however, will be small, since the conditions of interest are highly turbulent. The Reynolds number for water flow is the model chimney when simulating pony motor flow is 22,000, which is well into the turbulent range. Even higher velocity and turbulence will be present when the gas is released through the test assembly. A 1/4-in. bubble in water has a terminal velocity of 0.65 ft/sec and a Reynolds number (based on bubble diameter) of 1100; dependence on viscosity in this regime is slight. Therefore, viscosity will have only a minor effect on these tests and matching of Reynolds number is not necessary.

In both model and prototype the density of the gas is negligible compared to that of the liquid, behavior is not dependent on gas density, and modeling of fission gas by air introduces no significant distortion.

Therefore, proper modeling will be achieved if Froude number and Weber number are the same in the model as in the prototype and if all dimensions are scaled by the same factor. Bubble diameter would then be scaled by the same ratio as other linear dimensions.

To match Froude and Weber numbers requires that:

$$\frac{V_m^2}{L_m g} = \frac{V_p^2}{L_p g} \quad \text{and} \quad \frac{\rho_m V_m^2 L_m}{\sigma_m} = \frac{\rho_p V_p^2 L_p}{\sigma_p}$$

Therefore,

$$\frac{L_m}{L_p} = \sqrt{\frac{\sigma_m \rho_p}{\sigma_p \rho_m}} = 0.629$$

$$\frac{V_m}{V_p} = \sqrt{\frac{L_m}{L_p}} = 0.793$$

where: subscript m refers to test model,
subscript p refers to prototype (CRBR),
and the following values of physical properties have been used:

	Model	Prototype
Liquid	water	sodium
Temperature, °F	60	995
Density, lb/ft^3	62.3	51.4
Surface tension, dynes/cm	73.4	153

A scale factor of 0.512 was selected rather than the ideal 0.629 in order to permit use of available lucite tubing for the chimney and to reduce the vertical space required. Further, small deviations from ideal modeling were required to stay within the total height available in the OFM vessel. The height of the chimney (37 in.) was only 42 percent of that in CRBR, and the distance from the top of the chimney to the suppressor plate (55 in.) was 46 percent of that in CRBR. These distortions are expected to have only a small effect on measurements of bubble size and breakup. The height of the chimney and of the free plenum above it are considered to be great enough that whatever bubble coalescence and breakup might occur would take place within these distances. An uncertainty is introduced in the scaling factor relating bubble diameters observed in the test model to those to be expected in CRBR. This ratio may be expected to be in the range of 0.512 (bubble size determined by dimensions of chimney and fuel duct outlet) to 0.629 (bubble size determined by properties of liquid). The use of 0.512 will predict larger bubbles in CRBR and is therefore conservative.

6.0 TEST CONDITIONS

The following parameters were varied in these tests:

- Number of simulated fuel subassemblies from which gas was simultaneously released (1 or 6).
- Water flow rate of 0, 62, or 310 gpm. These flows were selected to give chimney velocities which modeled, on the basis of Froude number, 0 percent, 10 percent (pony motor flow) and 50 percent of CRBR normal operating flow. Attempted tests at higher flows resulted in extraneous bubble formation due to entrainment at the free surface at the top of the vessel.
- Volume of gas released (40 percent and 100 percent of total inventory). The maximum (100 percent) gas release was based on an estimated end-of-life fission gas inventory of 400 cc (STP) in each of 217 fuel pins in one CRBR fuel subassembly.* The gas volume under the actual conditions at the fuel subassembly outlet (taken as 1000°F and 7.7 psig) will be 5.96 ft^3 per subassembly. This scales to $5.96 \times (0.512)^3 = 0.800$ ft^3 in the model.
- Rate of gas release. In most runs the air was introduced as rapidly as possible; measurements with a stop watch showed that the initial surge containing the great majority of the gas volume lasted less than 1 second, followed by a tail-off of reduced and often intermittent flow. In other runs the rate of gas release was reduced by a 0.50-inch orifice in the 2-inch pipe; the same total amount of gas was introduced over a period of about 8 seconds for the initial surge, followed by several seconds of much reduced rate.

*Data supplied by R. P. Johnson, Atomics International.

Runs were made under eleven test conditions, described in Table I. Several runs were made at each test condition to permit repeated visual observation from different windows. High speed (500 frames per second) color motion pictures were taken through windows in the vessel wall. The rising gas was photographed at the following three locations for each of the eleven test conditions:

- In the region above the simulated fuel duct outlets and below the UIS lower plate and chimney.
- In the outlet plenum just above the top of the chimney.
- Near the top of the outlet plenum below the suppressor plate.

7.0 TEST OBSERVATIONS

7.1 Visual

The following description of bubble behavior is based on the visual observations recorded during several repeated runs at each test condition listed in Table I. The same general type of behavior was observed for all conditions tested, and the following apply to all test conditions unless otherwise noted.

- In the 12-inch gap between the fuel outlet and the bottom of the chimney the gas was in all cases broken up into small bubbles. No steady gas flow was noted above the fuel outlets; it appeared that bubbles were either formed in the simulated fuel subassembly or almost instantly at the outlet. Typical diameters were estimated to be about 1/4-inch, with some as large as 1/2-inch. No dependence of bubble size on test condition could be ascertained. With all the six subassembly injections and the higher flow rates with one subassembly, this region was completely filled with bubbles over the duration of the main burst. For the single injections at zero and 10 percent flow, the bubbles flowed directly to the chimney without occupying the full volume.
- The bubbles passed rapidly through the chimneys. The reduced cross section of the chimney tended to collect and concentrate the bubbles into a dense cloud or froth. In runs with rapid gas

TABLE I

CONDITIONS FOR BUBBLE BREAKUP/COALESCENCE TESTS

	Test Condition Designation										
	A	B	C	D	E	F	G	H	I	J	K
Liquid Flow Rate											
GPM of water	0	0	62	62	62	62	310	310	0	62	310
Percent of CRBR full flow modeled	0%	0%	10%	10%	10%	10%	50%	50%	0%	10%	50%
Number of Simulated Fuel Subassemblies with Gas Release	1	6	1	6	1	6	1	6	6	6	6
Amount of Gas Release											
Cubic feet in model	0.8	4.8	0.32	1.92	0.8	4.8	0.8	4.8	4.8	4.8	4.8
Percent of end-of-life inventory in CRBR	100%	100%	40%	40%	100%	100%	100%	100%	100%	100%	100%
Duration of Gas Release, seconds	<1	<1	<1	<1	<1	<1	<1	<1	8	8	8

NOTE: Water temperature was about 60°F for all runs.

release (less than 1 sec) a reverse liquid flow down the chimney was noted at the end of the initial gas surge as liquid displaced gas in the region below the chimney.

- The gas passed out of the chimney as a condensed mass. In the runs with slow (8-second) gas release, the gas was in the form of a very dense cloud of bubbles. With rapid release, the gas was present either as a froth or as a continuous gas phase; it was often difficult to tell which. The gas flow leaving the chimney was highly pulsating, particularly at low or zero water flow rates. This was manifested by variation of the diameter of the gas column, and in some cases by the presence of discrete gas bubbles with diameters slightly greater than the chimney. Several such surges or large bubbles were present in rapid succession during the main gas release (i.e., in about 1-second). These large-diameter slugs had highly agitated surfaces and appeared to be unstable.

- The gas flow passing out of the chimney became broken up into a cloud of small bubbles. This breakup usually took place in a small region about 1 foot above the top of the chimney. This breakup process was highly dynamic, with the gas-liquid interface in constant turbulent motion. The bubble sizes following this breakup were estimated to be about 1/4-inch (in some cases up to 1/2-inch) in diameter.

- In the top of the outlet plenum below the suppressor plate the gas was in all cases present as a large cloud of small bubbles. Nearly all the gas was in bubbles whose diameter was estimated to be about 1/4-inch or smaller. In some cases there were also a very few larger bubbles (1/2- to 1-inch) present near the end of the gas surge. The cloud of bubbles was typically 1 to 2 feet in diameter as it approached the suppressor plate and then spread out further as the flow was deflected by the plate.

Estimation of bubble diameters by visual observation is difficult under these transient conditions, and an accuracy only within a factor of 2 is claimed. As discussed in the section on modeling, the bubble diameters observed in this test should be divided by 0.512 (i.e., approximately doubled) to predict sizes in CRBR.

7.2 Photographic

A 16-mm color motion picture with explanatory captions has been prepared by HEDL to present the photographic data of bubble behavior. Nine still photographs covering six of the eleven test conditions were selected from the motion picture and are included as Figures 7 through 15 of this report.

Unfortunately, the still photographs can present only a small fraction of the information contained in the motion pictures from which they were taken. The passage of the gas through the liquid was a dynamic process with local conditions always changing; the still photographs are therefore only selected samples of what was observed at each test condition. The somewhat poor quality of the photographs in Figures 7 through 15 is due to reproduction and enlargement from frames of the motion picture. Because it can portray the movement of the gas, the motion picture presents a more vivid and clear presentation of the data.

The individual bubbles do not show up as well in the still photographs as they do by direct observation, probably because of limited depth of focus. Diameter measurements were made for those bubbles which are clearly visible in the photographs. In the region below the chimney (Figures 7 and 8), discrete bubbles are hard to identify and measure, but with few exceptions do not appear to be larger than 1/4-inch. In the region above the chimney, the individual bubbles following breakup are best seen in Figures 9, 11, and 12. The largest visible bubbles have diameters of about 0.3-inch, while most are 0.2-inch or smaller. In Figure 15, showing the top of the plenum, the one largest bubble is 0.8-inch diameter, a few others are 0.3- to 0.5-inch, and the great majority are in the neighborhood of 0.2-inch.

8.0 FURTHER WORK

It would be possible to determine the degree of iodine removal expected in CRBR directly from gas release tests similar to those described herein, rather than using observed bubble sizes in conjunction with separate tests of iodine removal from single quiescent bubbles.

Just as gaseous iodine reacts completely with sodium as rapidly as it diffuses to the wall of the bubble, so ammonia would be absorbed rapidly and completely by water or dilute boric acid. Furthermore, bubbles with the size and velocities encountered in reactor situations will have strong internal circulation. Mass transfer within the bubble will be controlled by this internal flow rather than by molecular diffusion, and reasonable dynamic modeling of CRBR behavior would very likely be possible with the present model.

Such a test should be preceeded by further analysis to demonstrate validity of modeling and by a comparison test of iodine-fission gas-sodium versus ammonia-air-water under simple conditions (e.g., single bubbles).

The direct measurement of gas stripping in the same test that bubble behavior is modeled would have the advantage of taking into account the dependence of mass transfer on dynamic changes in bubble shape and internal circulation due to interaction with the liquid flow and test geometry. It would also take into account the actual, rather than calculated, bubble transit time. Such a test would be desirable if a better prediction of iodine removal is required than can be obtained from using iodine stripping measurements on single quiescent bubbles.

FIGURE 5. Test Assembly Installed in OFM Vessel.

Lucite chimney, air inlet pipes, and some of vessel windows are visible.

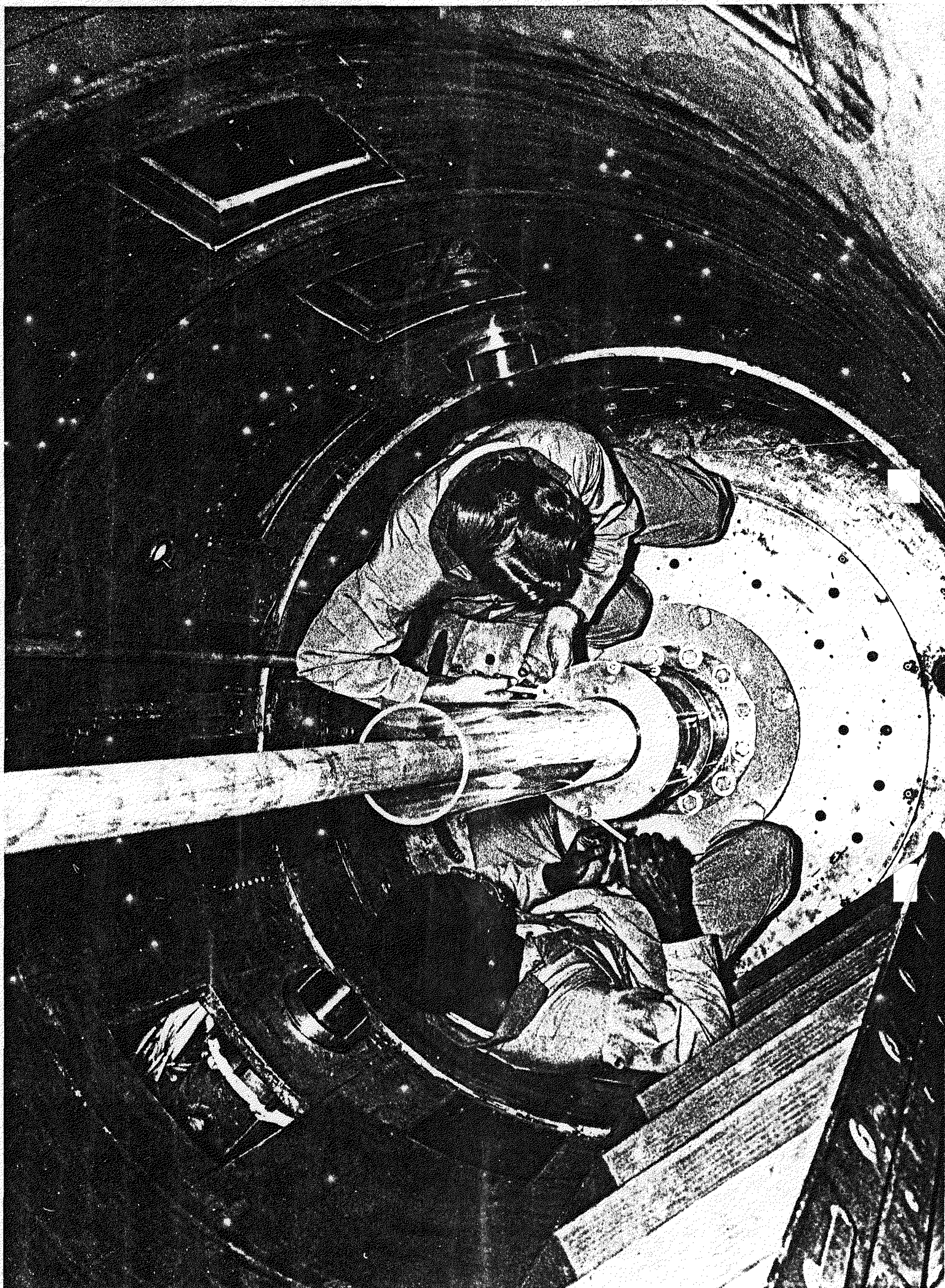

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FIGURE 6. Test Assembly Installed in OFM Vessel.

Simulated fuel outlet nozzles and lower end of chimney are visible. Central pipe models control rod shroud and introduces air.

FIGURE 7. Gas Flow in Region Between Fuel Outlet Nozzle and Bottom of Chimney.

Test Condition E:

10% liquid flow
100% gas volume
rapid burst
release from single fuel subassembly.

About 0.42X.

[Arrow in Figures 7 through 15 indicates direction of gas and water flow (i.e., up).]

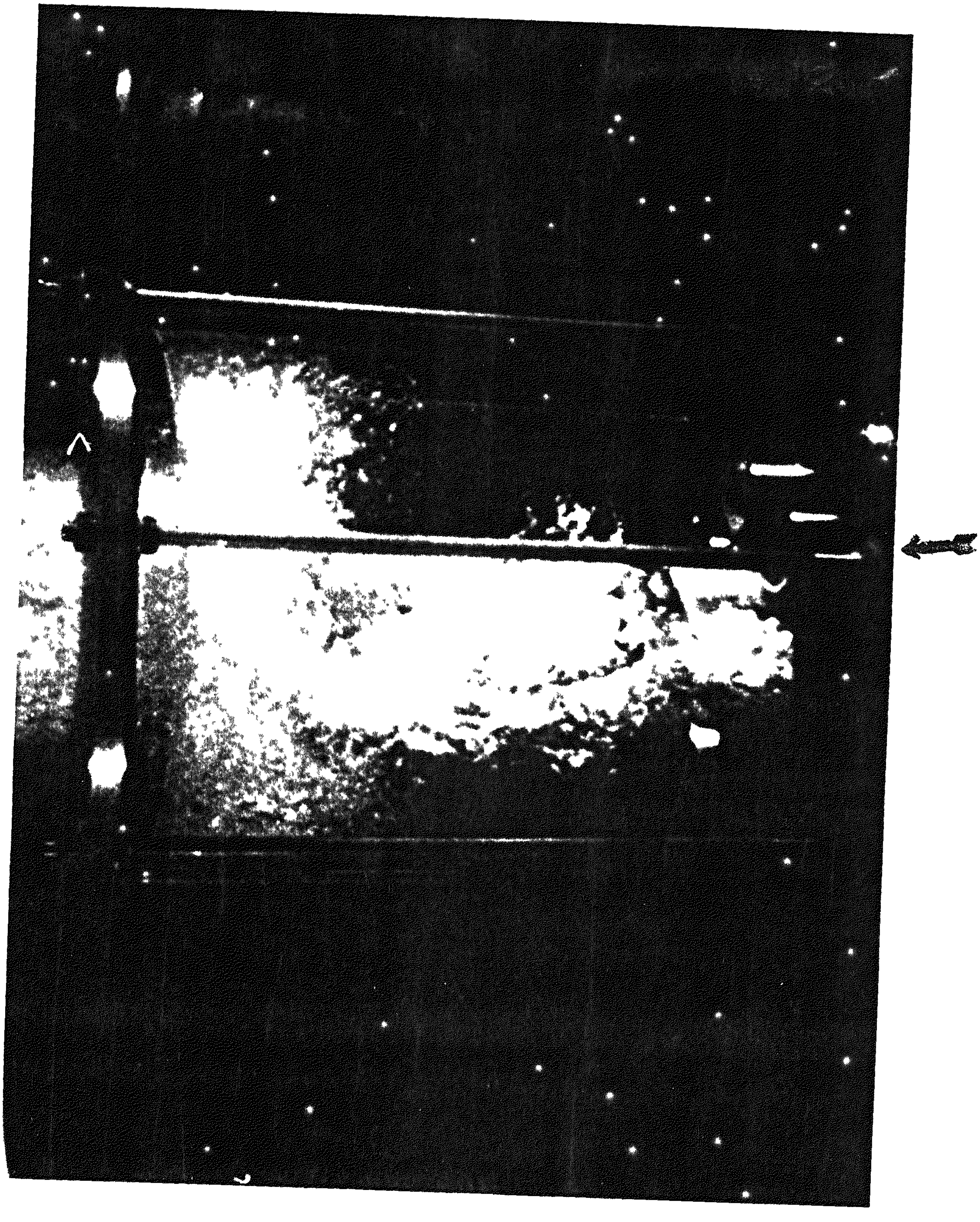

FIGURE 8. Gas Flow in Region Between Fuel Outlet Nozzle and Bottom of Chimney.

Test Condition F:

10% liquid flow
100% gas volume
rapid burst
release from six fuel subassemblies.

About 0.42X.

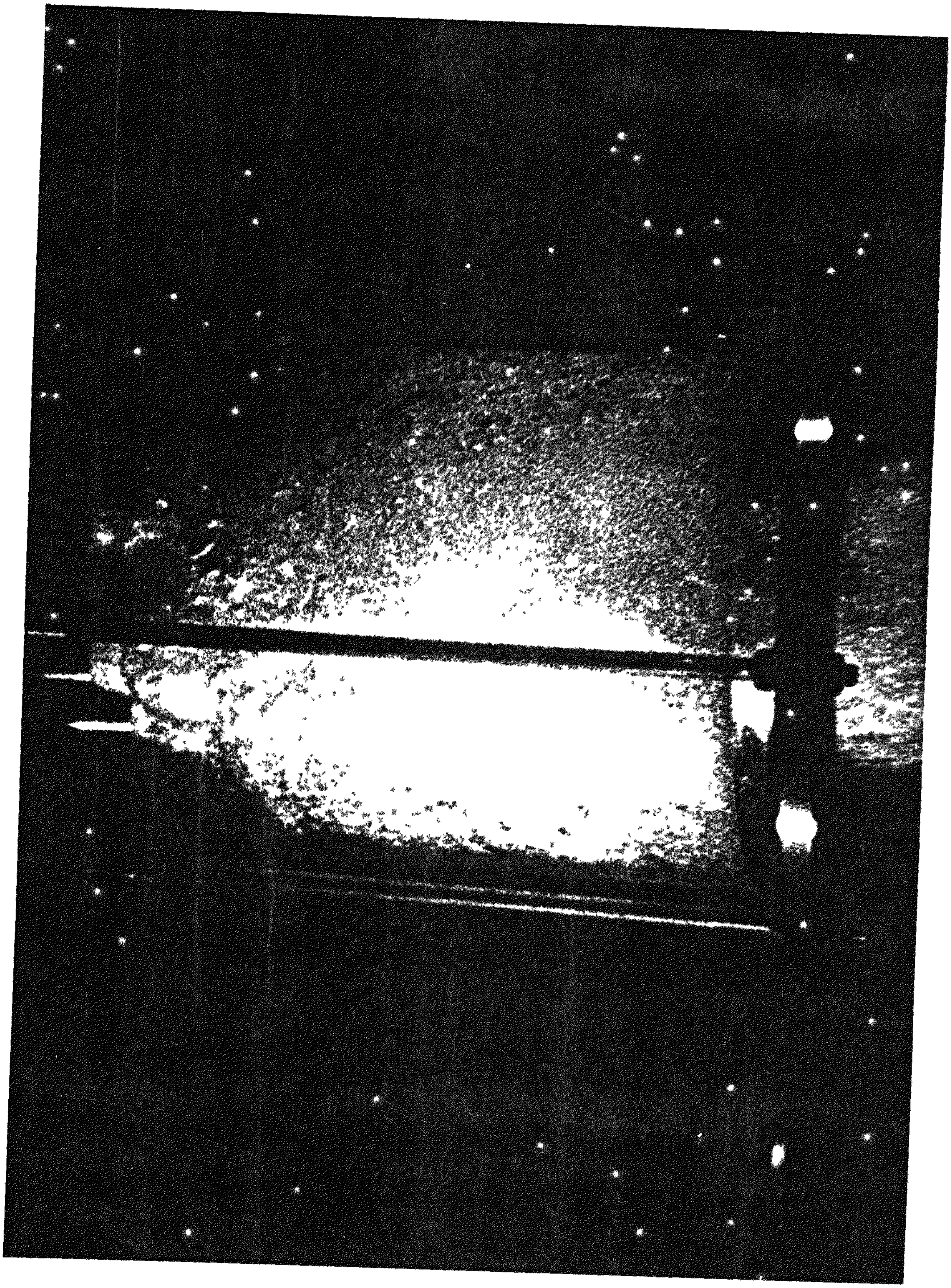

FIGURE 9. Gas Flow in Region Just Above Top of Chimney.

Test Condition A:

zero liquid flow
100% gas volume
rapid burst
release from single fuel subassembly.

Top edge of chimney is at bottom edge of photograph.
About 0.42X.

Note extreme pulsation of gas flow at low water and gas flows.

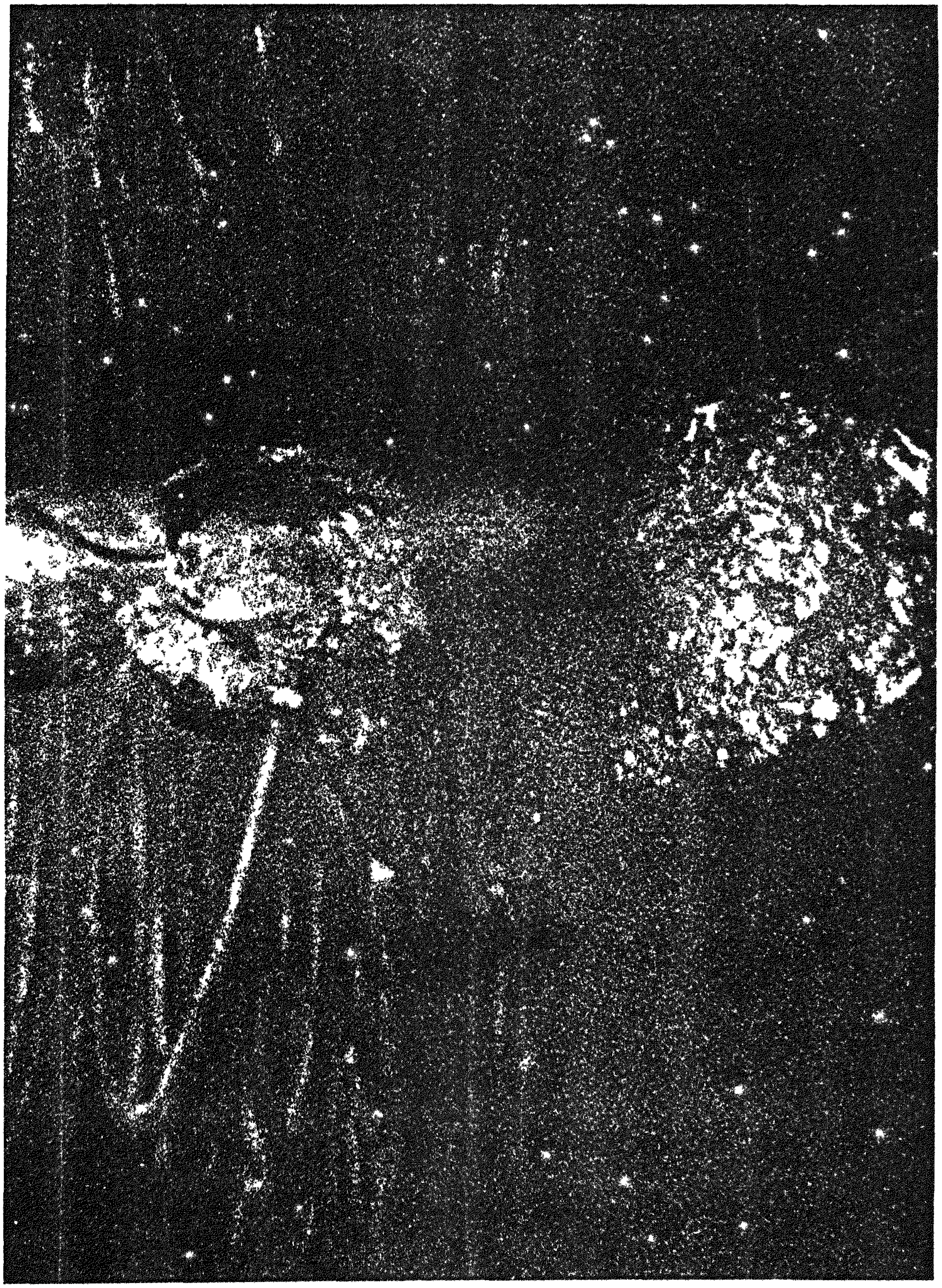

FIGURE 10. Gas Flow in Region Just Above Top of Chimney.

Test Condition B:

zero liquid flow
100% gas volume
rapid burst
release from six fuel subassemblies.

Top edge of chimney is at bottom edge of photograph.
0.42X.

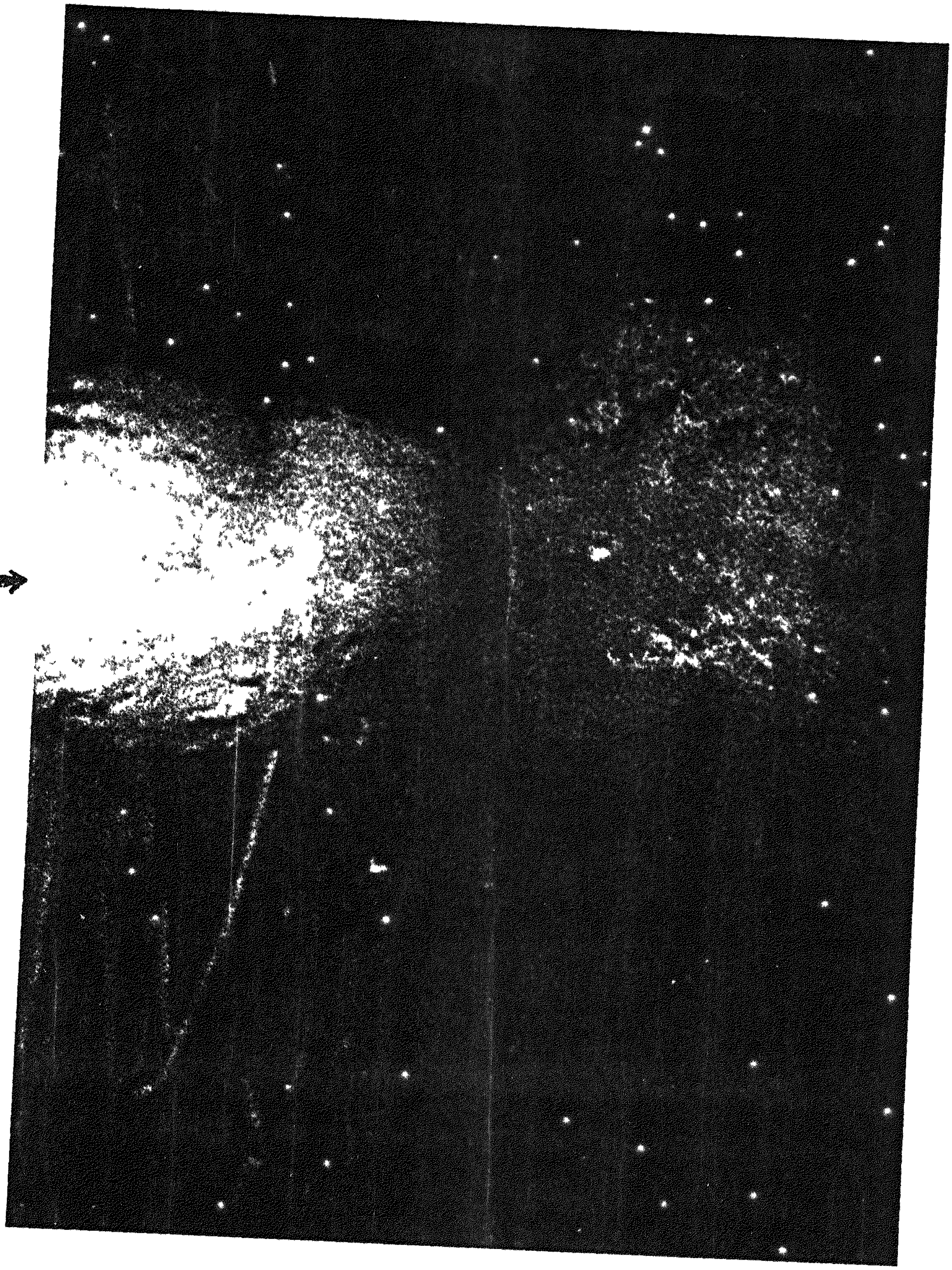

FIGURE 11. Gas Flow in Region Just Above Top of Chimney.

Test Condition E:

10% liquid flow
100% gas volume
rapid burst
release from single fuel subassembly.

Top edge of chimney is at bottom edge of photograph.
0.42X.

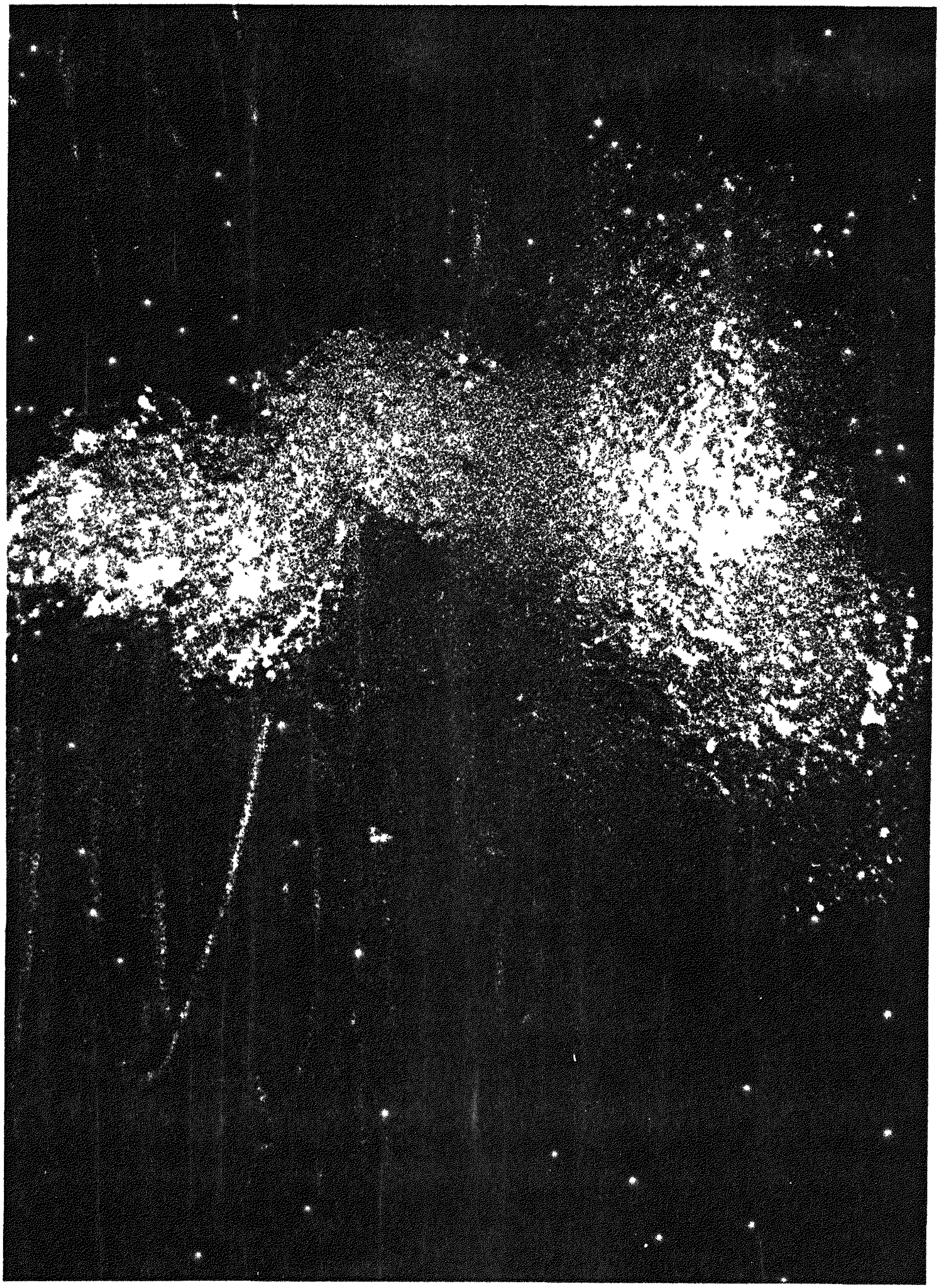

FIGURE 12. Gas Flow in Region Just Above Top of Chimney.

Test Condition F:

10% liquid flow
100% gas volume
rapid burst
release from six fuel subassemblies.

Top edge of chimney is at bottom edge of photograph.
0.42X.

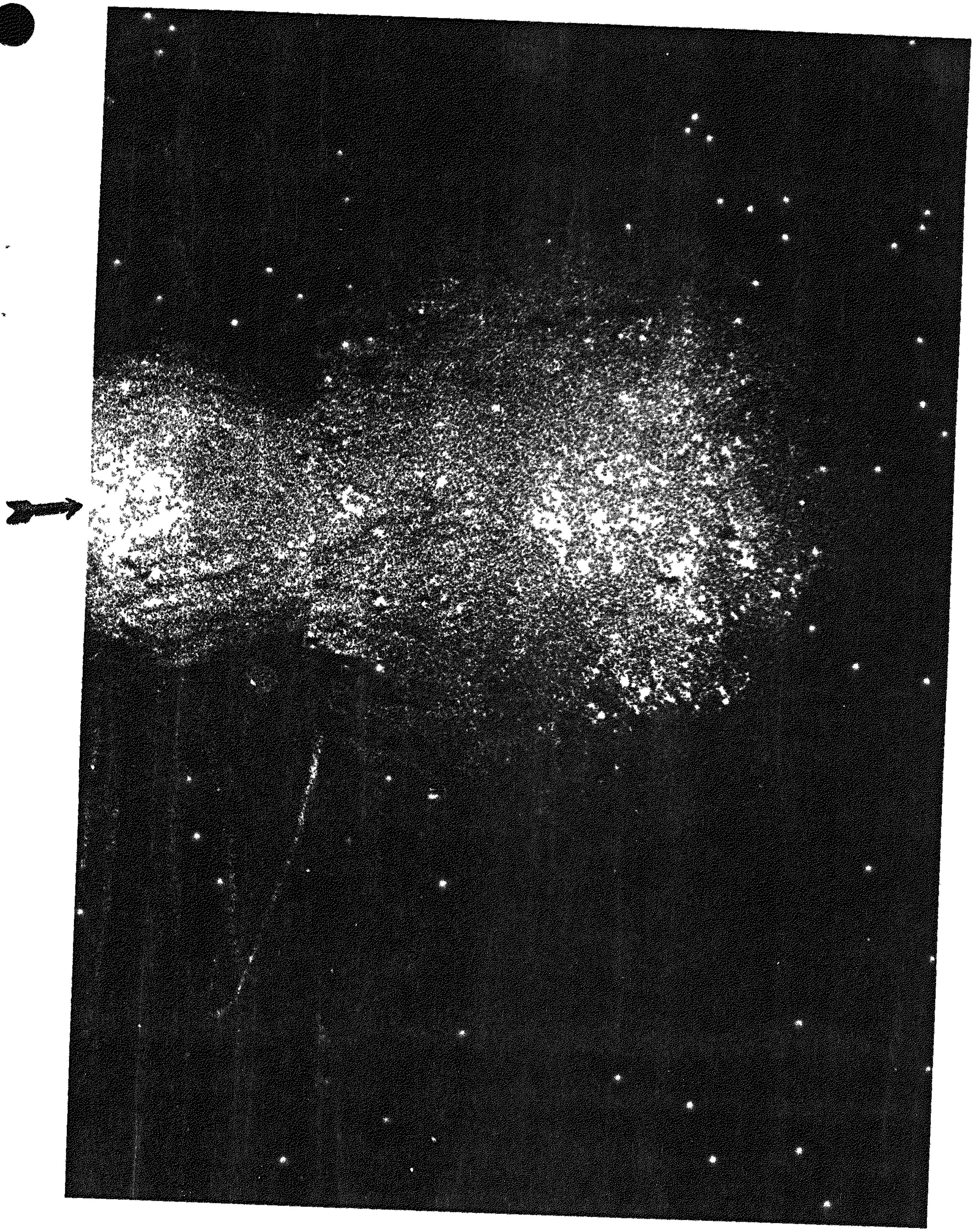

FIGURE 13. Gas Flow in Region Just Above Top of Chimney.

Test Condition G:

50% liquid flow
100% gas volume
rapid burst
release from single fuel subassembly.

Top edge of chimney is at bottom edge of photograph.
0.42X.

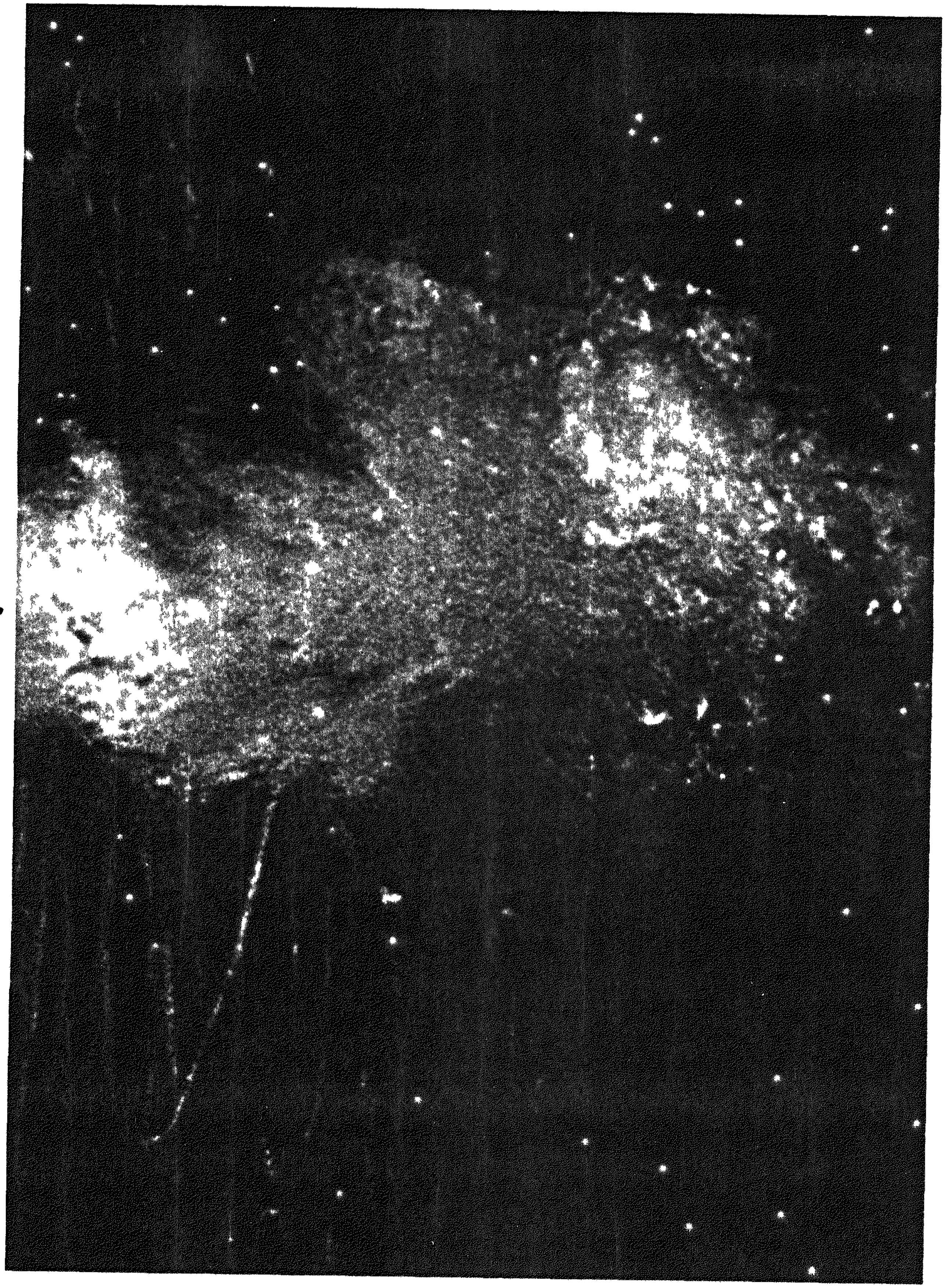

FIGURE 14. Gas Flow in Region Just Above Top of Chimney.

Test Condition H:

50% liquid flow
100% gas volume
rapid burst
release from six fuel subassemblies.

Top edge of chimney is at bottom edge of photograph.
0.42X.

Note relative absence of gas flow pulsations at high water and gas flows.

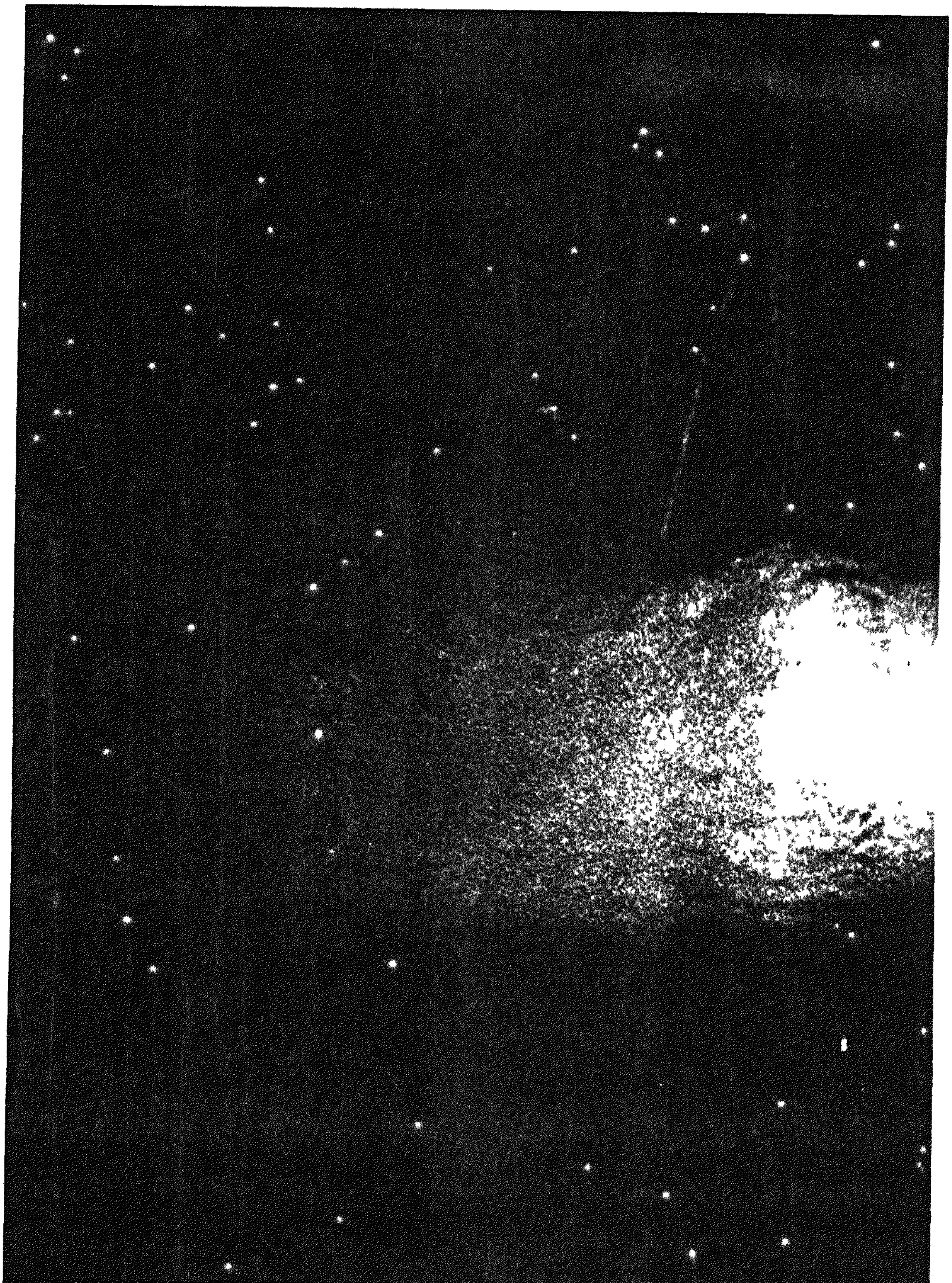

FIGURE 15. Gas Flow at Top of Outlet Plenum Near Suppressor Plate.

Test Condition E:

10% liquid flow
100% gas volume
rapid burst
release from single fuel subassembly.

Photograph taken as initial cloud of bubbles approaches suppressor plate.

0.35X.

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