Part V. An Experimental Study of the Collapse of Fluid Columns on a Rigid Horizontal Plane, in a Medium of Lower, but Comparable, Density
Author(s): J. C. Martin and W. J. Moyce
Source: *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, Vol. 244, No. 882 (Mar. 4, 1952), pp. 325-334
Published by: The Royal Society
Stable URL: http://www.jstor.org/stable/91520
Accessed: 20/10/2008 23:24

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at http://www.jstor.org/page/info/about/policies/terms.jsp. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at http://www.jstor.org/action/showPublisher?publisherCode=rsl.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is a not-for-profit organization founded in 1995 to build trusted digital archives for scholarship. We work with the scholarly community to preserve their work and the materials they rely upon, and to build a common research platform that promotes the discovery and use of these resources. For more information about JSTOR, please contact support@jstor.org.

The Royal Society is collaborating with JSTOR to digitize, preserve and extend access to *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences.*

http://www.jstor.org

PART V. AN EXPERIMENTAL STUDY OF THE COLLAPSE OF FLUID COLUMNS ON A RIGID HORIZONTAL PLANE, IN A MEDIUM OF LOWER, BUT COMPARABLE, DENSITY

By J. C. MARTIN and W. J. MOYCE

[Plates 3 and 4]

CONTENTS

The results of an investigation of collapse of fluid right-circular cylinders in a medium of comparable density are described. Qualitative and quantitative similarities between the surges produced by the collapse of such columns and the base surge observed at Bikini are examined, and by the use of simple scaling laws, an estimate of the quantity of finely divided water in the stem of the column of the Bikini plume is obtained.

1. Introduction

The experiments now to be described were performed in an attempt to reproduce on the laboratory scale the phenomenon of the base surge observed after the second atomic bomb explosion at Bikini. The base surge has been described in the General Introduction. Figure 1, plate 3, shows a photograph taken shortly after the collapse of the main part of the column. On the assumption that the surge was the result of the mass subsidence of a column of an aerosol of sea water, it was decided to study the analogous problem of the collapse of fluid cylinders in a medium of lower density. It is possible that the column of aerosol caused by the explosion of the bomb may not have been uniform. The investigations to be described were, however, confined to the study of the motion of surges produced by the collapse of liquid, homogeneous, right-circular cylinders in a medium of comparable density, and to this extent may not have been exact models of the Bikini base surge. The surges produced by the collapse of such columns nevertheless showed good qualitative agreement with that observed at Bikini. By adopting the simple scaling laws discussed in part IV it was found possible to fit experimental readings with those obtained at Bikini and so provide an estimate of the quantity of finely divided water required in the column to produce a surge whose motion would be similar to that observed. Because of the uncertainty involved in scaling, no great accuracy was attempted and attention was mainly directed to the motion of the surge front, since data on the variation of the radius of the surge with time have been published by the United States Atomic Energy Commission (1950).

2. NOTATION

In addition to those quantities listed in our previous paper as defining the motion of columns *in vacŭo* we now have to include

ρ_1 = density of the collapsing fluid,

ρ_2 = density of the surrounding fluid.

These give rise to an additional non-dimensional parameter defined as

$$\epsilon = (\rho_1 - \rho_2)/\rho_2.$$

We also find it convenient to use

$$V = u/(ga)^{\frac{1}{2}},$$

where u is the radial horizontal velocity of the surge front.

3. METHOD EMPLOYED

In the series of experiments to be described, water was mainly used as the outer medium and was contained in a wooden tank 22 in. cube, the front and back faces of which were made of glass to enable observations to be taken. The tank was filled to a depth of 10 in. with tap water and a cylindrical paper tube, which had been impregnated with paraffin wax to stiffen and waterproof it, rested upright on the bottom of the tank with the bottom edge in a small mercury sump inset into the centre of the floor. This mercury sump acted as a seal, preventing the denser solution placed inside the tube from leaking out over the bottom of the tank. The top of the paper tube was held in a block which could be raised smoothly upwards along the axis of the cylinder. A coloured solution of the required density was fed into the bottom of the tube, displacing the water there until the volume added produced a column of the required height. Most of the paper tube above this level had been cut away in order to minimize its effect on the main flow in the tank in the period during which the tube was being withdrawn upwards. When a column of the required density and height had been produced, the constraining paper tube was pulled smoothly and swiftly upwards, leaving behind the column which subsequently collapsed. This collapse, and the motion of the surge produced, was photographed with a Bolex 16 mm. ciné camera, the speed of which could be altered from 8 to 64 frames per second as required. A clock was included in the field of view to give the time co-ordinate, and a grid was occasionally photographed in position inside the tank to enable space measurements to be made directly, without correction for the optical displacements caused by the water and the glass of the tank.

Series of experiments were performed with tubes of three different radii, namely 2·2, 2·82 and 3·45 cm., using different height-radius ratios and different densities of the liquid forming the column. At first, the heavier solution was prepared by dissolving potassium permanganate in tap water to a known concentration and hence known density difference $\rho_1 - \rho_2$ from the tap water used as the bulk medium in the tank. The potassium permanganate also served to colour the denser solution and so render the column and surge visible. When the density difference was deduced from the concentration of the permanganate, correction was made for the temperature of the water and solution. Potassium

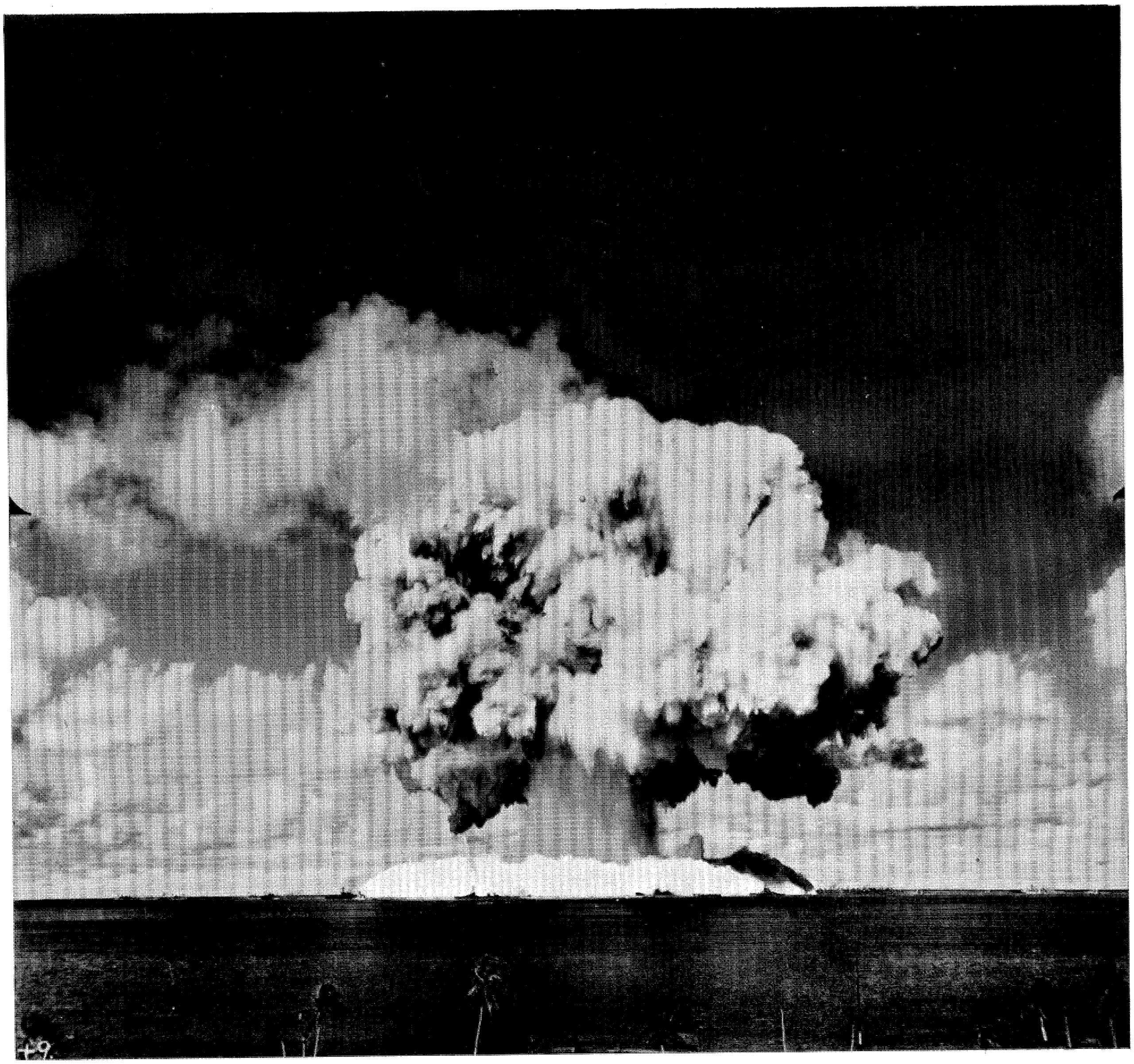

FIGURE 1. The Bikini base surge shortly after collapse of main column. The column seen at the centre of the surge is composed of thin mist which has been drawn down from the cauliflower cloud by the collapse of the main column.

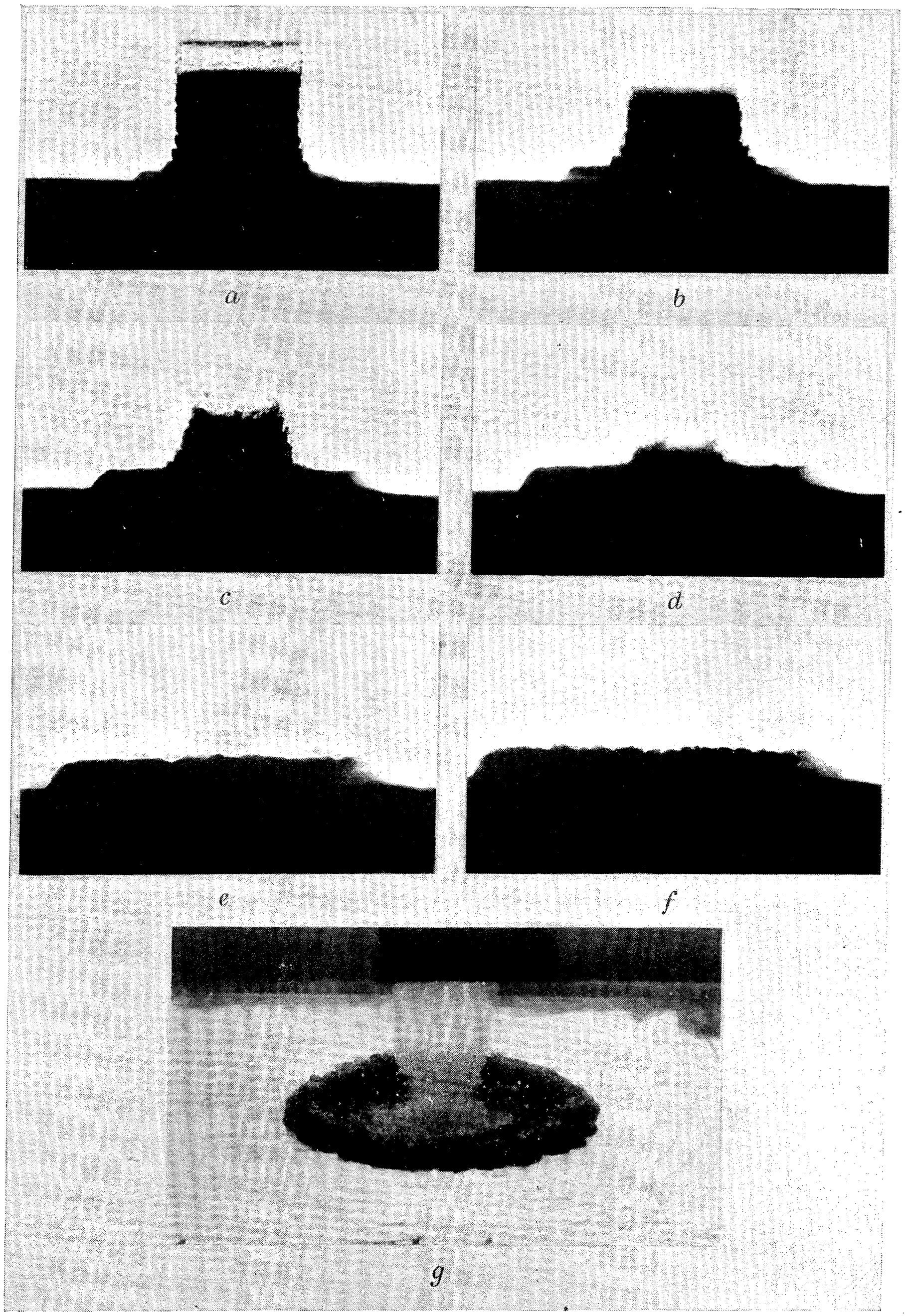

FIGURE 2. Collapse of cylindrical column. $a = 3{\cdot}45$ cm., $n^2 = 2$. *a* to *f*, side view of collapse; *g*, slant view of surge after collapse of column.

permanganate solutions were used to give a range of values $0{\cdot}00014<\rho_1-\rho_2<0{\cdot}04$. Above this range, aqueous solutions containing zinc chloride, a small percentage of hydrochloric acid to prevent hydrolysis, and ink powder to colour were used to give a range $0{\cdot}06<\rho_1-\rho_2<0{\cdot}75$. The densities of these solutions were directly determined and the temperature of the tank water was raised to 20° C before each experiment.

With the densest zinc chloride solutions used, the viscosity had risen appreciably, but not excessively, above that of water. In an attempt to determine if this was having a serious effect on the results obtained, a series of experiments was performed in which water was placed inside the cylinder to form the column, the outer medium being air. As before, the column was rapidly withdrawn and the motion of the surge so produced was recorded. The experiments were then repeated using the densest zinc chloride solution employed, $\rho_1 = 1{\cdot}75$. If the increase of viscosity were having an appreciable effect it would appear as a difference between the readings obtained in the two cases. The two sets of readings were, however, in good agreement, indicating that the increase in viscosity necessitated by the use of dense solutions was not having a considerable effect on the results obtained.

RESULTS

4. Experimental errors

Errors in the readings obtained came mainly from the fact that usually only one diameter of the surge could be measured from the photographs, which were 'side elevations', so that measurements on the fall of the column and the surge height could also be made. The surges produced were in all cases circular at first but in the later stages irregularities appeared, which could have produced errors of 10 to 15 % in the value of the radius measured round the surge. Apart from this expected error there may have been consistent errors involved in the experimental procedure.

These would comprise:

(1) Energy introduced by the raising of the tube.

(2) Increased energy dissipation due to the finite size of the tank.

The raising of the tube would tend to retard the downwards flow of the sides of the column and thus influence the initial outflow of the surge. An estimate of the order of the energy introduced by the lifting of the tube can be obtained by considering the energy dissipated when fluid flows down a length of pipe of the same radius as the tube, with a velocity equal to the maximum rate of lifting of the tube, the length of pipe traversed being considered as equal to the distance of pull-up, i.e. approximately twice the height of the column. Calculation shows that for the values of the densest columns used, the flow down the pipe would be turbulent and that the energy dissipated would be less than 2 % of the original potential energy of the column for the case of the largest tube used ($a = 3{\cdot}45$ cm.). For the smallest tube the energy dissipated might be up to 10 % of the original energy in the column. In the actual experiments, most of the energy is communicated to a thin layer round the boundary of the column drawn up by the sides of the tube, while the main bulk of the column is undisturbed. To check this estimate, a series of experiments was performed, with the tube of largest radius, with different rates of pull-up and with the densest solution used. In the experiments, no systematic variation of the surge velocities could be detected outside the experimental errors, and it is therefore considered likely that, for the experiments using the tube of radius 3·45 cm. at least, the energy introduced can be neglected.

The volume of water in the tank was always at least 400 times that of the column and, as a further precaution, no readings for the surge motion were taken when it was close to the walls of the tank. It is difficult to be sure that these precautions prevented the finite bulk of the water in the tank from influencing the results obtained but no increase in energy dissipation with increasing volume of the column was observed at any time.

5. QUALITATIVE CONSIDERATIONS OF THE COLLAPSE OF A COLUMN

The shape of the collapsing column would be influenced by energy introduced in raising the tube, but for the reasons given above and also because of the fact that in all the experiments with density differences varying over the range $0{\cdot}00014 < \rho_1 - \rho_2 < 0{\cdot}75$ the same sequence of shapes occurred, it seems probable that the fall of an undisturbed column follows a similar shape sequence to that shown in figure 2, plate 4, in which is also shown a general view of the surge shortly after the column has collapsed. It is perhaps of interest to notice that the diameter of the top of the column, in the latest of our photographs in which the column can be seen above the surge, is approximately three-quarters of the initial value. In *The effects of atomic weapons*, p. 104, it is stated that the diameter of the Bikini column of 450 ft. above sea level decreased from 2050 to 1500 ft. between 15 and 33 sec. after the explosion, by which latter time the main column of water droplet laden air had collapsed, leaving only a tenuous mist which had been drawn down behind it.

6. THE SURGE: GENERAL CONSIDERATIONS

The shape of the face and head of the surge can be seen in the photographs of figure 2. During the initial stages the face of the surge slopes back, being slightly concave downwards. Later it develops into a more rounded form, concave upwards, the complete shape of the surge being like that of a half anchor ring expanding out over the bottom of the tank. This shape is very similar to that of the Baker Surge.

When the surge came to rest inside the tank, due to a low value of the initial potential energy in the column, it collapsed upon itself and ended up as a thin washer-like ring. For low values of the energy in the column, the motion of the surge was streamline, the face and head being smooth and undisturbed, but for a non-dimensional velocity $V \simeq 0{\cdot}05$ of the surge front, on the scale of our experiments, the top of the ring became turbulent. For higher values of V, the surge became very turbulent, much mixing taking place at the face and the head of the surge.

7. SPACE-TIME RELATION OF THE SURGE FRONT

A typical Z, τ curve for the motion of a surge from a column of low initial energy is given in figure 3. For this curve, the value of n^2 is 2, ϵ is $0{\cdot}0058$ and a is 3·45 cm. As the maximum V attained is approximately 0·04, the surge in this case is not turbulent. A non-turbulent case has been chosen, as this yields, under the conditions of the experiment, the complete form of the curve, the surge coming to rest before reaching the walls of the tank.

The curve can be roughly divided into three parts.

Part A. During this phase, the surge accelerates from rest, while the column collapses. The height of the surge increases rapidly and, at the end of the phase, is reaching its maximum value. This part of the curve extends to a point of inflexion, after which the surge front retards continuously. Shortly after the point of inflexion, the column has gone.

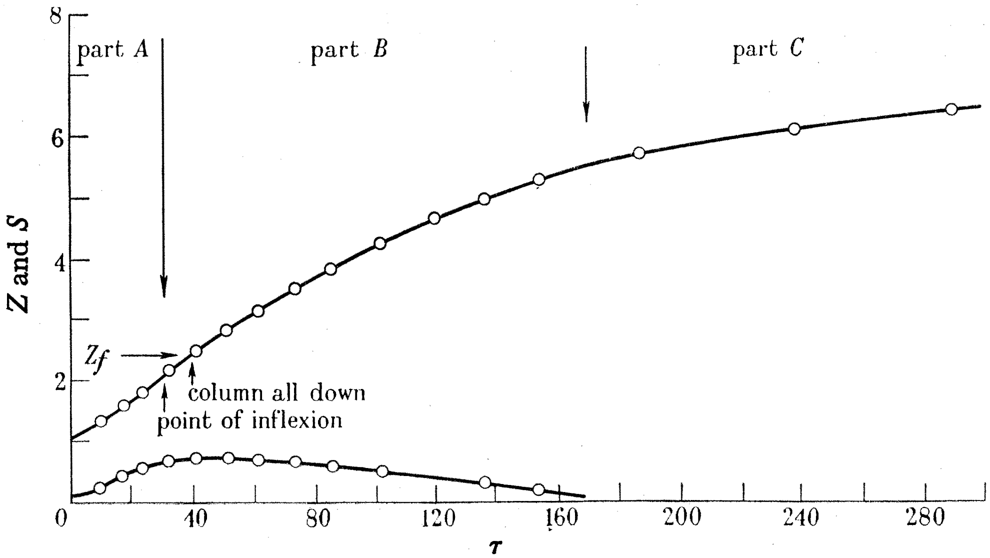

FIGURE 3. Z against τ (upper curve) and S against τ. $n^2 = 2{\cdot}0$; $\epsilon = 0{\cdot}0058$; $a = 3{\cdot}45$ cm. The height of the surge is aS.

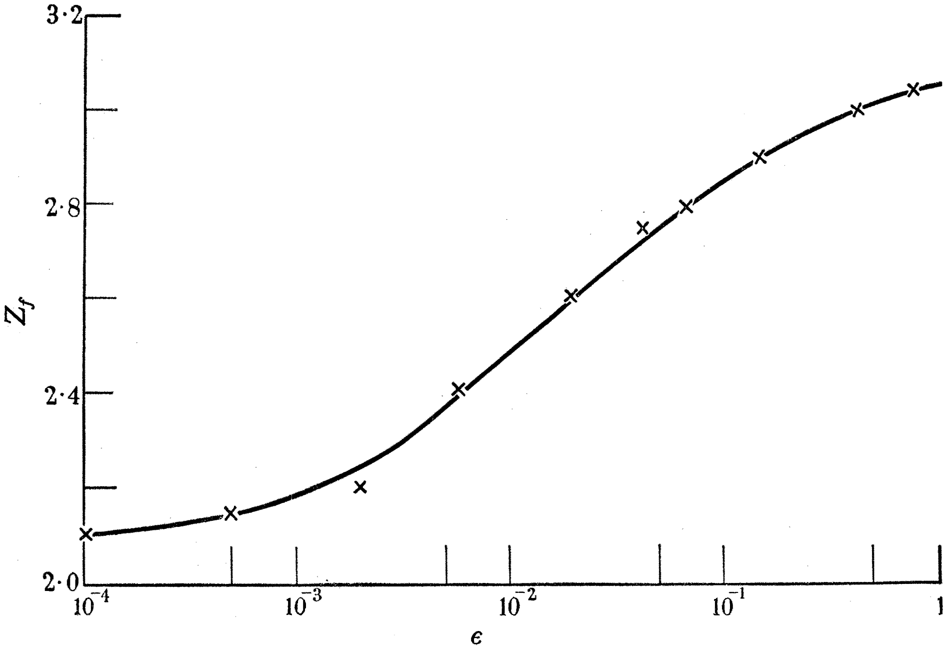

FIGURE 4. Z_f against ϵ.

Part B. Over this portion of the curve, the main energy of motion comes from the initial momentum imparted by the fall of the column, but in the later part of the section a not inconsiderable amount of energy is derived from the collapse of the surge upon itself. Thus the height of the surge, after reaching an early maximum, remains constant for some time and then decreases to a low value at the end of part B of the curve. When this has occurred, there is a fairly sharp discontinuity in the slope of the curve, marking the point where there remains no appreciable amount of potential energy in the surge to be converted into motion.

Part C. This consists of the remainder of the curve where the model-scale surge, now sensibly flattened, reaches a low terminal velocity which persists for some time.

In the case of the Z, τ curves of surges that are turbulent, part C of the curve is usually not recorded, as the surge reaches the walls of the tank early in its development. Also, because of turbulence, the surge reaches a greater height and remains at this height for a longer scaled time.

Dealing in greater detail with the initial stages of development of the surge, the value of Z at which the column vanishes (called Z_f) does not remain constant for varying ϵ. In figure 4, the relation between Z_f and ϵ is shown. As Z_f is not very easy to determine with high accuracy from the photographic records, the plot can only be considered as a rough guide to the general behaviour.

8. HORIZONTAL VELOCITY VERSUS RADIUS: VARIATION WITH DENSITY RATIO PARAMETER

Because of a distortion of the initial motion of the Bikini surge, discussed in § 10 below, it is not possible to compare the Z, τ curves of it and the small scale surges directly. In order to make comparison possible, the non-dimensional velocities $V_{Z=m}$ determined at the points $m = 2, 3, 4$, etc., were obtained from the curves and used to tabulate the experimental results. In table 1 and figure 5 is shown the variation $V_{Z=m}$ with ϵ for constant values of $a = 3{\cdot}45$ cm. and $n^2 = 2$. With the lowest values of ϵ the velocities at $Z = 2$, 3 and 4 only are given, since at higher integral values of Z the surge had either come to rest or was moving with a very small velocity.

TABLE 1. $V_{Z=m}$ AGAINST ϵ FOR $n^2=2$, $a=3{\cdot}45$ CM.

ϵ	$V_{Z=2}$	$V_{Z=3}$	$V_{Z=4}$	$V_{Z=5}$	$V_{Z=6}$	$V_{Z=7}$
0·75	0·37	0·40	0·37	0·32	0·25	0·21
0·48	0·31	0·36	0·32	0·27	0·22	0·18
0·35	0·26	0·29	0·26	0·22	0·18	0·16
0·14	0·18	0·19	0·17	0·14	0·12	0·10
0·074	0·124	0·128	0·116	0·105	0·088	0·074
0·042	0·096	0·100	0·090	0·080	0·060	0·051
0·012	0·047	0·050	0·038	0·029	0·018	0·005
0·0058	0·034	0·032	0·026	0·021	0·012	—
0·0011	0·015	0·012	0·0092	0·0064	—	—
0·0006	0·011	0·010	0·0069	0·0041	—	—
0·0001	0·0062	0·004	0·002	—	—	—

9. HORIZONTAL VELOCITY VERSUS RADIUS: VARIATION WITH HEIGHT-WIDTH RATIO

In table 2 the variation of $V_{Z=m}$ with n^2 is shown for constant $\epsilon = 0{\cdot}75$ for the three values of the radius used. It will be seen that the values of the non-dimensional velocities for the surges from the columns with $a = 2{\cdot}2$ cm. are mostly some 10 to 18 % lower than those corresponding to columns with $a = 3{\cdot}45$ cm. the difference being attributed to energy introduced during the raising of the constraining paper cylinder. The difference between the readings for $a = 2{\cdot}82$ cm. and $a = 3{\cdot}45$ cm. is in general not outside the expected errors in observations.

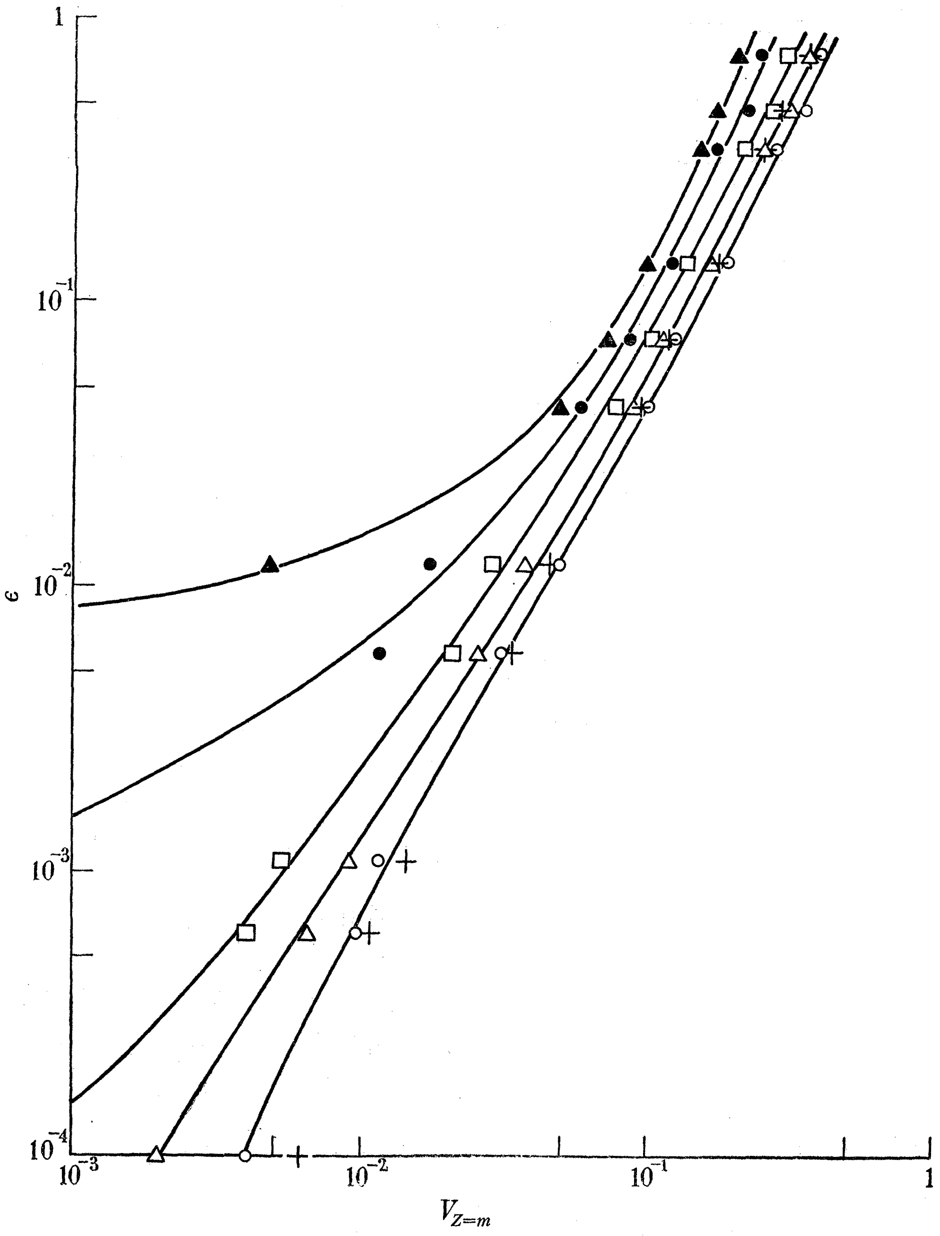

FIGURE 5. $r_{Z=m}$ against ϵ for $n^2 = 2$, $a = 3{\cdot}45$ cm.

+	○	△	□	●	▲
$V_{Z=2}$	$V_{Z=3}$	$V_{Z=4}$	$V_{Z=5}$	$V_{Z=6}$	$V_{Z=7}$

The locus of the points $V_{Z=2}$ is not drawn.

TABLE 2. $V_{Z=m}$ AGAINST n^2 FOR $\epsilon = 0{\cdot}75$

n^2	a (cm.)	$V_{Z=2}$	$V_{Z=3}$	$V_{Z=4}$	$V_{Z=5}$	$V_{Z=6}$	$V_{Z=7}$
1	2·2	0·30	0·32	0·25	0·15	0·07	—
	2·82	0·33	0·34	0·27	0·18	0·08	—
	3·45	0·34	0·35	0·27	0·22	0·13	—
2	2·2	0·32	0·34	0·32	0·30	0·23	0·17
	2·82	0·36	0·37	0·33	0·30	0·25	0·19
	3·45	0·37	0·40	0·37	0·32	0·25	0·21
3	2·2	0·40	0·41	0·39	0·36	0·31	0·26
	2·82	0·40	0·43	0·42	0·38	0·33	0·29
	3·45	0·41	0·44	0·41	0·37	0·32	0·30
4	2·2	0·41	0·44	0·41	0·36	0·33	0·31
	2·82	0·46	0·48	0·44	0·40	0·37	0·34

In figure 6 the values of $V_{Z=m}$ are plotted against n^2 using the readings obtained from the column with $a = 3{\cdot}45$ cm. for the set $n^2 = 1$, 2 and 3 and readings from the column with $a = 2{\cdot}82$ cm. for $n^2 = 4$, experimental reasons making it inadvisable to use columns of $n > 3$ with the largest radius employed.

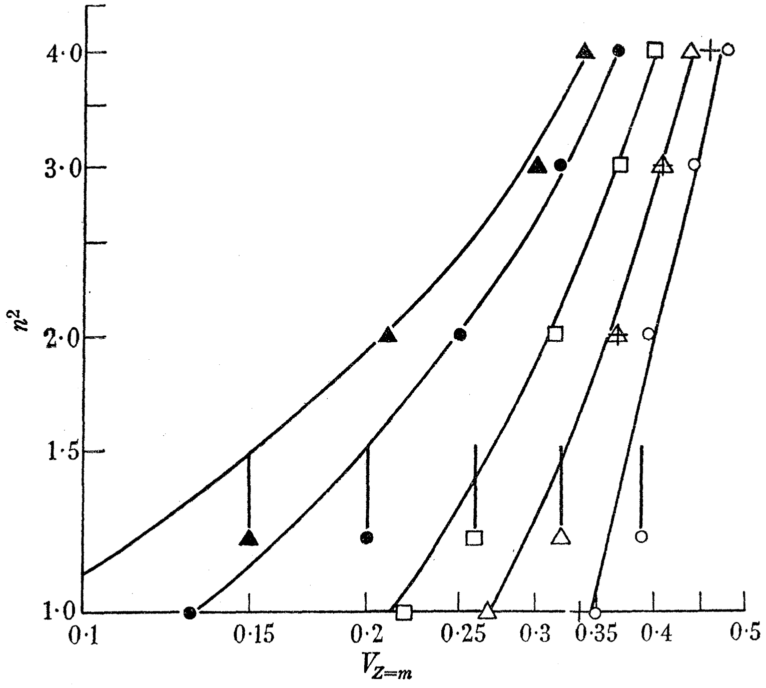

FIGURE 6. n^2 against $V_{Z=m}$. $\epsilon = 0{\cdot}75$; $a = 3{\cdot}45$ cm.

+	○	△	□	●	▲
$V_{Z=2}$	$V_{Z=3}$	$V_{Z=4}$	$V_{Z=5}$	$V_{Z=6}$	$V_{Z=7}$

The locus of the points $V_{Z=2}$ is not drawn. The vertical lines correspond to the values of $V_{Z=m}$ for the Baker surge for $m \geqslant 3$.

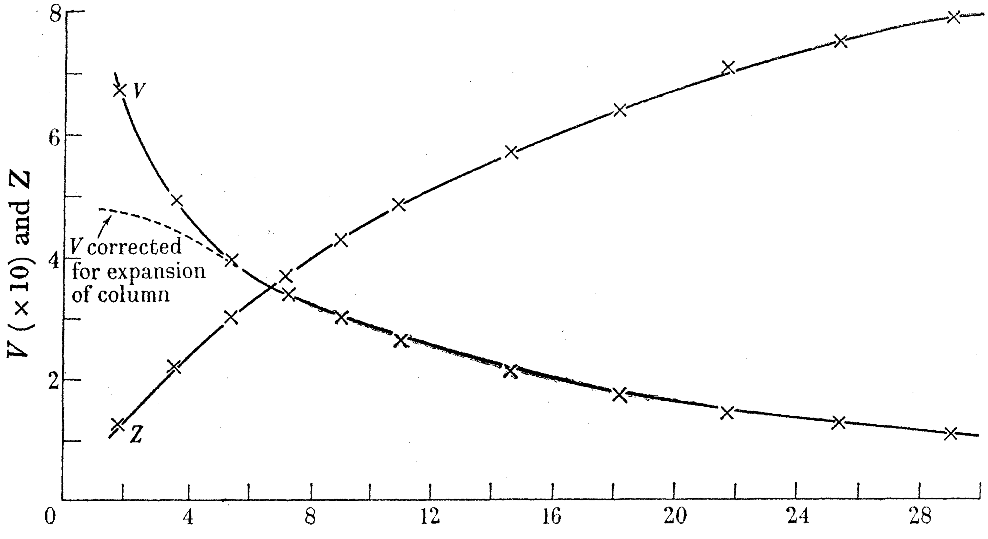

FIGURE 7. V and Z against τ for Baker surge.

10. Comparison of results with Bikini data

Figure 7 shows the Z, τ relation for the surge observed at Bikini. The origin for τ is the instant of detonation and the column started to collapse some 10 to 12 sec. later, i.e. at $\tau = 2{\cdot}0$ approximately. In calculating the non-dimensional co-ordinate, the initial radius of the column is taken as $a = 1000$ ft. Also shown on the same graph is the velocity of the surge front. The initial motion of the surge is unusual since it shows no period of acceleration, as any surge must, which is formed by the undisturbed collapse of a column. Part of the reason for this behaviour of the Bikini surge is that the column itself was expanding during the initial stages although this expansion fairly quickly ceased. An attempt has been made, using newsreel records of the test, to correct for this expansion by taking the motion of the surge relative to the column face, this giving the dotted curve in figure 7. As the speed of the recording camera was unknown and had to be deduced from other measurements, this correction is only approximate. The corrected curve still does not show any initial period of acceleration but careful examination of the newsreel camera records suggests that the initial motion of the very base of the column is an almost impulsive movement outwards, due perhaps to motion of the lip of the bubble cavity, this impulsive movement being overwhelmed later by the build-up of the true surge from the collapsing column. For the above reasons it is thought that the velocity of the surge before it reaches $Z = 2$ or more may not be characteristic of the true motion of a surge formed by the collapse of an initially undisturbed column.

In figure 6 the vertical lines correspond to the values of $V_{Z=m}$ for the Baker surge, for $m \geqslant 3$. It is seen that the agreement between the experimental and Baker readings is good at a value of $n^2 = 1{\cdot}5$. In general the values of $V_{Z=m}$ for any particular ϵ would be above or below those of the Bikini surge, and interpolation of ϵ would be required to make the two sets of results coincide. Such adjustment in our case happens to be unnecessary, because the fortuitous choice of our $\epsilon = 0{\cdot}75$ itself gives a fit. Thus on the scaling assumptions used, a homogeneous column of height 1500 ft. and a density 1·75 times that of the outside air would have produced a surge which would have had a space-time curve similar to that observed at Bikini for $Z \geqslant 3$. This corresponds to a weight of water in such a column, in the form of fine droplets, of 120,000 tons.

In connexion with the time of fall of the column, from figure 4, strictly for columns with $n^2 = 2$ but reasonably accurate for $n^2 = 1{\cdot}5$, it is seen that for $\epsilon = 0{\cdot}75$ the value of Z_f is 3·05. From figure 7 this value of Z corresponds to $\tau = 5{\cdot}6$, which gives the time by which the collapse was complete as 31 sec. after detonation, which is in good agreement with the value in *The effects of atomic weapons* of from 30 to 35 sec.

11. Conclusions

The surges produced by the collapse of fluid cylinders in a medium of comparable density are found to be qualitatively similar to the base surge observed after the second test at Bikini. By the adoption of simple scaling laws it has been found possible to obtain a fit between the motion of a laboratory surge and the base surge except during the early stages of motion. This leads to an estimate of the weight of finely divided water in the column stem of the order of 120,000 tons.

The authors wish to express their gratitude to the Armed Forces Special Weapons Project of the United States of America, who provided the photograph printed as figure 1 and who also gave permission for its publication. They are also indebted to Dr W. G. Penney, F.R.S., for his encouragement of the investigation and to the Chief Scientist, Ministry of Supply for permission to publish this paper.

REFERENCE

United States Atomic Energy Commission 1950 *The effects of atomic weapons.* New York: McGraw Hill.