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OPERATION JANGLE

PROJECT 1(9)b

BASE SURGE ANALYSIS FOR NUCLEAR TESTS

by

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5 JUNE 1952

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ABSTRACT

Base surge and related surface phenomena produced by underground TNT explosions at depths scaled to the JANGLE underground shot are described. Empirical formulas showing the effect of charge weight on column and jet are listed and a method of scaling base surge flow for various charge weights and depths is presented.

The cloud phenomena formed by the JANGLE surface shot are described briefly and compared with TNT results.

Measurements of the base surge, column, jet, and smoke crown produced by the JANGLE underground shot are presented. The data indicate that column size can be predicted on the basis of TNT measurements but that overall cloud heights do not scale because of the thermal energy of the fireball. Froude scaling of the JANGLE base surge data shows a slower rate of growth and a smaller extent than the surges formed by scaled TNT explosions.

A method is presented for predicting the rate of growth and maximum extent of base surges formed by atomic weapons with different energies than the JANGLE one kiloton bomb, but scaled to the same depth.

CHAPTER 1

INTRODUCTION

1.1 RESULTS WITH HIGH EXPLOSIVES

In the Operation JANGLE report on Project 1(9)-4, titled "Base Surge Analysis - HE Tests",[1] data were summarized on the behavior of the base surge and related surface phenomena produced by underground TNT explosions in three types of soil at Dugway, Utah in 1951 and by similar underground explosions in the Operation JANGLE HE Tests. Combining the two sets of results gave a total range of charge weight from 216 to 320,000 lb. For comparison of charges of different weights, a scaled depth, λ_c, was used:

$$\lambda_c = \frac{d}{W^{1/3}} \qquad (1.1)$$

where d = depth to center of charge, ft
W = weight of charge, lb (TNT)

The base surge radial growth curves presented for high explosives showed that dry sand is the most favorable of the three Dugway soil types for the formation of a base surge and wet clay the least favorable, with dry clay intermediate in effectiveness. The results at the Dugway dry clay site were generally similar to the HE results obtained at the Frenchman Flat and Yucca Flat sites.

1.1.1 Description of Surface Phenomena

Three TNT rounds at Nevada were fired at scaled depths similar to the JANGLE underground nuclear shot: Round HE-1, 2560 lb at λ_c = 0.147 ft/lb$^{1/3}$; Round HE-2, 40,000 lb at λ_c = 0.135 ft/lb$^{1/3}$; and Round HE-9a, 216 lb at λ_c = 0.139 ft/lb$^{1/3}$. These rounds were all fired with the top of the charge tangent to the ground surface; the differences in λ_c are due to differences in charge shape.

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[1] G. A. Young, Base Surge Analysis - HE Tests, Operation JANGLE Project 1(9)-4, U. S. Naval Ordnance Laboratory, 20 May 1952.

At these scaled depths, the earth bulges upward at detonation and appears to explode radially into a roughly crown-shaped cloud of smoke and dust. A hollow conical column of earth, initially much smaller in diameter at the base than at the top, forms beneath the cloud and grows rapidly in height and width, becoming approximately cylindrical in shape. At about the same time, a broad jet appears at the center of the smoke crown, rising at a high velocity and expanding horizontally.

The column settles and a shallow surge cloud appears at its base, while the jet cloud continues to rise and expand. The assumption is made that the base surge is produced by the bulk subsidence of a suspension of soil particles in air, constituting the column, which falls at a rate considerably greater than the rate of fall of individual particles and flows outward along the ground. At this relatively shallow charge depth the base surge is tenuous and moves slowly. In the Nevada tests its initial formation was often obscured by radial throwout of earth clods and the lifting of a layer of surface dust by the passage of the shock wave in air.

The jet continues to rise because of its buoyancy and is gradually diluted by the surrounding air until it becomes an irregular diffuse cloud. Probably the lower portions of the jet and smoke crown flow downward and add material to the base surge, but this contribution is relatively slight at these depths.

The rate of radial growth of the base surge gradually decreases and the surge eventually rises in the form of a circular cloud which is difficult to distinguish from the remains of the jet and smoke crown. The entire diffuse cloud mass is transported by the wind and is dispersed by atmospheric turbulence.

Relatively shallow explosions, such as these, are not favorable for the formation of a large base surge. The optimum condition was attained at a scaled depth of about 1.0 ft/lb$^{1/3}$.

1.1.2 Formulas Obtained from High Explosive Data

Empirical formulas for the maximum dimensions of portions of the surface phenomena produced in the Dugway dry clay and in the Nevada soil were obtained in the study of high explosive results. Those pertinent to the JANGLE underground test are the following:

$$D_{max} = 8.38\ W^{0.304} \quad (\lambda_c = 0.135\ ft/lb^{1/3}) \qquad (1.2)$$

$$C_{max} = 5.71\ W^{0.304} \quad (\lambda_c = 0.135\ ft/lb^{1/3}) \qquad (1.3)$$

$$J_{max} = 116\ W^{0.224} \quad (\lambda_c = 0.512\ ft/lb^{1/3}) \qquad (1.4)$$

where
D_{max} = maximum column diameter, ft
C_{max} = maximum column height, ft
J_{max} = maximum jet height, ft
W = charge weight, lb (TNT)

Maximum column diameter (D_{max}) is defined as the greatest horizontal extent of the base of the column. The measurement is made before the column loses its relatively smooth appearance and radial throw-out appears. Column height (C) is measured to the base of the smoke crown. The maximum value (C_{max}) is used for scaling, assuming that any part of the column extending into the smoke crown can be neglected. Maximum jet height (J_{max}) is defined as the limit of the buoyant rise of the jet. The jet cloud that remains may subsequently rise or fall, depending upon atmospheric conditions. Formula 1.4 may be used at scaled depths between zero and 0.6 ft/lb$^{1/3}$ with a 15% possible error.

1.1.3 Froude Scaling of Base Surge Radial Growth

The radial growth measurements of the base surges from TNT charges in dry clay at Dugway and at the Nevada Test Sites were reduced according to Froude scaling with the following parameters:

$$r = \frac{R}{D_{max}} \qquad (1.5)$$

$$\tau' = \frac{t\,(C_{max})^{1/2}}{D_{max}} \qquad (1.6)$$

where
r = scaled surge radius (dimensionless)
R = surge radius, ft
D_{max} = maximum column diameter, ft
τ' = scaled time, sec/ft$^{1/2}$
t = time, sec
C_{max} = maximum column height, ft

When scaled in this manner, measurements of the radial growth of the base surge formed by explosions at the same scaled depth fell on the same curve. As agreement could be obtained only if complete geometrical similarity existed between the columns formed by charges of different weights fired at the same scaled depth, the ratio of the diameter of the hollow core of the earth column to the outer column diameter (D_c/D) must be the same when the values of λ_c are equal.

Column cores have not been measured directly, but by assuming that the diameter of the true crater is equal to the diameter of the jet at the ground, and that the jet fills the entire core, estimates of D_c/D were obtained at different scaled depths.

Liquid model results were available with a wide range of column height, column diameter, column density, and core diameter. The simulated base surges formed by the collapse of the liquid model column had been measured and were scaled with r, as defined herein, and a more generalized Froude scaling parameter for reducing values of time:[2]

$$\tau^* = \frac{t\,(\sigma\, C_{max})^{1/2}}{D_{max}} \qquad (1.7)$$

where τ^* = scaled time, sec/ft$^{1/2}$

$\sigma = \frac{\rho - \rho_0}{\rho}$ (dimensionless)

ρ = density of moving fluid

ρ_0 = density of ambient fluid

Combining 1.6 and 1.7 gives the following expression:

$$\tau^* = \sigma^{1/2}\ \tau' \qquad (1.8)$$

Using the estimated values of D_c/D, the scaled growth curves for base surges produced by underground explosions were compared with scaled results for the simulated base surges formed by liquid models with the same ratio of core to outer column diameter. As the ratio of column to atmospheric density was unknown for the earth columns,

[2] A. B. Arons, G. A. Young, and M. L. Milligan, Further Investigation of the Base Surge, Interim Report No. 3 of NOL Project 152, NAVORD Report 2144, 1 June 1951, pp 1-8.

τ' values were multiplied by various assumed values of $\sigma^{1/2}$ and re-plotted against r to obtain a series of r vs τ^* curves for direct comparison. When consistent agreement was obtained between curves from the liquid model and prototype, it was assumed that the ratio of the bulk density in the earth column to atmospheric density was the same as the ratio of column to ambient density in the liquid model.

This procedure proved to be adequate at a scaled depth of about 0.5 ft/lb$^{1/3}$ and a density ratio of 1.9 was obtained. It was therefore possible to estimate the weight of soil in the earth column which contributed to the formation of the base surge.

The method could not be used successfully for very shallow and very deep explosions. It failed for a scaled depth of 0.135 ft/lb$^{1/3}$ because the slope of the assumed r vs τ^* curves was considerably less than the slope of liquid model r vs τ^* curves with the same D_c/D ratio and similar density ratios.

Physically, this would indicate that frictional drag becomes important at an early stage, retarding the radial growth of the base surge. The relatively slow growth of the base surge and its tenuous appearance at a scaled depth of 0.135 ft/lb$^{1/3}$ indicate that the bulk density of the column and surge is low. The ratio of column to atmospheric density is almost certainly less than the ratio at a scaled depth of 0.5 ft/lb$^{1/3}$, which was estimated to be 1.9.

A second factor contributing to the slow rate of surge growth is the relatively small contribution of the jet and smoke crown to the base surge. At scaled depths of 0.5 ft/lb$^{1/3}$, and at greater depths, virtually all of the jet and smoke crown drop and flow outward into the base surge, adding considerable material and energy. At a scaled depth of 0.135 ft/lb$^{1/3}$ almost all of the smoke crown and jet remain airborne.

1.2 SOURCES OF DATA FOR NUCLEAR TESTS

Ground-level photographic records of the Operation JANGLE surface and underground nuclear shots were analyzed by the Data Reduction Unit of the Sandia Corporation, Albuquerque, New Mexico.[3] Measurements of the height of the base and top of the cloud produced by the surface shot as a function of time are reproduced herein. The following Sandia

[3] J. J. Miller, Photographic Analysis, Operation JANGLE Project 4.1a, Sandia Corporation, 26 March 1952.

data from the underground shot are also used in this report: overall height and diameter of the cloud vs time, and height and diameter of the base surge vs time; these measurements were limited to one camera station.

Measurements of the crosswind radial growth of the base surge from the underground shot, obtained from aerial photographs, were provided by Cpl. Alvin A. Krum of the Radiological Division, Army Chemical Center, Md.

CHAPTER 2

SURFACE SHOT

2.1 DESCRIPTION OF SURFACE PHENOMENA

The visible surface phenomena produced by the JANGLE atomic explosion on the ground can be separated into three distinct parts: the rapidly rising fireball, a large irregular dust cloud which rose beneath it, and a vertical pillar of ascending air and soil particles, which flowed from the ground surface into the irregular dust cloud. As the expanding fireball cooled, it formed a white cloud which merged with the dust cloud to form an elongated diffuse mass. Its subsequent behavior was determined by atmospheric conditions.

Considerable surface dust was raised by the passage of the shock wave. The thermal current created by the ascending ball of fire formed the rising pillar of air and soil, which had a diameter of about 400 ft. The main cloud mass continued to rise because of its buoyancy, and attained a maximum height of about 6400 ft.

The Sandia measurements of overall cloud height and height of the cloud base as functions of time are presented in Fig. 2.1. Smoothed curves are given, as the data points from cameras at Stations 1 and 2 show some scatter.

No downward density flow was observed and no base surge was formed.

2.2 COMPARISON WITH HIGH EXPLOSIVE TEST

One surface high explosive test record is available for comparison: Round HE-4 at Nevada,[1] a 2560 lb TNT charge fired on the ground (scaled depth, λ_c = -0.149 ft/lb$^{1/3}$). The surface phenomena were similar, except for the absence of a fireball. An irregular particulate cloud formed and rose into the air, while a narrow current of air and dust ascended beneath it, flowing from the ground surface into the base of the upper cloud. No base surge was formed.

[1] G. A. Young, Base Surge Analysis - HE Tests, Operation JANGLE Project 1(9)-4, U. S. Naval Ordnance Laboratory, 20 May 1952.

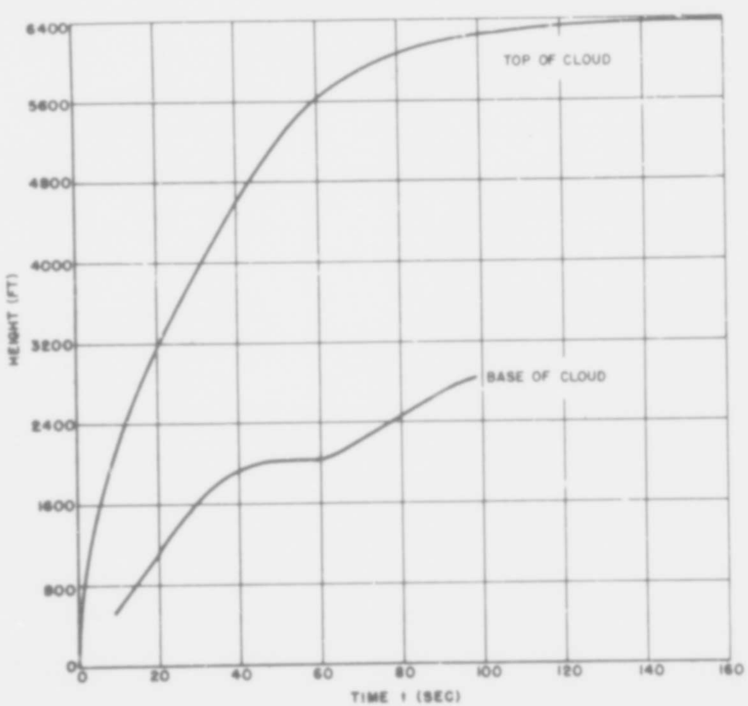

Fig. 2.1 Height of Top and Base of Cloud vs Time - Surface Shot

CHAPTER 3

UNDERGROUND SHOT

3.1 MEASUREMENT OF SURFACE PHENOMENA

In general, the surface phenomena produced by the JANGLE underground shot were similar in appearance to the surface effects from TNT explosions at the same scaled depth (λ_c), except for the emergence of the fireball after the nuclear explosion.

The smoke crown formed at the initial breakthrough was irregular and of great lateral extent, with several jet-like "arms" which grew radially for a long period.

The earth column beneath the smoke crown was similar to those formed by shallow TNT explosions, reaching a maximum diameter of 660 ft at its base prior to the appearance of radial throwout. Maximum column height, measured to the base of the smoke crown, was 420 ft.

The rounded top of a broad irregular central jet rose above the top of the expanding smoke crown at about 18 seconds. A plot of overall height vs time is presented in Fig. 3.1, the first part of the curve representing the rising smoke crown. The jet expanded and merged with the smoke crown to form an irregular "cauliflower" cloud. Initially, the diameter of the cauliflower cloud increased at a greater rate than its height. (See Fig. 3.2.)

While the jet rose, radial throwout was observed, giving a spikey appearance to the column. The material in the column then fell, and a surge cloud appeared at the base. The initial growth of the base surge was obscured by dust trails from the radial throwout and by a layer of surface dust which rose to about 200 ft after the passage of the shock wave.

Sandia measurements of the cauliflower cloud diameter and surge diameter as functions of time are presented in Fig. 3.2. These measurements were obtained from Camera Station 2 (15,000 ft, S 20° W from ground zero). The surface wind at the time was from the south at 5 mph. As the measurements from different camera records do not coincide, mean curves are given. The Sandia measurements, however, extend only for 76 seconds and are subject to some doubt due to dust obscuration. Measurements of the crosswind radial growth of the base surge, obtained from aerial photographs at the Army Chemical Center, are reproduced in Fig. 3.3. The outline of the base surge was clearly visible from the air,

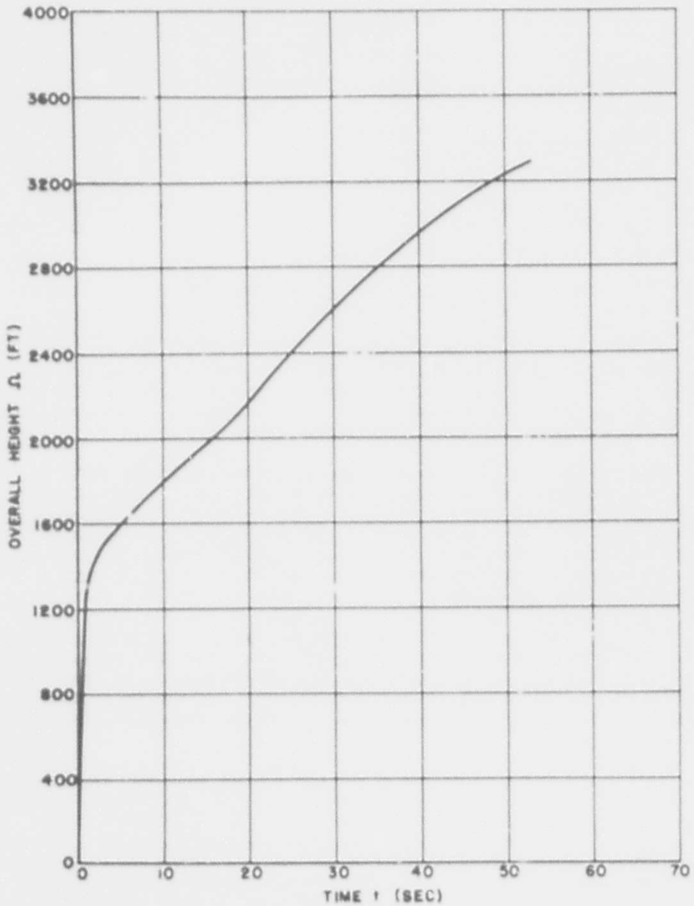

Fig. 3.1 Overall Height vs Time - Underground Shot

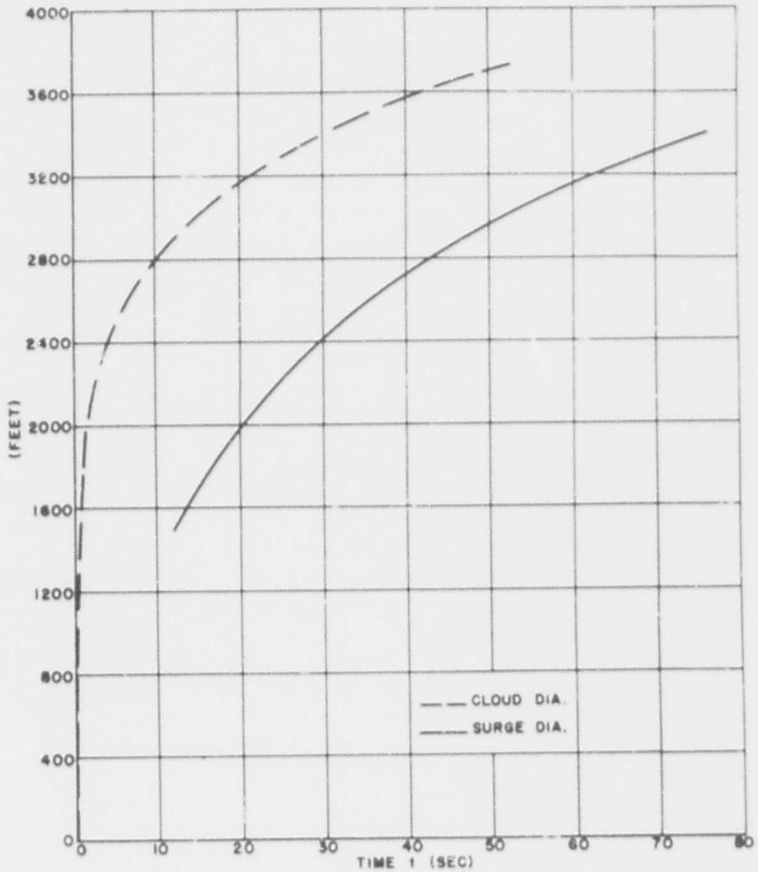

Fig. 3.2 Cloud and Base Surge Diameters vs Time from Camera Station 2 - Underground Shot

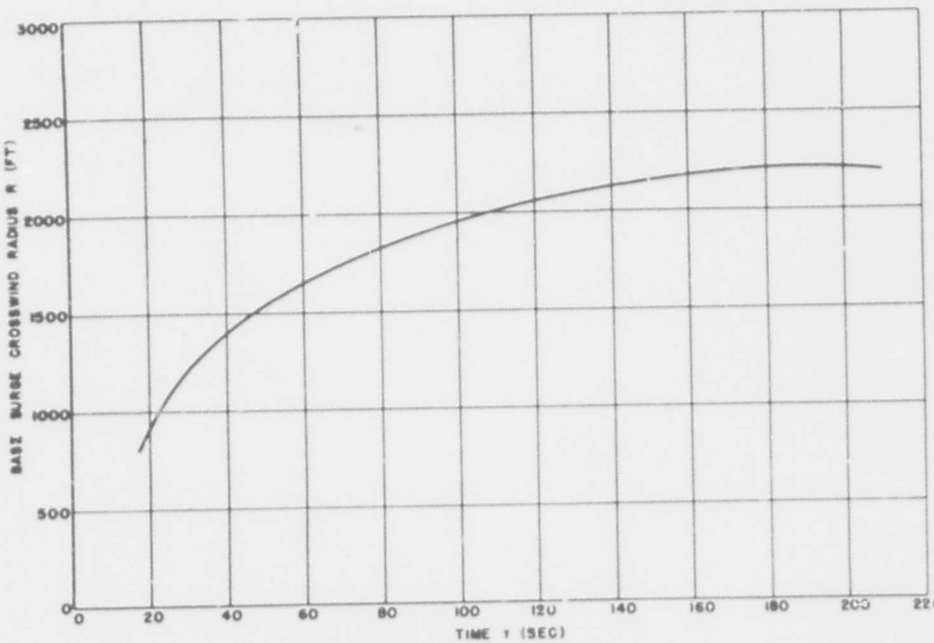

Fig. 3.3 Base Surge Crosswind Radius vs Time from Aerial Photographs - Underground Shot

and these measurements show that the base surge attained a maximum crosswind radius of about 2200 ft 3 minutes after detonation. Sandia surge height measurements from Camera Station 2 are given in Fig. 3.4.

Considerable fall-out from the cauliflower cloud into the base surge was observed. After 180 seconds, when radial growth of the surge had ceased, large quantities of material continued to fall into the surge, increasing the surge height but having little effect on surge diameter.

The upper part of the cauliflower cloud continued its buoyant rise until more than 200 seconds after zero time, reaching a height of about 5000 ft. It retained distinct outlines even after the lower part, containing the original smoke crown, became diffuse and started to settle. Surge height increased continually, due to mixing with the surrounding air. After about 10 minutes the surge and the remains of the smoke crown merged to form a roughly cylindrical diffuse cloud mass beneath the cauliflower cloud, which was rapidly distorted by the upper wind.

3.2 SCALING OF SURFACE PHENOMENA

3.2.1 Column and Jet

In order to test the applicability of the empirical formulas given in Chap. 1 to the results of underground atomic explosions, the maximum dimensions of the column and jet that would be produced by the explosion of one kiloton of TNT at a 17 ft depth in the soil at the Nevada Test Site have been computed. These estimates are compared with the NOL measurements of the JANGLE underground shot in Table 3.1.

TABLE 3.1

Computed and Observed Dimensions of Column and Jet
JANGLE Underground Shot

	Computed from TNT data (ft)	Measured at NOL (ft)	Percentage Difference (%)
Max Col. Diameter (D_{max})	690	660	4.54
Max Col. Height (C_{max})	470	420	11.9
Max Jet Height (J_{max})	2990	5000	40.2

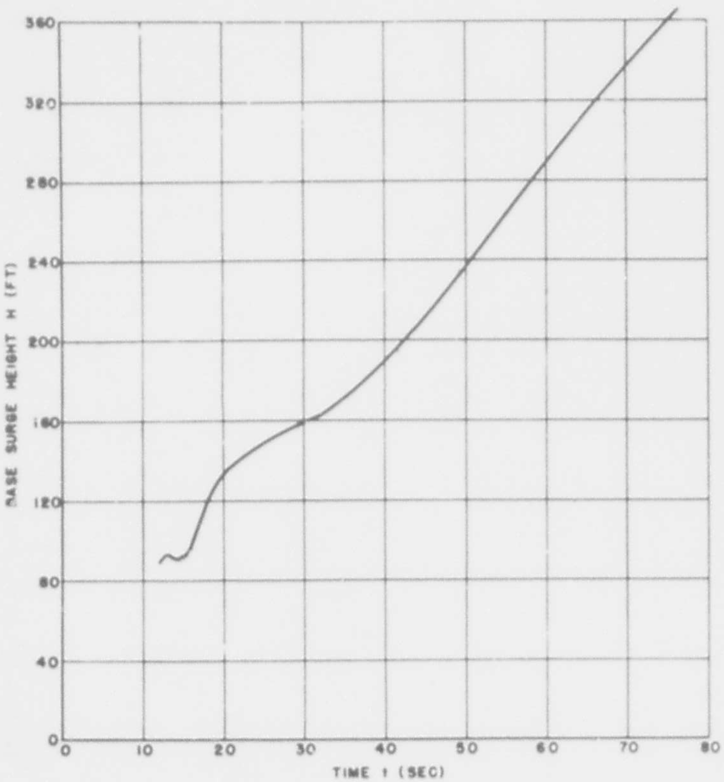

Fig. 3.4 Base Surge Height vs Time from Camera Station 2 - Underground Shot

The agreement between computed and observed values of D_{max} is good. As the scatter in measurements of column height is generally greater than in measurements of column diameter,[1] the agreement between the computed and observed values of C_{max} can also be considered reasonably good. The greater observed jet height is due to the high temperature attained in the atomic explosion, and the consequent greater buoyancy of the jet.

In the study of HE results, the assumption was made that the rising and expanding jet pushes the earth column outward into the form of a hollow, approximately vertical cylinder and that the true crater diameter is equal to the jet diameter within the column. On this basis an average ratio of core to outer column diameter (D_c/D) of 0.46 was obtained for high explosive charges at a scaled depth of 0.137 ft/lb$^{1/3}$.

The diameter of the true crater formed by the JANGLE underground shot is unknown, but the apparent crater diameter at ground level was 280 ft. As the true crater would be somewhat larger, the ratio of core to outer column diameter is estimated as a value greater than 0.42.

From this it appears that the earth columns formed by underground atomic explosions are geometrically similar to the columns formed by TNT explosions with the equivalent energy at the same depths in the same type of soil. Therefore, column size can be predicted by extrapolating the results of experiments with TNT.

The jet produced by an underground atomic explosion rises higher than the jet formed by an equivalent TNT charge, due to the larger proportion of energy emitted as heat at the time of the explosion and the consequent greater buoyancy of the jet cloud. This thermal effect can not be reproduced with conventional high explosives.

3.2.2 Base Surge

The Army Chemical Center radial surge growth data, reduced according to Froude scaling parameters, is shown in Fig. 3.5, superimposed upon scaled curves for TNT charges fired in similar soil at scaled depths ranging from zero to 2.05 ft/lb$^{1/3}$. The initial part of the scaled JANGLE underground shot curve is similar to the curve for

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[1] G. A. Young, Base Surge Analysis - HE Tests, Operation JANGLE Project 1(9)-4, U. S. Naval Ordnance Laboratory, 20 May 1952.

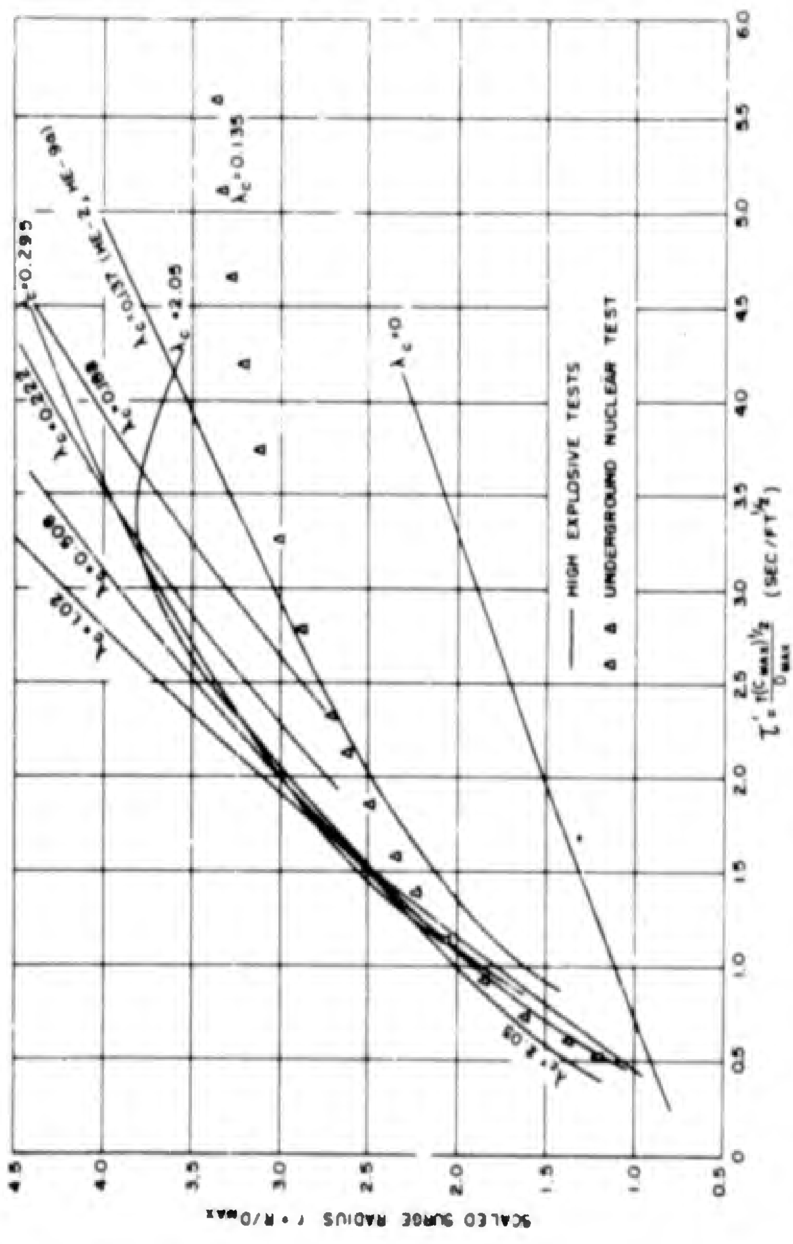

Fig. 3.5 Scaled Radial Growth of Base Surge from TNT Explosions at Different Scaled Depths

high explosives at a scaled depth of 0.508 ft/lb$^{1/3}$. However, the slope of the JANGLE curve decreases rapidly and the growth levels off at a scaled radius of 3.36.

TNT rounds at scaled depths ranging from zero to 1.02 ft/lb$^{1/3}$ did not produce base surges that behaved similarly. The surge clouds continued to grow in extent, first due to gravity flow and then as a result of eddy diffusion, until their limits could no longer be determined visually.

The initially rapid rate of radial growth of the base surge from the JANGLE underground shot indicates the possibility that the column density may be somewhat greater than the density of columns produced by TNT charges at the same scaled depth, though the column size can be scaled to TNT results. The similarity of the JANGLE curve to the HE curve for a λ_c of 0.508 ft/lb$^{1/3}$ is evidence that the ratio of the bulk density of the column to ambient density may also be about 1.9.

Making use of the observed values of column height and diameter, and assuming a cylindrical shape and a 304 ft diameter hollow core ($D_c/D = 0.46$), a volume of 113,000,000 cu ft is obtained for the column. The surface weather observation at the test site at 1200 PST, 29 Nov. 1951, indicates an atmospheric density of 0.0651 lb/cu ft. The bulk density of the column would therefore be 0.124 lb/cu ft. On this basis, the estimate can be made that the base surge was produced by 3310 tons of finely divided falling soil in the walls of the column. This result should be considered very approximate, because of the many assumptions that were necessary in the application of the scaling technique.

The leveling of the surge radial growth curve is partly due to the absence of any observable contribution of the jet material to the surge cloud. Because of its great heat, the jet cloud rose and expanded rapidly, remaining airborne and not falling into the surge.

3.3 PREDICTED SURGE RADIAL GROWTH FOR NUCLEAR EXPLOSIONS SCALED TO JANGLE

The success of Froude scaling for the comparison of surge flow from high explosives of different weights fired at the same scaled depth indicates that it would be reasonable to assume that atomic weapons with different energy yields, when fired at a scaled depth of 0.135 ft/lb$^{1/3}$, would produce base surges whose radial growth can be scaled with the same parameters. Data from explosions of different size, reduced in the form of r and τ', should lie on the same curve if this assumption is valid. It is therefore possible to derive an expression for maximum surge radius as a function of equivalent charge weight for nuclear explosions at a scaled depth of 0.135 $ft/lb^{1/3}$ in the Nevada soil. Combining equations 1.2 and 1.5 and using the scaled maximum radius of 3.36 shown in Fig. 3.5 gives the following result:

$$R_{max} = 28.2\ W^{0.304} \quad (\lambda_c = 0.135\ ft/lb^{1/3}) \qquad (3.1)$$

where R_{max} = maximum surge radius, ft
W = charge weight, lb (TNT)

In a similar way, it is possible to combine equations 1.2, 1.3, 1.5, and 1.6, thereby deriving the following expressions:

$$R = 8.38\ r\ W^{0.304} \quad (\lambda_c = 0.135\ ft/lb^{1/3}) \qquad (3.2)$$

$$t = 3.51\ \tau' W^{0.152} \quad (\lambda_c = 0.135\ ft/lb^{1/3}) \qquad (3.3)$$

where R = surge radius, ft
r = scaled surge radius (dimensionless)
W = charge weight, lb (TNT)
t = time, sec
τ' = scaled time, $sec/ft^{1/2}$

By substituting equivalent weights of TNT in formulas 3.2 and 3.3, and using the values of r and τ' obtained in measurements of the JANGLE underground shot, it is possible to obtain a predicted curve for radial base surge growth for atomic bombs of different energy release at a scaled depth of 0.135 $ft/lb^{1/3}$. Curves derived in this manner for energy equivalents of 10, 20, 50 and 100 kilotons of TNT are presented in Fig. 3.6.

For convenience, r and τ' values for the JANGLE underground shot are listed in Table 3.2.

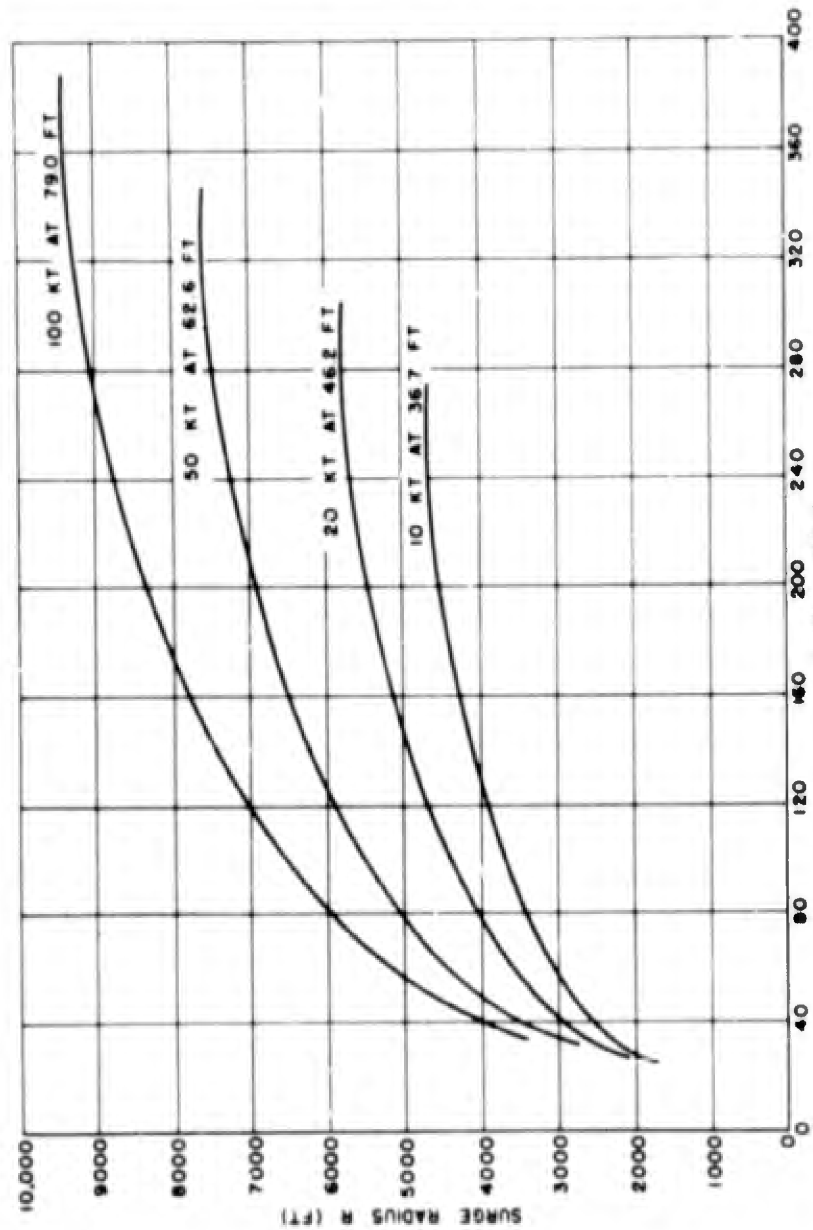

Fig. 3.6 Predicted Radial Growth of Base Surge for Atomic Weapons at a Scaled Depth of 0.135 Ft/Lb$^{1/3}$

TABLE 3.2

Base Surge Scaled Radius-Time Data
JANGLE Underground Shot

Scaled Surge Radius (r)	Scaled Time (τ')	Scaled Surge Radius (r)	Scaled Time (τ')
1.21	0.528	2.72	2.33
1.37	0.622	2.88	2.79
1.61	0.742	3.01	3.26
1.85	0.935	3.12	3.73
2.07	1.15	3.21	4.19
2.24	1.40	3.28	4.66
2.35	1.58	3.33	5.12
2.50	1.87	3.36	5.59
2.63	2.14	3.36	6.05

It is important to emphasize that the numerical results presented herein apply only to nuclear weapons fired at a scaled depth of 0.135 $ft/lb^{1/3}$ in a soil similar to the Nevada Test Site soil. Results with TNT indicate that the largest, most rapidly-spreading surge clouds are formed by explosions at a scaled depth of about 1.0 $ft/lb^{1/3}$. The data also show that a base surge produced by an explosion in dry sand is larger and grows faster than the base surge produced by an equivalent explosion in the Nevada soil. The limited information available indicates that soils with low seismic velocities have the physical characteristics best suited for the formation of a base surge.

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