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EXCAVATION OF CONTAINED TNT EXPLOSIONS IN TUFF

Nicholas M. Short

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SUMMARY

The effects of two contained H.E. explosions in volcanic tuff were examined by mining directly into the explosion sites. One explosion (516 lb of TNT) increased its initial shot chamber volume of about 9 cu ft by a factor of about 5 and produced in addition some 126 cu ft of broken rock. Around this explosion, only natural joints in one direction were filled with carbon to a maximum distance of 42 ft, and no new fractures in other directions were developed. The other explosion (973 lb of TNT) expanded its 17 cu ft chamber to 10 times this initial volume and led to rock breakage, mostly by subsequent roof collapse, of 345 cu ft. Because this shot vented on firing, very little of the carbon-carrying gases entered joints, and fractures caused by the explosion are almost absent. The features characteristic of these two explosions are compared to an earlier 1000-lb explosion in salt in which, by contrast, numerous radial carbon-filled cracks were produced, and the less expanded chambers survived without collapse. For the explosions in tuff it is concluded that 1) joints exercised a primary role in locating the surfaces of fracture failure, 2) early venting inhibits development of carbon-marked fractures, and 3) the medium undergoes greater expansion and more readily collapses after the shot than does salt.

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Fracturing and related phenomena produced by two explosions in bedded volcanic tuff within the Rainier mesa at the Atomic Energy Commission's Nevada Test Site were studied in detail by mining directly into the detonation chambers and surrounding rock about each explosion. This study was a part of a program sponsored by the Plowshare group at Lawrence Radiation Laboratory, designed to further the definition of fracture geometry and the understanding of mechanisms of rock breakage. The first such study was Project Plowboy at Winnfield, Louisiana, in which the fractures from a contained 1000-lb TNT explosion in salt were mapped during a postshot excavation.[1] The salt explosions occurred during a series of H.E. experiments carried out in 1959-60 as part of the AEC's seismic improvement program. A similar series of experiments (Project Hobo) was conducted in tuff during 1960 as an extension of this program. This paper will summarize the field investigation of ftacturing that resulted from two of these explosions in tuff.

EXPLOSION CONDITIONS

Both explosions took place in a sequence of tuff beds in unit 3 of the Oak Springs formation.[2] Samples of the tuff in this unit have an average natural state bulk density of 1.82 g/cc, a water content between 18 and 23 percent, a static uniaxial tensile strength of about 150 psi, an (estimated) compressive strength of 5000 psi, and sonic velocities from 9000 ft/sec to

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11,400 ft/sec for longitudinal waves. A simplified stratigraphy for individual layers in the immediate vicinity of one of the shot sites is given in Table I.

Table I. Stratigraphic Section for Shot Chamber 14A.

Subunit No.	Distinctive Features of Tuff Beds	Thickness (in.)
00	thin, red-brown band (marker)	2
0	buff, uniform-colored	30
I	maroon-colored	14 -16
II*	light cream to buff layers alternating with 1/2 in. to 1 in. red bands (marker)	12- 18
III	(a) buff-colored	11
	(b) brick red	12
IV	light buff to white	12- 14
V	alternating light buff and red-banded tuff (marker)	18- 20
VI	red-brown, spotted (scalloped)	14
VII	light brown, occasional red mottled; also red-brown, discontinuous bands 2 in. to 12 in. thick	54- 66

Part of the Hobo series of explosions took place in a drift in the tunnel complex associated with the Blanca nuclear event. Shot Nos. 11 and 14A, discussed in this paper, were located along lines 580 and 620 ft, respectively, north of the ground zero position of Blanca.[3] Both shots were detonated in chambers formed first by drilling a pilot hole beyond the desired depth of explosion and then reaming a segment of each hole to a diameter of 30 in. A given section was reamed to that length which would hold approximately the amount of granular TNT (Pelletol) calculated to produce a particular yield.

Shot chamber 11, which contained 973 lb of TNT was reamed for 4.1 ft to give a volume of 17.3 cu ft. The top of this chamber was tapered from a

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*At chamber, top of subunit II is 93 ft below tunnel drift floor; this and other beds strike N 10 W and dip 3° to 7° to west.

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30-in. diameter to 11 3/4 in. at the loading hole at an angle of 40° from the vertical. This formed a cylinder with a truncated cone at its top.

Shot chamber 14A has only a crudely known shape because preshot dimensional surveying was incomplete. This chamber, which held a 516-lb charge, is presumed to have consisted of an 8.8-ft-long cylinder 10 5/8 in. in diameter with a poorly formed truncated cylinder of about 30 in. in diameter near its top. The length of this cylinder is unknown; it was probably less than 2 ft. The volume of this chamber was certainly in excess of 8 cu ft and presumably less than 15 cu ft. The total charge, as it normally packs, should occupy about 7 cu ft. Because the chamber appeared to be filled from its base (grouted) to the top (also sealed by grout to the drill collar in the tunnel drift floor) with Pelletol, it has been assumed that the explosive granules bridged upon loading in such a manner as to allow a large void to develop somewhere within the chamber.

The center of shot chamber 11 was 101.5 ft below the tunnel drift floor. The center of chamber 14A was approximately at a 100-ft depth.

METHOD OF INVESTIGATION

In general, the procedures and mapping techniques followed in the Hobo excavations were similar to those used in Plowboy.[1] In Hobo a shaft was sunk 108 ft at a point midway between the two shot sites. Two drifts were then driven simultaneously along slight inclines in nearly opposite directions to the edge of each chamber. The north edge of Shot 11 was first broken into 35 ft from the shaft center; the south wall of Shot 14A was 39.5 ft away. After the cavity was mapped, fractures about Shot 14A were followed by extending the entry drift for 44 ft beyond the cavity center along a line which changed 10° from the original entry direction. Fractures and shot chamber dimensions were mapped with the aid of Brunton compass and tape using control points established by surveying. Photographs were taken of exposed fractures in the headings and walls after each advance of the drift.

RESULTS

Prior to the excavations it was assumed that the fractures would be distributed in a pattern similar to that observed about the Plowboy salt cavity. The general character of this salt cavity and the fractures associated with it are depicted in Figs. 1 and 2. Figure 1 shows the cavity to have remained intact with no roof or wall collapse, although the 1000-lb explosion expanded the preshot chamber to a volume which was 4.4 times larger. Figure 2 indicates that most of the Plowboy fractures were radial and that many extended to 15 to 25 ft from the cavity (one was traced a distance of 45 ft). Several fractures, however, were parts of conical sections which emanated from the top and base of the barrel-shaped cavity.

Both Hobo Shots 11 and 14A provided many surprises and were unlike the Plowboy results in many respects.

Shot 11 was a successful firing except that it vented almost immediately. Upon excavation into the shot area and subsequent removal of rock debris, several striking features were evident:

(1) The cavity, as seen after rock removal, was now approximately 8.0 ft in diameter by 8.5 ft in height.* This represents a rubble-free volume of about 535 cu ft as compared with the preshot volume of 17.3 cu ft for a 2.5 ft (diameter) by 4.1 ft cylindrical shot chamber.** In cross section (see Fig. 3) the cavity is roughly shaped like a section through an apple.

(2) This apparent increase in volume by a factor of 31 is valid only for the condition of complete removal of the rock rubble and muck. Approximately 425 cu ft of this loose material was removed in exposing the final cavity walls. This material filled the cavity to a level between 1 1/2 and 3 ft from the top. The volume of the actual void above the rubble pile, computed from field and photographic measurements, was close to 150 cu ft. However, this volume

*In this paper, the term chamber refers to the preshot reamed container; excavated volume to the space occupied by rubble and muck loosened by the explosion; cavity to the final opening which is exposed after rubble removal (is equivalent to the surface at the limit where rock fragmentation and slabbing ceases); and void to the actual volume of open space within the rubble-containing cavity.

**Cavity and void volumes were computed by application of Simpson's Rule to the cross sections of 11 and 14A.

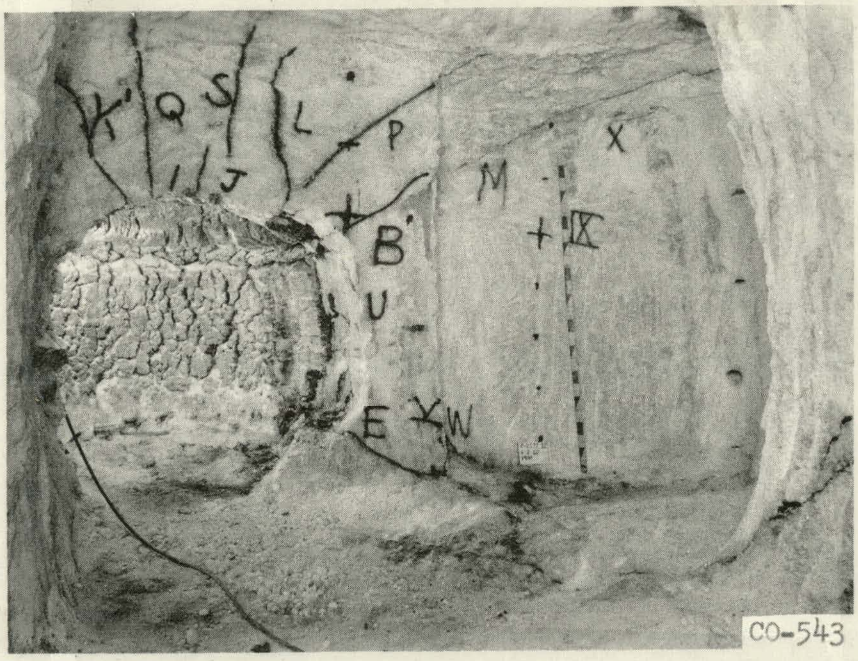

Fig. 1. Cavity in salt and associated fractures (painted black for emphasis): Plowboy explosion, in a salt dome at Winnfield, Louisiana.

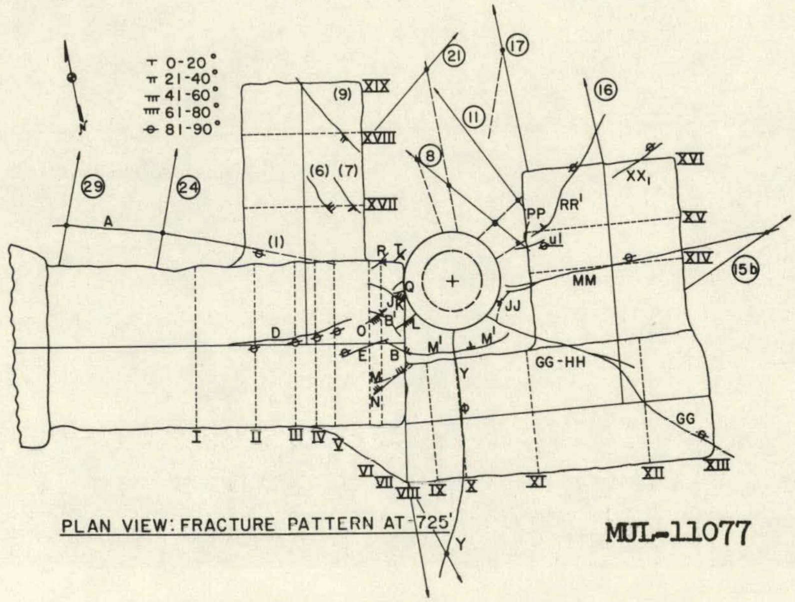

Fig. 2. Plan view of drift and explosion cavity: Plowboy event, at -725 ft level, showing fracture pattern. Numbered arrows are probe drill holes.

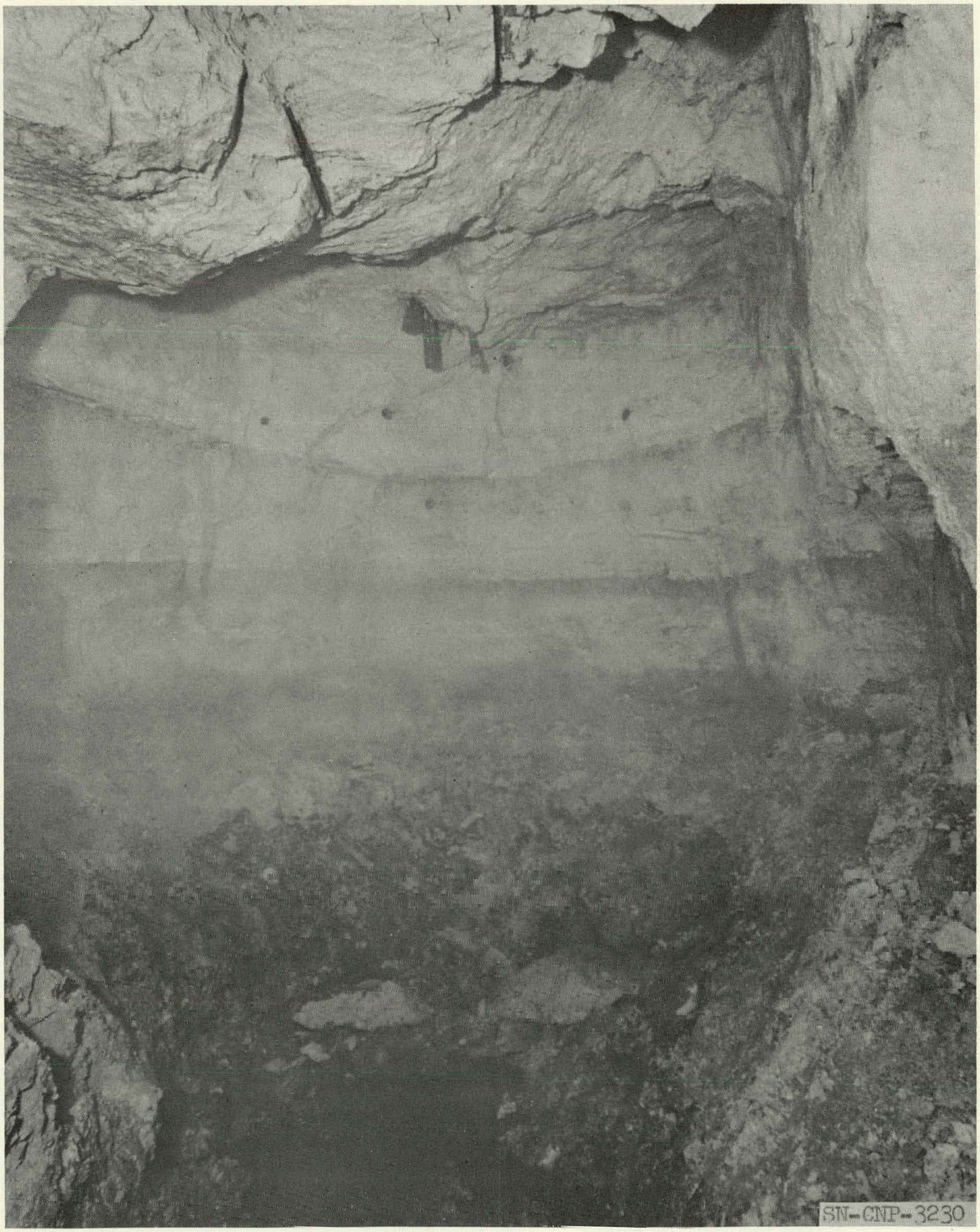

Fig. 3. Cavity of Hobo Shot 11, approximately 8-1/2 by 8 ft in dimension. Note remnant of explosive loading pipe in roof. Black at bottom of picture marks limit of expanded shot chamber after explosion.

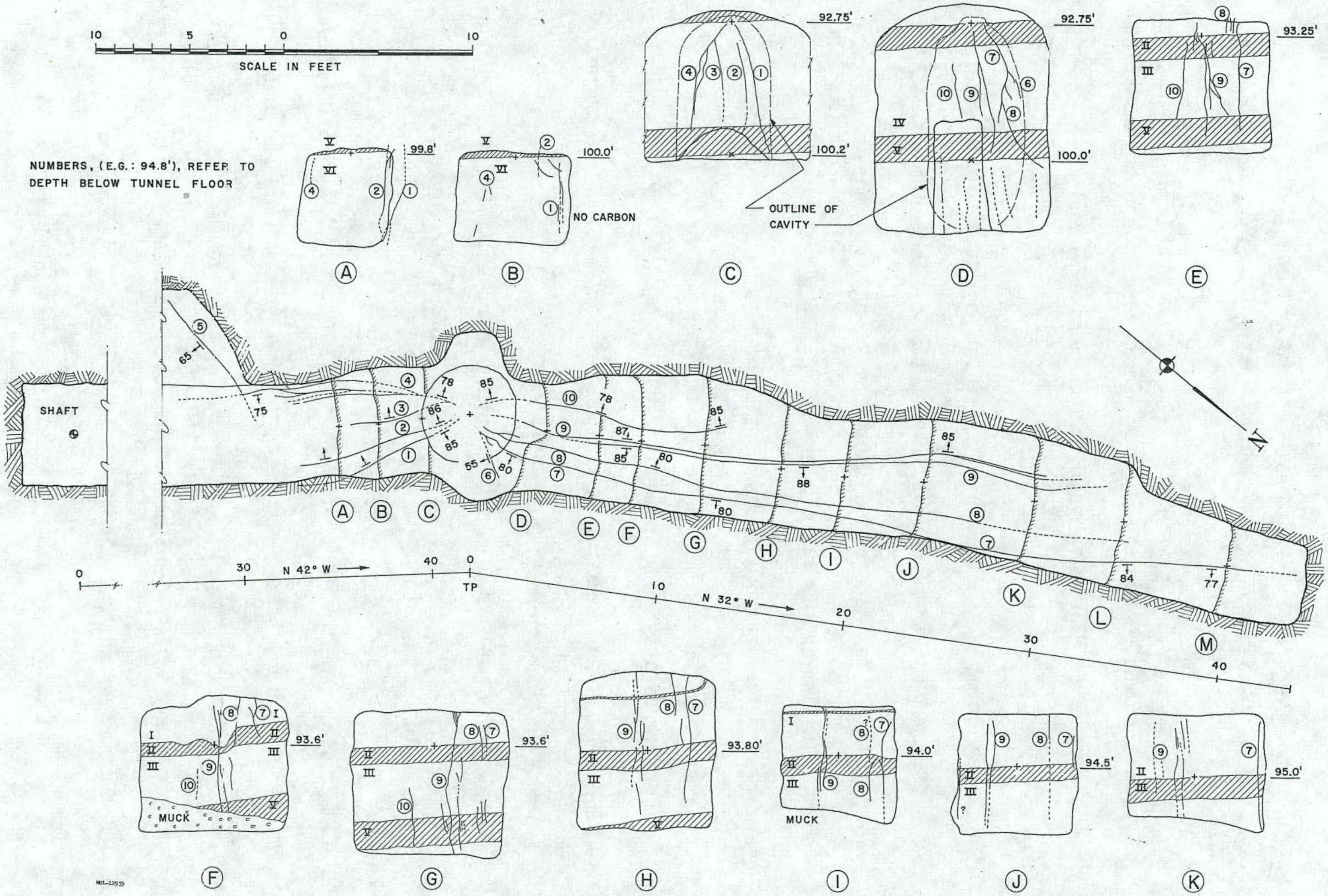

Fig. 4. Plan map of the excavations around Hobo Shot 14A showing the exposed carbon-filled fractures (solid lines) and related joints (dashed lines). Individual headings in the drifts are denoted by circled letters which correspond to the cross-sections (above and below the map) on which the orientation of fractures is illustrated in relation to the principal marker beds (Roman numerals).

was then adjusted for an assumed porosity of 10%* to give a total void volume of 190 cu ft. The volume of rubble in the cavity on this basis is therefore 345 cu ft, somewhat less than the material removed during mucking.** The apparent volume increase of 31 now becomes an actual volume increase of 11, by taking the ratio of total void volume to preshot volume.

(3) The cavity walls, floor and roof were almost entirely devoid of carbon-filled fractures. However, in the west wall near the floor, two of the several near-vertical joints, trending N 45 W, that pass through the cavity were filled with a carbon residue that did not continue beyond 2 ft from the point of exposure.

(4) Venting was accomplished through a 2-in. i.d. steel pipe which extended over 100 ft from the drift floor to the top of the chamber. The pipe was initially sand-filled, but this sand blew out along with the escaping gases. This pipe, the bottom of which was in place but engulfed by the rubble pile as seen on cavity entry, was essentially undamaged and must have remained open during the explosion.

A notably different picture is present in the Shot 14A explosion. This explosion, about one half the yield of Shot 11, did not vent. The principal features associated with this explosion are illustrated in Fig. 4, which is a plan map and a series of sections across the drift corresponding to the various headings. With this figure as reference, the following points are given particular mention:

(1) The shot chamber, originally from 11 in. to around 30 in. in diameter, has now been enlarged to a maximum of 60 in. (Fig. 5). The shape of this cavity, after muck and rubble was removed, is shown in section D of Fig. 4. This cavity has a volume estimated to be around 168 cu ft. However, the rubble level reached to within 2 to 3 ft of the roof, leaving at the top a

*This is a reasonable guess based on the observation that the lower part of the rubble had disintegrated to muck, whereas the upper half was composed of loosely packed slabs.

**This material no doubt contained some additions from the drift floor and cavity walls and was also packed more loosely in the mine cars.

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Fig. 5. Lower 2/3's of Hobo Shot 14A cavity after rubble was removed. Cavity about 5 ft in diameter and 11 ft high. Note vertical fractures on either side of geologist's left leg. Subunit V begins just above his waist.

Fig. 6. Near vertical carbon-filled fractures in roof and in face of Heading H, Hobo Shot 11. Black patches are water-smeared carbon. Light, banded layer is subunit II.

void volume between 21 and 29 cu ft. Assuming 29 cu ft and a 10% porosity in the rubble, the adjusted total void volume is 42 cu ft. Since the original volume is not known, the actual volume increase is also uncertain but appears to be about four.

(2) Carbon-filled fractures have been formed by this shot. However, instead of being radially distributed, the fractures are restricted to an axial zone from 3 to 5 ft wide extending generally along a bearing between N 25 W and N 50 W. The majority of fractures are vertical to 75 to 85° (both to east and west) in inclination. A typical fracture pattern is displayed in Fig.6 which shows several fractures (8, 9, and 10 of Fig.4) in the roof and in heading H. Except for several very short cracks adjacent to cavity walls, no fractures extending in directions other than just specified were found anywhere else about the cavity. Two alcoves driven to the east and west from the chamber verified the absence of filled joints in these directions. Because the fracture orientation is nearly identical to that of local joints and because several fractures can be traced directly into unfilled joints, it is suggested that the mode of failure and ejection of explosion gases about the explosion chamber was controlled by the presence of these preexisting natural discontinuities.

(3) The first carbon-filled joints were encountered in the entry drift about 10 ft from the cavity center. As seen in Fig. 4, at 11 ft from the center, fracture 4, following a N 45 W trend, suddenly intersects a joint bearing N 10 E. The carbon thereafter follows this latter joint (fracture 5) for a distance of 10 ft to the southwest; carbon persists beyond that point, but excavation stopped there. To the south and east of the intersection both joints continue but are free of carbon. On the north side of the cavity fractures 7 through 10 extend to distances from 12 to 41 ft as shown in Fig.4. Excavation above the roof of the cavity revealed that fractures 7 and 8 are carbon-filled to at least 8 ft above the uppermost level in the chamber. Carbon and gases in this crack may have penetrated many more feet upward inasmuch as slight gas escape and bubbling were noted in the tunnel floor 90 ft above some minutes after the shot.

(4) In the roof immediately above the chamber center, the fractures approach a radial orientation (see Fig. 4 and 7). At distances of 4 to 6 ft from this center the fractures begin to follow the joint trends. Thus in the immediate vicinity of the chamber, the fracture pattern is determined by the cylindrical shape of the container whereas only at distances greater than several chamber radii do the joints exercise the dominant control.

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Fig. 7. View of top of Hobo Shot 11 cavity, explosive loading hole in center, showing initial radial character of fractures. Bottom of picture to east; right to south.

(5) Most of the fractures are concentrated in the upper half of the cavity. However, several fractures originate in, or extend into, the layers below the explosion center. Fractures 1 and 2 extend outward 10 ft south from the cavity center. In section D (Fig. 4) are shown several un-numbered fractures which were followed for 7 to 8 ft north from the center.

(6) From cavity surfaces to distances of 25 ft or more, the main fractures consist of joint fillings, but associated with these are many subsidiary fractures which a) parallel the larger fractures, b) branch or offshoot from these, or c) form lenticular and interweaving segments with the parent fractures (Fig. 8). This effect diminishes with increasing distance from the cavity. This observation implies that some rock breakage and new surface development occurred as a result of the explosion but were localized along the joints which opened up as the rock about the cavity went into tension.

In Table II, the volume-producing and rock-breaking abilities of the two explosions 11 and 14A have been summarized. The values shown are only approximations because of the uncertainties involved in measurements of dimensions and in volume calculations.

Table II. Significant Changes in Volume for Shots 11 and 14A.

	Shot No. 11	Shot No. 14A
$\frac{Volume_{postshot\ void}}{Volume_{preshot\ chamber}}$	10.5	4.7*
$\frac{Volume_{void^{**}}}{Volume_{excavated\ cavity}}$	0.35	0.25
Increase in volume/unit charge:		
$\frac{Vol_{void} - Vol_{chamber}}{Yield}$	0.17/ cu ft/lb	0.06/* cu ft/lb
$\frac{Volume_{broken\ rock^{**}}}{Yield}$	0.35/ cu ft/lb	0.24 cu ft/lb

*Volume of 14A preshot chamber assumed to be 9 cu ft (volume occupied by 516 lb Pelletol with loaded density of 0.9/ g/cc).

**Adjusted to 10% porosity in rubble pile.

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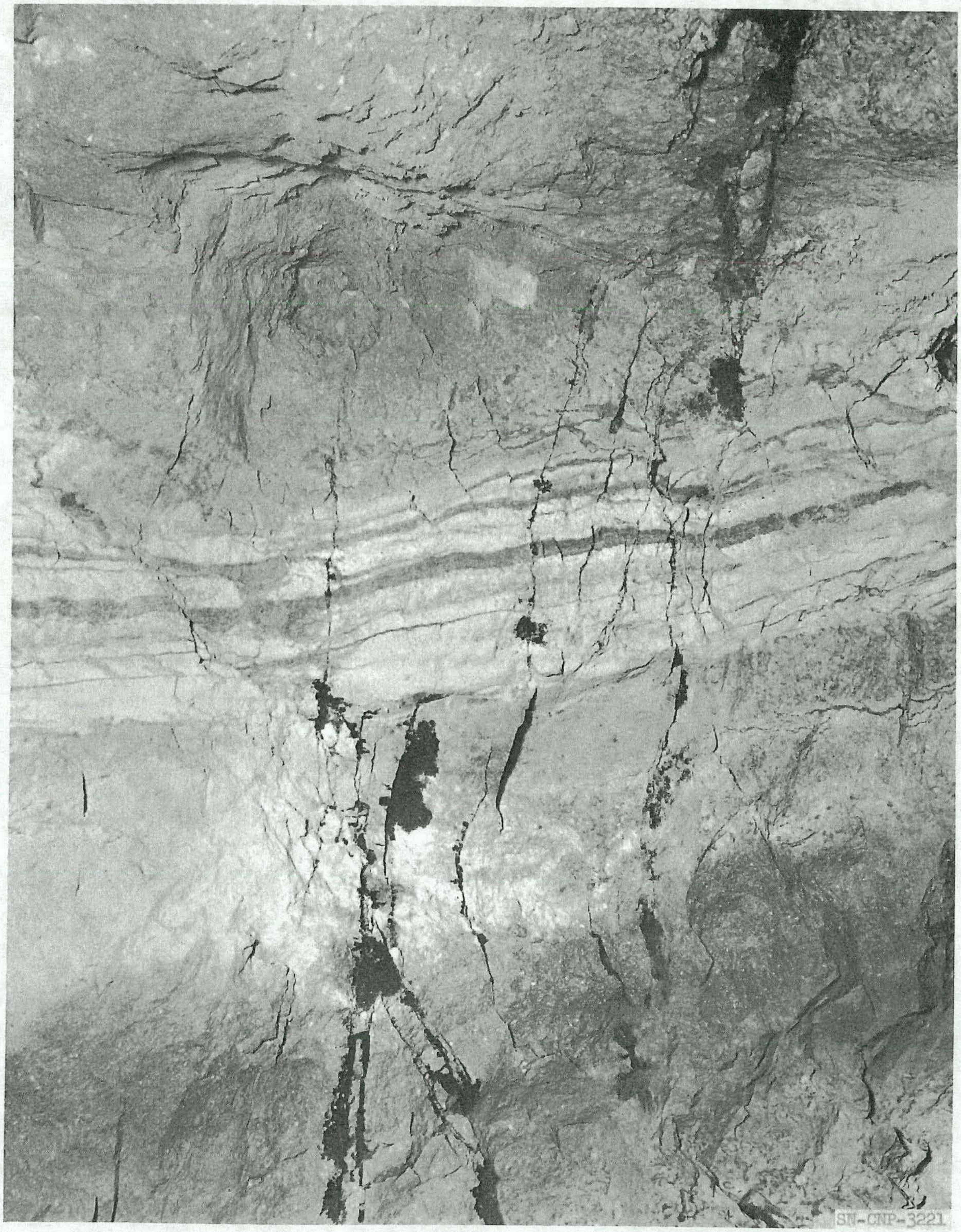

Fig. 8. Face of Heading E, Hobo Shot 11, looking north. Note branching and subparallel splitting character of fracture system. Subunit II is prominent banded layer in center of picture. The black blotches are carbon stains made by percolating ground water.

INTERPRETATIONS AND CONCLUSIONS

Many of the following comments on the results represent tentative conclusions and, in some instances, speculations by the writer. The validity of some of the interpretations below is limited by the inadequacy of preshot and, to a lesser extent, postshot data.

(1) The Hobo Shot 14A demonstarated the importance of preexisting discontinuities in controlling the manner of rock failure during the explosion. The existence of joints, together with the retention of gases within the chamber, provided a particular combination of factors which permitted the rapid entry and deep penetration of these gases in cracks that opened up during the passage of the primary shock and perhaps also re-opened upon return of the reflected shock waves. It should be noted that the earlier Blanca event, some 600 ft away, may have opened or otherwise weakened the local joints in the Hobo area.

(2) Comparison between Plowboy and Hobo fracture phenomena points up an essential difference between a homogeneous (salt) and a jointed (tuff) medium. The salt fractured approximately as expected for a homogeneous medium. Radial cracks were prevalent; the departure from ideal distribution about a "sphere" was a function of the actual cylindrical shape of the chamber. The tuff, however, ruptured according to control exercised by the joints, the dominant surfaces of weakness, producing therefore a single axial planar zone of fracture failure. It is likely that the relative ductility or "softness" of the tuff, as evidenced by its low compressive strength and flow properties[4] inhibited the development of new major fractures during the explosion, with relief of stress being accomplished mainly by expansion across joints.

(3) In plowboy the fractures at the cavity surface were open gashes to a depth of 6 to 12 in. Nothing similar was found in Hobo. As seen at several remnants of the pre-collapse surface of the expanded chamber wall, the fractures were tight (less than 1/10 in. wide) up to that surface. However, it is significant that the number of individual subsidiary fractures associated with the main carbon-filled joints increases with decreasing distance from the shot chamber. These have the effect of raising the total volume of a specific fracture system in the vicinity of the cavity. Such a system may be analogous to the more open parts of fractures observed at Plowboy.

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(4) The most obvious visible difference between 11 and 14A, the absence of carbon-filled cracks in the first shot, is attributed to the venting that occurred during detonation of Shot 11. This venting probably began early in the explosion event and may have been completed by the time reflection shock waves returned to the cavity. This suggests that the appearance of carbon-filled fractures in the tuff depends on the retention of explosion-released gases which may aid in the formation and maintenance of open spaces and also serve to carry carbon into these spaces to delineate them with noticeable deposits. For Shot II the existence of preshot joints was insufficient in itself to promote the development of filled fractures. These conclusions, however, may not be applicable to media with different properties and discontinuity distributions.

(5) In contrast to the explosion in salt, the chambers around both explosions in tuff experienced some collapse. Each chamber had been expanded by a factor exceeding 4 before this collapse was initiated. The collapse and accumulation of rubble does not appear to have been caused by general fracturing of the walls. Rather, the rock debris which fell into the expanded chamber appears to result from a) spalling immediately following the explosion as the walls went into tension during the arrival of reflected shock waves and b) slabbing of the roof and upper walls over an extended period after the shots, as caused by stress relief in the cavity arch, aided no doubt by the effects of inflowing groundwater.*

The evidence from Shot 11 favors roof slabbing as the principal mechanism of collapse. At the base of the cavity walls there appears a conspicuous, nearly hemispherical remnant of the original chamber wall in its expanded position. From a measurement of 7.2 ft at its maximum breadth, this chamber wall, if extended in the shape of a sphere, would include a volue of 230 cu ft. This agrees reasonably well with the estimate of 190 cu ft for the total void volume within the cavity. By plotting the outline of this expanded chamber on a cross section through the cavity, with the center of the chamber coincident with the explosion center, it becomes apparent that the majority of the rock debris must have come from the roof and upper walls. This viewpoint is supported by the observation that the present roof is several feet further from the center of the pre explosion chamber than are the walls and floor.

*Both cavities were "wet," with several hundred gallons of water drained out during entry. Part of the rock debris had been softened to a clayey muck.

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(6) The data in Table II also indicate other differences between Shots 11 and 14A. The differences cannot be attributed to the different yields as these should scale for the two explosions, nor do the differences follow the slight variations in medium properties. It would appear at first glance that these differences are related to a greater effectiveness in expansion and rock breakage for Shot 11. This is surprising in view of the venting that accompanied that shot, for early loss of gases would be expected to reduce the efficiency of the explosion.

It is not clear which, if either, of these shots produced effects that could be considered as typical or normal for a completely tamped explosion in tuff. Shot 14A may exhibit reduced effects because of pockets or gaps within the Pelletol charge resulting from incomplete loading of the abnormally shaped chamber. This could have led to an uneven or partial detonation, non-uniform and asymmetrical passage of shock waves into the surrounding rock, and partial decoupling or attenuation of the explosive energy.

No adequate explanation for the effects observed in Shot 11 has been proposed. A greater relative volume of rock debris could be accounted for by assuming more extensive roof and wall collapse about a larger, more unstable postshot void. But the reason for the void itself being relatively larger than 14A is not obvious unless it is postulated that Shot 11 is typical and 14A is subnormal. The role that venting played in the cavity development and history is also not discernible from the field evidence. Venting would reduce, perhaps rapidly, the internal pressure of the void. If this were to occur by the time that reflected shock waves have returned, the effect would be to facilitate spalling by increasing the pressure gradient between walls and void.

(7) One objective of the Hobo study was to compare the characteristic phenomena of an intermediate-yield H.E. explosion to the features associated with nuclear explosions of much higher yields. There are several noteworthy differences. The Rainier event[3] produced a cavity (before collapse) whose actual radius is only 0.57 and 0.44 that which results when the radii of the two Hobo H.E. shots 11 and 14A are scaled (by $W^{1/3}$) up to the same yield as Rainier (1.7 kilotons). In the scaling the radii used were obtained by recalculating the volumes of the total voids as equivalent volumes of spheres. The 11 and 14A voids would occupy spheres of 3.6-and 2.2-ft radii, respectively. At face value this would seem to imply that H.E. explosions, at least at lower yields, produce larger cavities than nuclear explosions. However, direct

comparison with Rainier is complicated by the absence of melting and vaporization, the influence of joints, differences in scaled depths, and probable differences in mode of collapse which are characteristic of explosions of the Hobo type.

Detailed excavation around Rainier has indicated that, up to several tens of feet beyond the cavity, the tuff deformed plastically and adjusted by flow in response to the large shock pressures (hundreds of kilobars) which affected the rock immediately adjacent to the cavity.[3] Under such conditions extensive fractures connecting with the cavity apparently were not developed and preexisting joints, which may have opened momentarily, would be effectively closed. The absence of such fractures would prevent the escape of radioactivity by this mechanism. Thus, any large unconnected fractures which originated at some distance from the cavity would not be recognized as explosion-related because of this absence of enclosed radioactivity (analogous to carbon-filling). Recent digging into the plastically deformed tuff below the lower half of the Rainier cavity has revealed that the close-in deformation was more intensive and complex than originally believed. Some intricate underthrusting, block faulting, and gash-like fracturing have now been identified in the 25-ft zone adjacent to the cavity. Up to now no long continuous fractures analogous to the opened Hobo joints have been observed.* In Hobo the peak shock pressures were too low to initiate and sustain the "self-sealing" plastic deformation that results when the jointed tuff is overstressed by a nuclear explosion. Such plastic deformation appears to inhibit extension of connected fractures to considerable distances.**

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* Recent work around Blanca and Logan nuclear events has shown the presence of radioactive fissures (some apparently concentric); these are now being examined by direct excavation into the cavity area.

** It is evident that the distance to which Hobo joints are carbon-filled cannot be directly extrapolated to the Rainier yield by conventional $W^{1/3}$ scaling, as then one would expect radioactive joints to extend as far as 1700 ft from Rainier. Nothing like this has been observed, although bedding plane movements were recorded at distances greater than 1000 ft from ground zero and joints at the mesa surface were opened up upon reflection of the shock waves.

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In summary, the Hobo shots have shown the relative importance of geological discontinuities and of venting in the development of recognizable fractures associated with an explosion. The shots have shown further that there are notable differences between a low-yield H.E. and a high-yield nuclear explosion in tuff in the manner in which this medium responded and in the features produced. Experiments in other media (e.g., granite and limestone) will be needed to demonstrate whether the particular effects observed in Hobo were peculiar to the explosion chamber conditions and to theproperties of the medium or represent instead a general case for layered and jointed rock.

I gratefully acknowledge the support given my by personnel at the Nevada Test Site, and in particular wish to thank William D. Richards for his assistance in mapping the Hobo excavations. This work was performed under auspices of the U. S. Atomic Energy Commission.

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[1]Short, N. M., Fracturing of Rock Salt by a Contained High Explosive, Quarterly of the Colorado School of Mines, Vol. 56, No.1, Jan. 1961, pp 222-257; also University of California report UCRL-6054 (1960).

[2]Warner, S. E., and Violet, C. E., Properties of the Environment of Underground Nuclear Detonations at the Nevada Test Site, Lawrence Radiation Laboratory, University of California report UCRL-5542, Rev. (1959).

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[4]Thompson, T. L., and Misz, J. B., Geologic Studies of Underground Nuclear Explosions Rainier and Neptune, Final Report, Lawrence Radiation Laboratory, University of California report UCRL-5757 (1959).

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