UNDERGROUND NUCLEAR EXPLOSIONS*

Gary H. Higgins

Lawrence Radiation Laboratory, University of California
Livermore, California 94550

ABSTRACT

In the Third Plowshare Symposium, held in 1964, data from a number of nuclear explosions were presented. At that time the basic elements of the nuclear explosion appeared to be well understood and relationships for predicting the gross nuclear effects were presented. Since that time, additional work has been done and many of the concepts have been extended. For example, nuclear explosions have been conducted at greater depths and with much greater yields. The physical and chemical properties of the material in which the explosions occur have been more accurately measured and related to explosion effects. Interpretation of the new information seems to indicate that the earlier relationships are valid over the ranges of energy and depths for which data is available but that effects relating to cavity and chimney sizes or fracturing had been overestimated at great depths of burst and higher yields.

INTRODUCTION

This paper reviews the state of understanding of nuclear explosion effects that might be applied to industrial or civil engineering works. The word we have used to describe all of these effects is "phenomenology." Figures 1a and 1b describe the effects of nuclear explosions that are included in the definition of this term.

DISCUSSION

Explosion effects relevant to the Plowshare Program, now almost 13 yr old, have been reviewed several times. The Third Plowshare Symposium in 1964 did not have a summary paper on explosion phenomenology, but among the thirty-odd papers included in the Proceedings[1] four established the state of the art as it existed at that time. Boardman, Rabb, and McArthur described their impressions of the importance of geologic factors in determining cavity radii, chimney heights, extent of fracturing, permeability of the wall rock, and so forth. They derived their conclusions in the form of empirical scaling laws based on observations of a number of nuclear explosions performed for weapons testing and Plowshare purposes.

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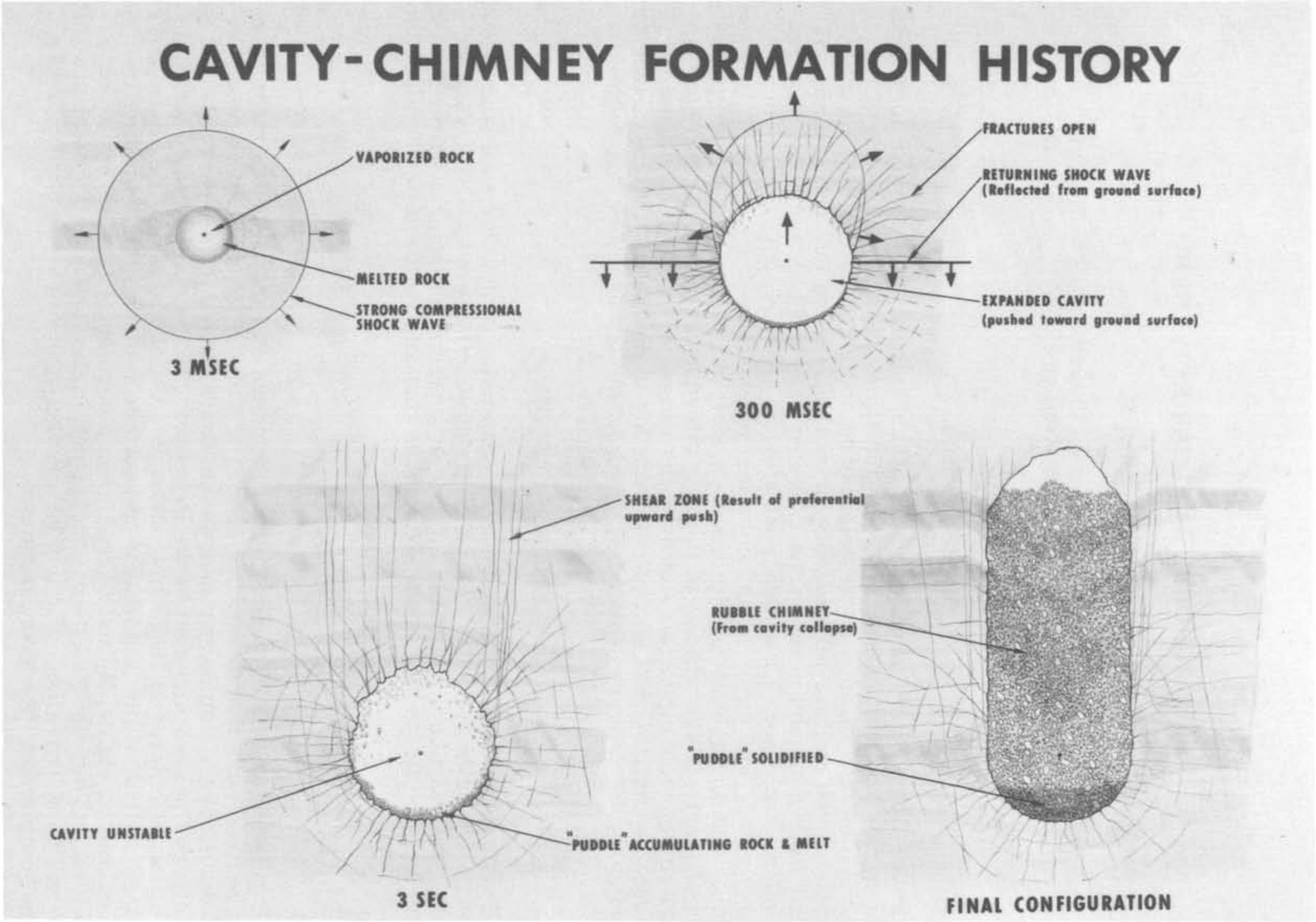


Fig. 1a. Cavity and chimney formation history.

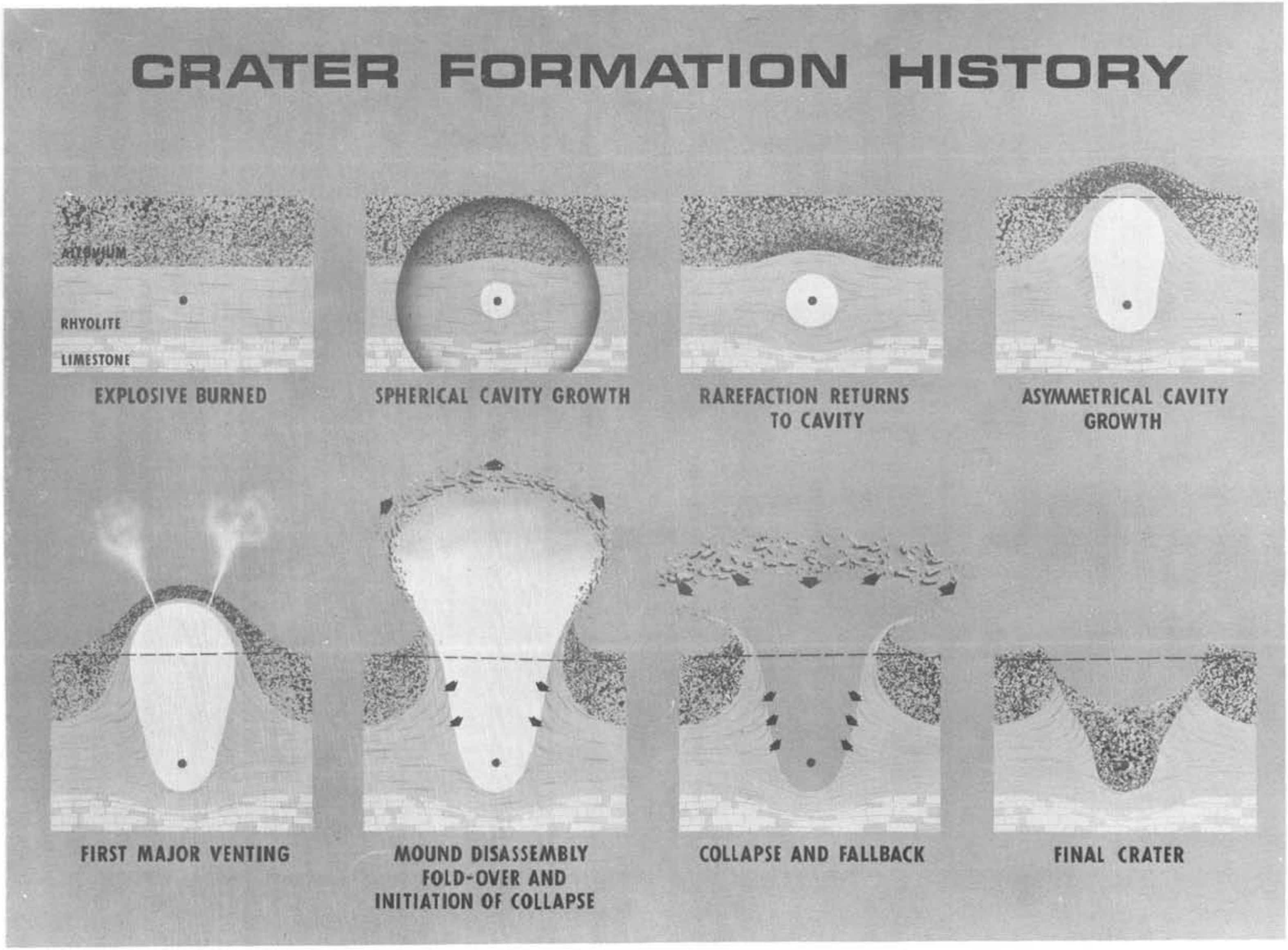


Fig. 1b. Crater formation history.

T. R. Butkovich, in his paper, described the first successful SOC code calculations of explosion effects in which measurable properties of the rock and the conditions of the explosion (such as yield, depth of burst, and so forth) were related through integration of a differenced form of the equations of motion. He calculated the cavity size and the stress amplitude vs distance. He did not attempt a discussion of fracturing, chimney height, or permeability.

Milo Nordyke summarized the state of the art in nuclear and chemical cratering. He presented empirical scaling laws that could be used for predicting crater dimensions from explosive yields and depth of bursts. Separate curves were presented for each material. He also discussed the equivalence of rows of single explosives with continuous line charges for producing trenches and summarized an empirically based scaling theory used by the Soviets for HE cratering calculations.

Knox and Terhune described an attempt to calculate crater dimensions using, for the early part of the calculation, the same method described by Butkovich for deeply buried explosions. After the very early spherical process was complete and as the crater was formed, the material to be excavated was treated as an incompressible fluid with friction. Calibrating friction from one explosion, they were able to reproduce the results of another in the same material but unable to correctly describe craters in a different material.

Since the Third Plowshare Symposium there have been several other papers that have attempted to summarize nuclear explosion phenomenology.[2-5] Reviewing all these documents allows some general conclusions to be drawn. The focus of efforts to understand phenomenology applicable to the Plowshare Program has been understanding those effects that have some applications. In other words, the research conducted in the program has been aimed at applications rather than at purely academic understanding. Efforts to quantitatively explain the cavity size, fracture radius, chimney height, chimney permeability, and permeability of the fractured region for contained explosions and the cratering dimensions, air blast, and radioactivity in dust from cratering explosions have evolved in directions dictated by needs for gas stimulation, ore leaching, harbor construction, canal building, and so forth.

In January 1961 a working symposium was held at the University of Nevada in Reno. At that time nuclear explosion effects applicable to the mining industry were described to the mining faculty and the Bureau of Mines. All of the data—the hard facts—were based on explosions in volcanic tuff, a rock of little practical interest to the mining industry. Their obvious question was, "But what happens in granite?" The 1964 paper of Boardman, Rabb, and McArthur[1] was the answer. Five widely different geologic materials were described. When the Interoceanic Canal was evaluated using nuclear explosives as a hypothetical excavation technique (in 1959), engineers engaged in the study were presented cratering data and speculations based on experience in Nevada Test Site alluvial material. Their obvious question was, "How do craters form in columnar basalt?" Papers in the afternoon session today provide some of the answers.[6]

Thus we see a continual development in which research is used to provide the basis for an engineering assessment of applications. In this dialectic, the research discipline groups evolve theories. Field experiments are conducted, measurements made, the data are analyzed, the theory is modified, and new experiments are designed. Finally, there will be a satisfactory conformity between theory and experiment. This circle of evolution is demonstrated in Fig. 2. Members of the Soviet Academy of Sciences have proceeded in developing their assessment of the Plowshare Program and nuclear explosive phenomenology in much the same way.[7] Their conclusion is:

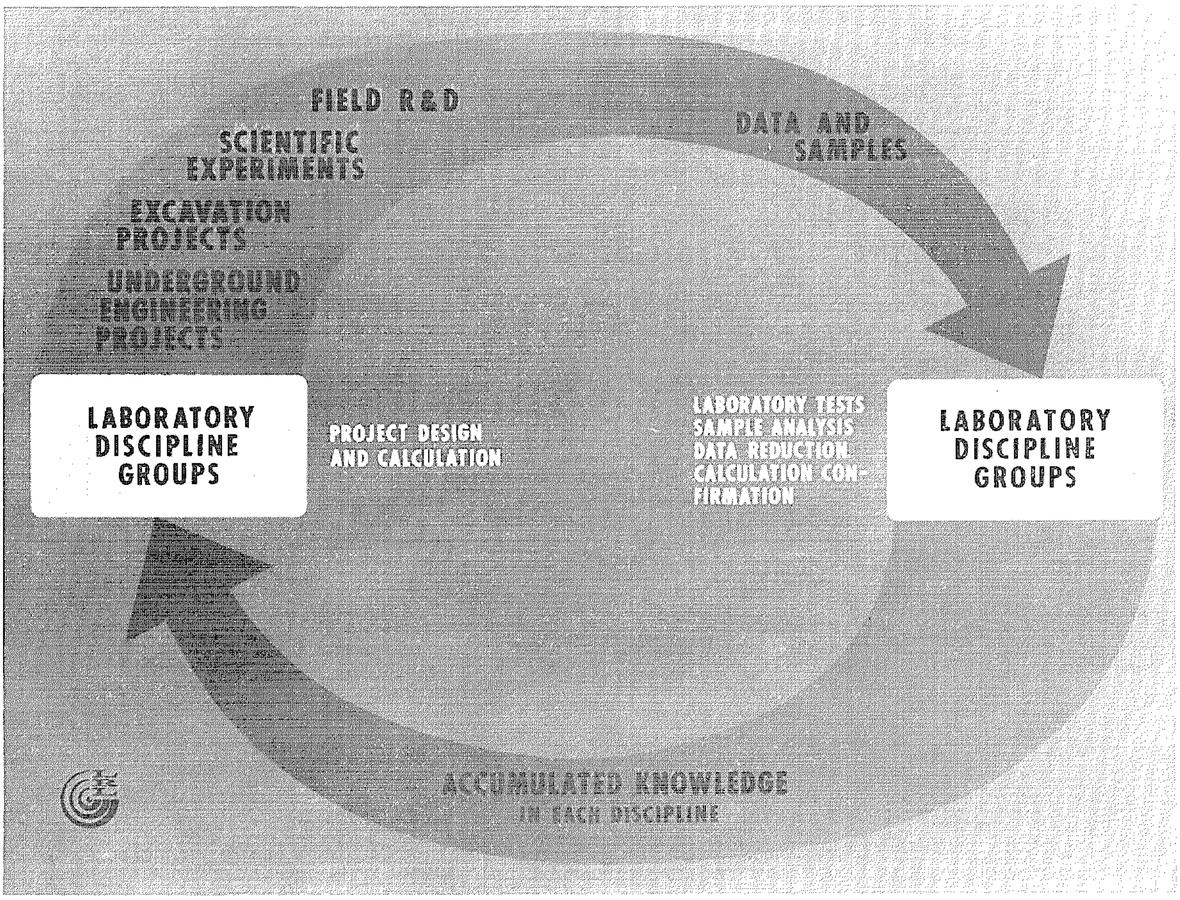
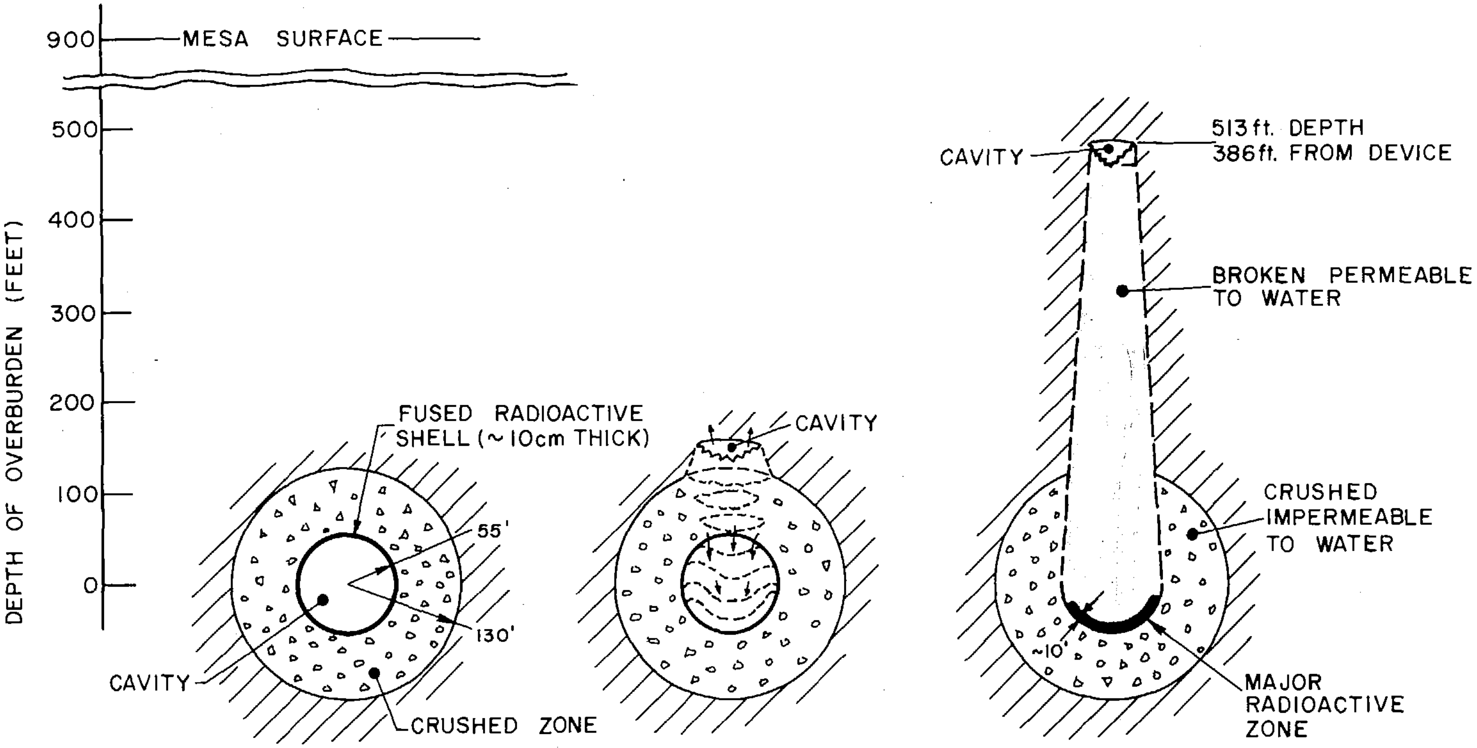


Fig. 2. Circle of evolution of theory and experiment.

> "An underground nuclear explosion is a complex phenomenon, and its description by stages seems to be a waste of time since we shall encounter countless unsolved problems in the process, which will in no way clarify the possibilities of a practical use of the explosion.
>
> "If, however, we decide to analyze the concrete purpose of an explosion, the necessary detailed description of the phenomenon and an adequate evaluation of the desired effects may be obtained with ease even at the present level of knowledge.
>
> "Keeping in mind the pertinent applications possible at the present time, we attempted to isolate the basic parameters of the explosion effect and analyze prognostication methods. We also investigated certain unsolved problems important for practical applications.
>
> "The experience necessary for a more accurate definition of the prognostication of the mechanical effect may be accumulated during the conduct of both types of explosions, industrial as well as investigative."

In the succeeding section evolution of two of the phenomena related to explosions will be examined as examples of changes in understanding.

Following the first series of underground nuclear explosions in volcanic tuff, Johnson and Violet[8] in 1958 published a summary of the phenomenology as it was understood from postshot explorations and calculations. Figure 3 is a reproduction of their understanding of the formation of the chimney. They



-A-
Cavity before collapse

-B-
Intermediate collapse

-C-
Final collapse

Fig. 3. Strongly affected zones surrounding detonation point (reconstruction).

show an initial cavity surrounded by a crushed region that was, in their view, compacted and impermeable to the migration of fluids. As the cavity in the center of this region collapsed, it formed a broken, permeable chimney that progressed upward roughly 4-1/2 times the radius of the initial cavity.

By late 1964, after experiments in salt and granite had been performed, Boardman, Rabb and McArthur[9] had evolved a somewhat more sophisticated view based on analyses of applications of nuclear explosives to mining. Their concern was almost exclusively with the chimney, which they thought was the most useful aspect of the explosive for mining. They observed empirically that the chimney height in these materials was related to the cavity radius and that the height of broken material was between 4 and 6 times the radius of the cavity. Further, they observed that the cavity radius could be predicted from an empirical equation relating the explosive energy W, the depth-of-burst h, and the material density with the relationship

$$R_c = C \frac{W^{1/3}}{(\rho h)^{1/4}} .$$

The experimental determinations of the constant C varied from 260 to 350, depending on the material. While they discussed the vertical extent of fractures and related it empirically to the cavity radius, their picture of the Rainier Event (shown in Fig. 4) makes no indication of a concern for the fractured radius in other directions or the crushed region described earlier by Johnson and Violet.[8]

As interest in the stimulation of petroleum production grew in the Plowshare Program, more emphasis and interest was focused on the fractured region. Starting with the observations of Rawson[10] of fractures from the Gnome results, Coffer et al.[1] concluded that the fractures that extend beyond the chimney could have a significant effect on gas production in addition to the gas that would be produced by the well bore represented by the nuclear chimney. Subsequently, Cherry, Larson, and Rapp,[11] after several years of research and the development of a model for brittle failure, were able to compute the distance to which fractures would extend. They then observed an amazing coincidence between the limit of fracturing and the height of the chimney, and with this observation they were able, for the first time, to suggest a reason for the anomalously small chimney (only three times the cavity radius) observed in dolomite. Figure 5 is the view of the chimney region that has resulted from all of these conclusions. Note the presence of a spherical fractured region extending in all directions from the explosion point and a chimney resulting from migration of the cavity upward just through the fractured zone.

Later, in the sessions titled "Underground Nuclear Effects I and II," the calculational and experimental methods that allow analysis such as shown in Fig. 5 will be discussed in great detail.

Taking nuclear excavation as a completely different example, the development of the understanding of crater dimensions as a function of explosive yield and depth of burst can be followed. In 1961, Milo Nordyke[12] presented a brief history, analysis, and theory of cratering. He concluded from the analysis of a large number of events in desert alluvium that crater dimensions could be defined by scaling the 3.4 root of the energy and that a curve, as shown in Fig. 6, could be used to derive a radius and depth, given an explosive yield and depth of burst. In addition, he suggested that the calculational method later developed and presented by Knox and Terhune[1] might be used to compute crater dimensions from more basic input parameters. In his paper in 1964, after the presence of subsidence craters was noted in desert alluvium, Nordyke modified the curves to include the effect of material compaction. Figure 7 is his presentation of the radius as a function of depth-of-burst scaling curve

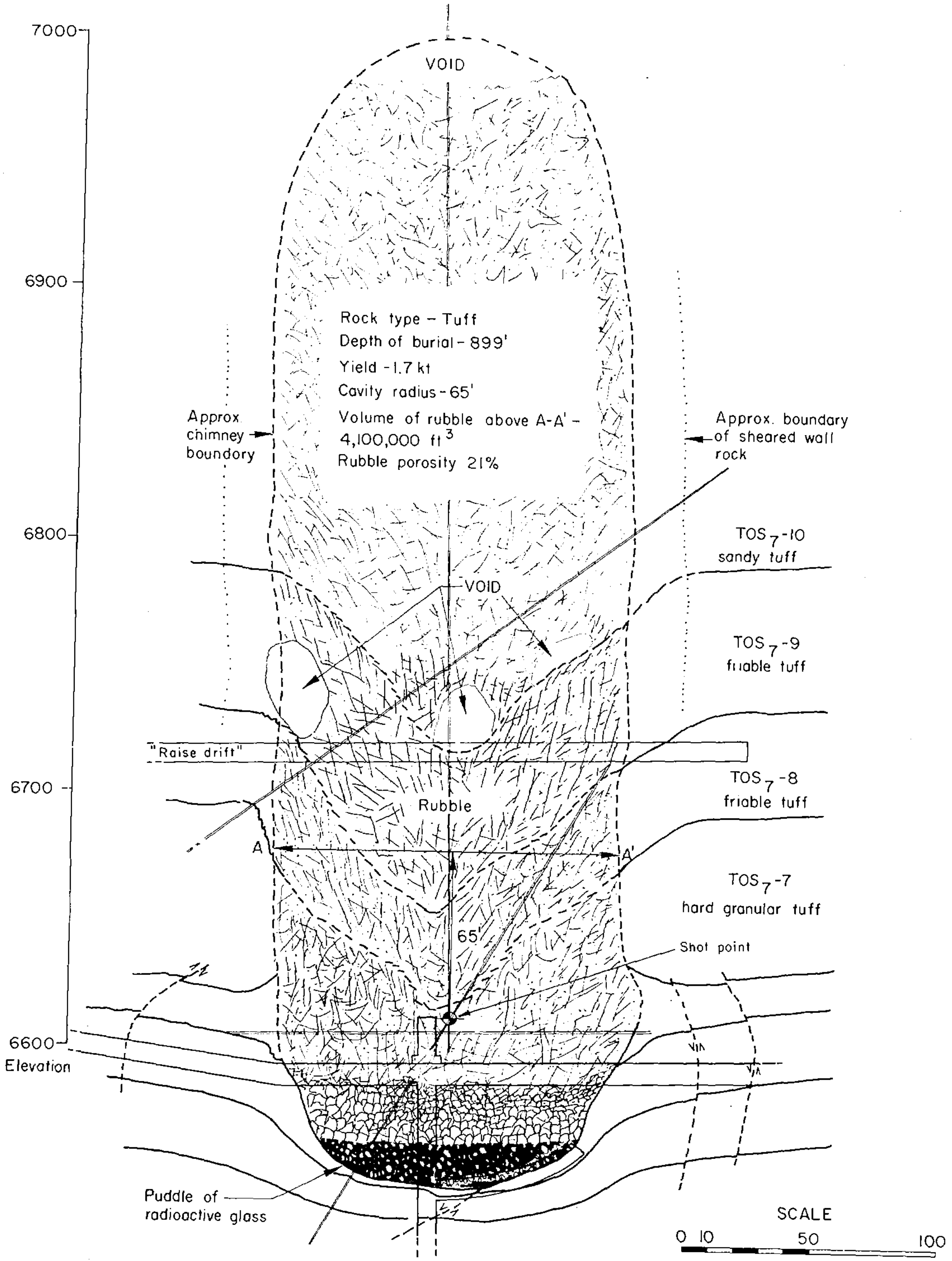


Fig. 4. Rainier schematic cross section.

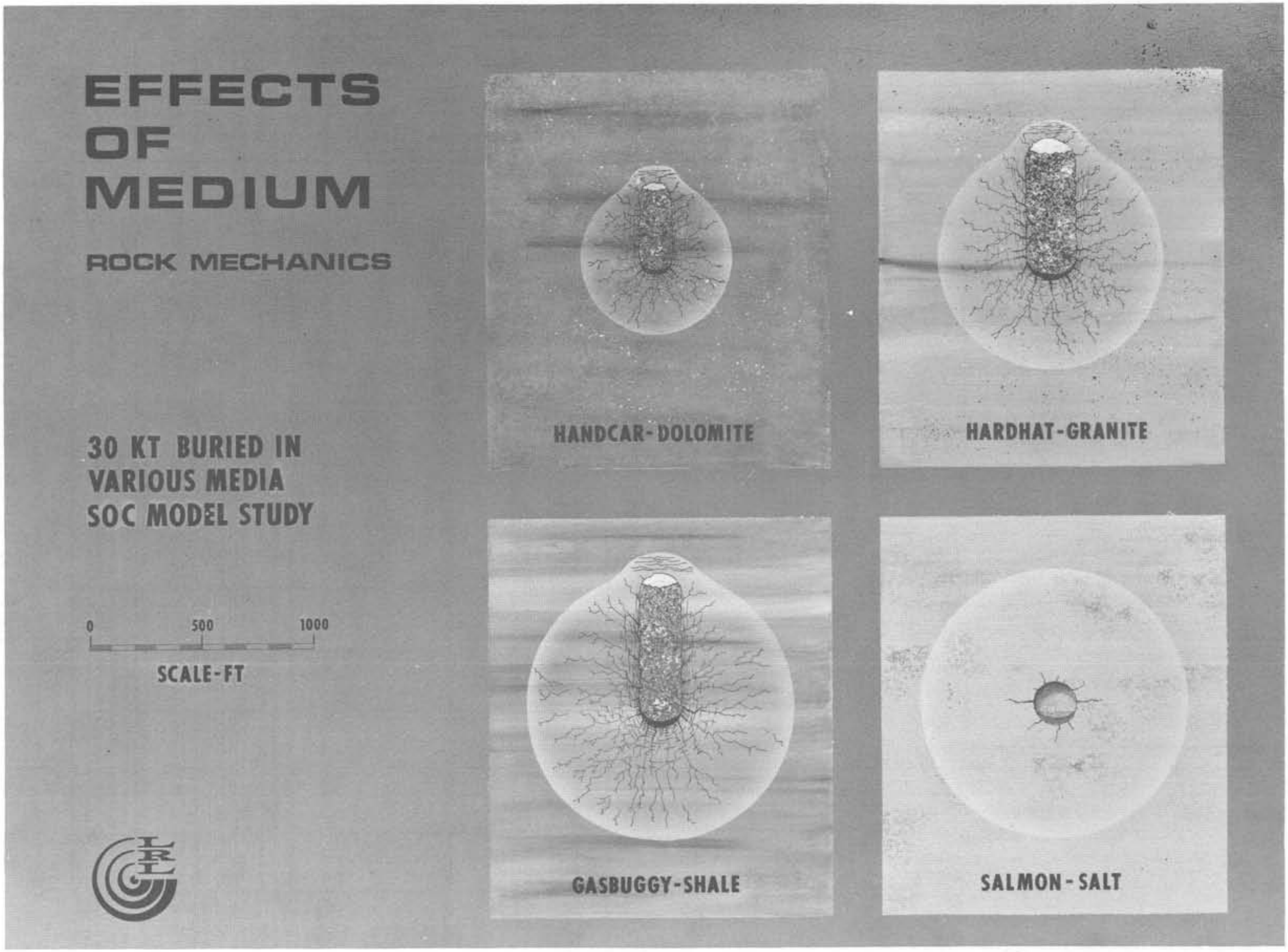


Fig. 5. Effects of the medium on a 30 kt shot.

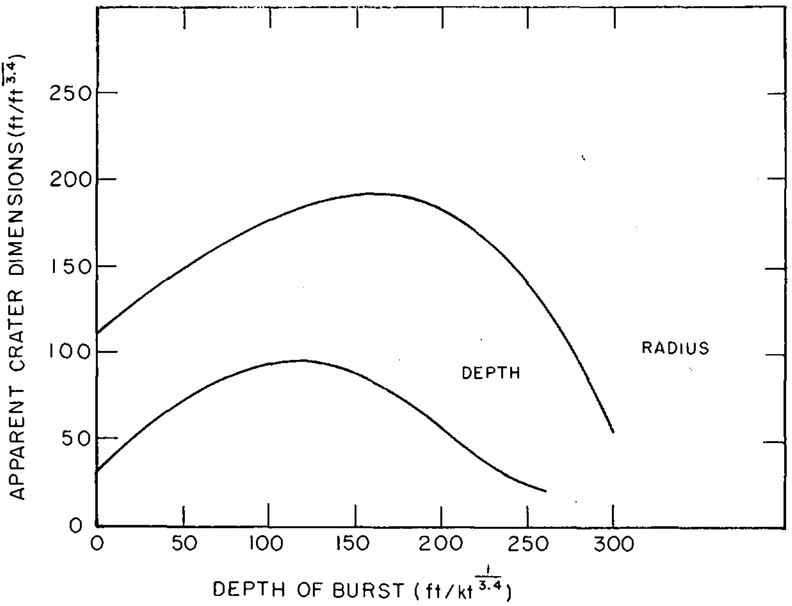


Fig. 6. Correlation of apparent crater dimensions with depth of burst for NTS alluvium. Curves were fitted to the data by least squares. Data are from HE craters.

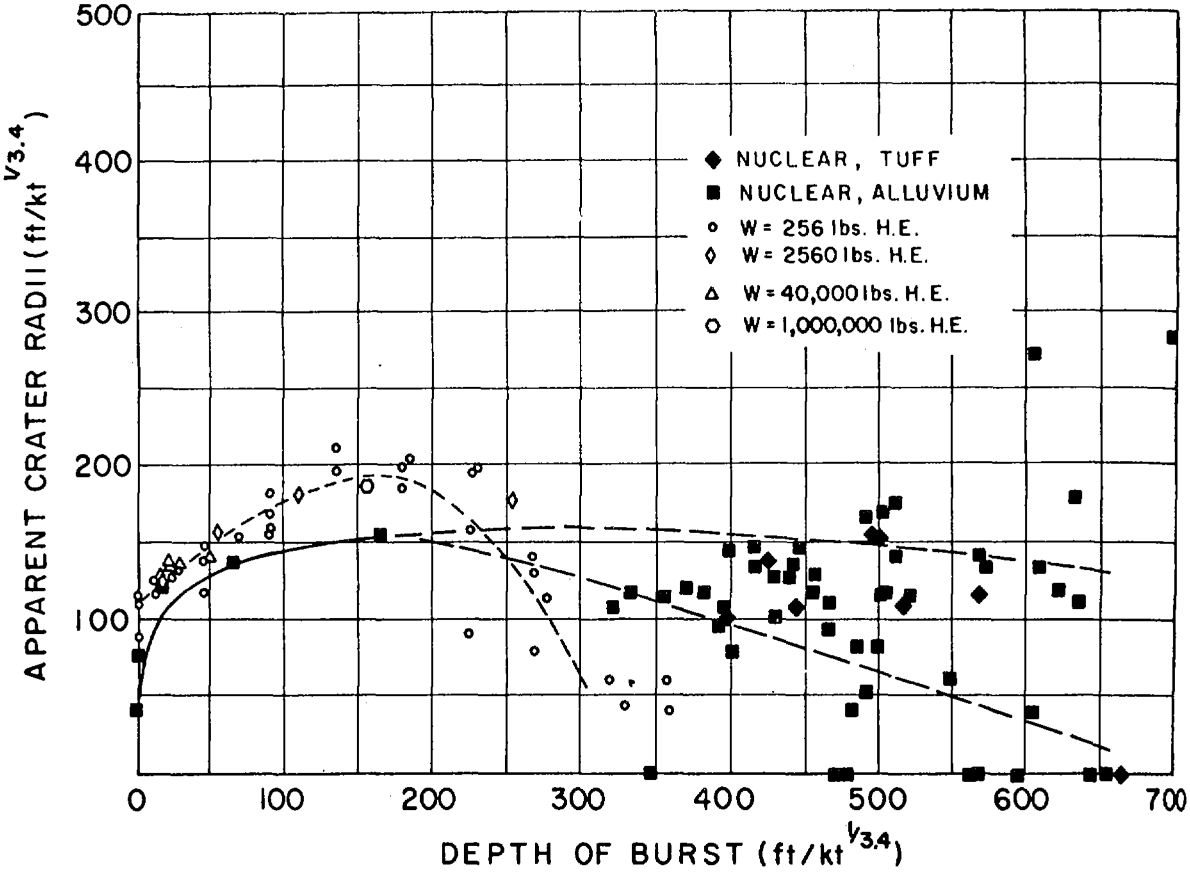


Fig. 7. Correlation of HE and nuclear explosive apparent crater radius with depth of burst for NTS desert alluvium.[1]

still using the 3.4 root of yield. Figure 8 is his presentation of the data as it then existed, applied to basalt. After an additional nuclear experiment in basalt, in which no crater was produced by a nuclear explosion buried at a scaled depth of 183 $\mathrm{ft}^{1/3.4}$, Johnson and Higgins analyzed the same data as shown in Fig. 9.

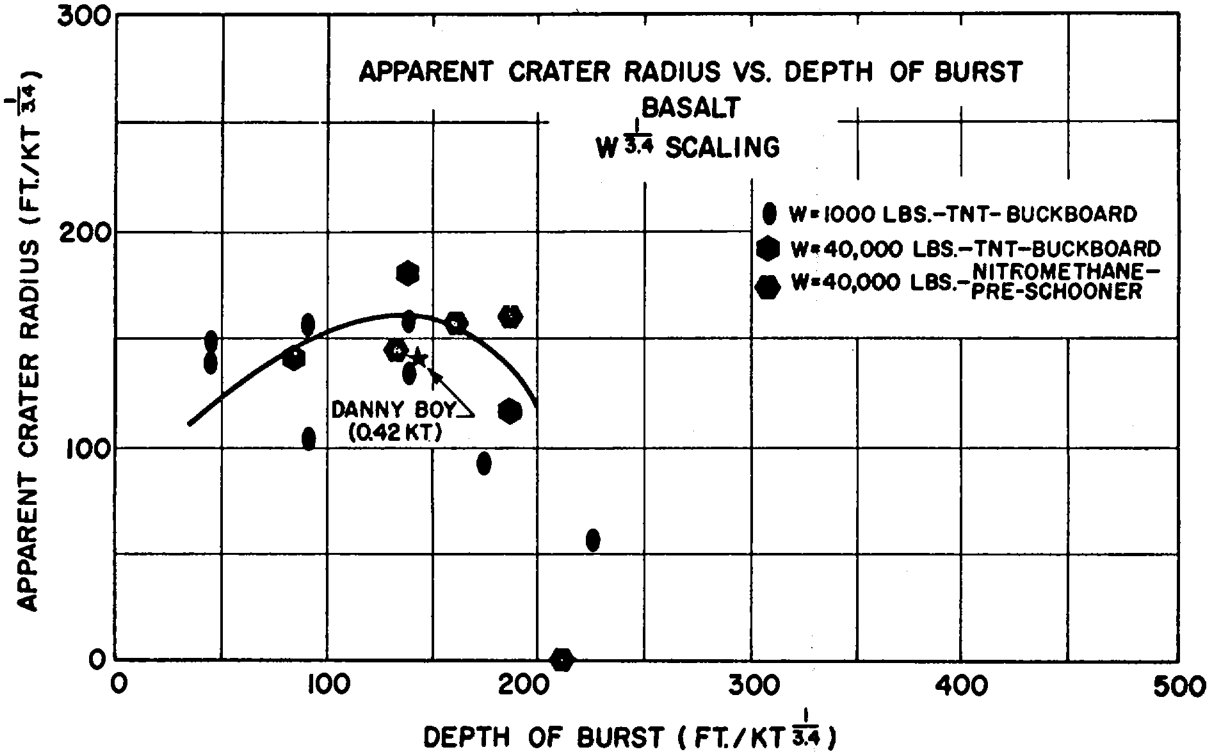


Fig. 8. Correlation of HE and nuclear explosive apparent crater radius with depth of burst for basalt.[1]

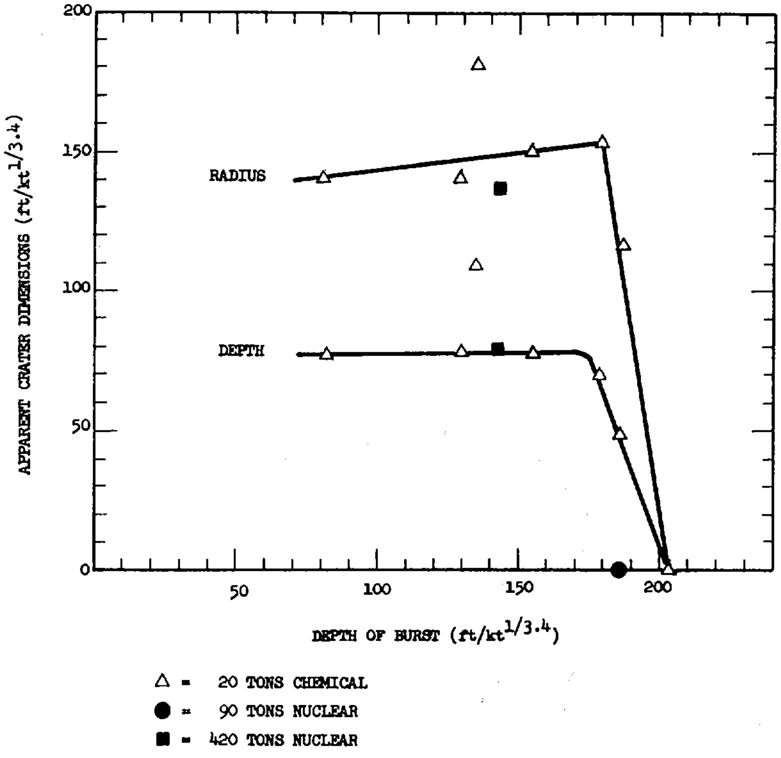


Fig. 9. Fig. 8 reworked using newer data.[13]

The dilemma presented by the failure of the Sulky Event to crater stimulated research efforts in understanding cratering on a more fundamental basis. The development of the understanding of fracturing and materials properties discussed earlier was, at about this time, extended to the two-dimensional problem of cratering using the TENSOR calculation. This evolved through several field experiments and continuing laboratory research until the cratering curves shown in Fig. 10 were calculated. The afternoon session "Excavation I" contains a more detailed discussion of these results.

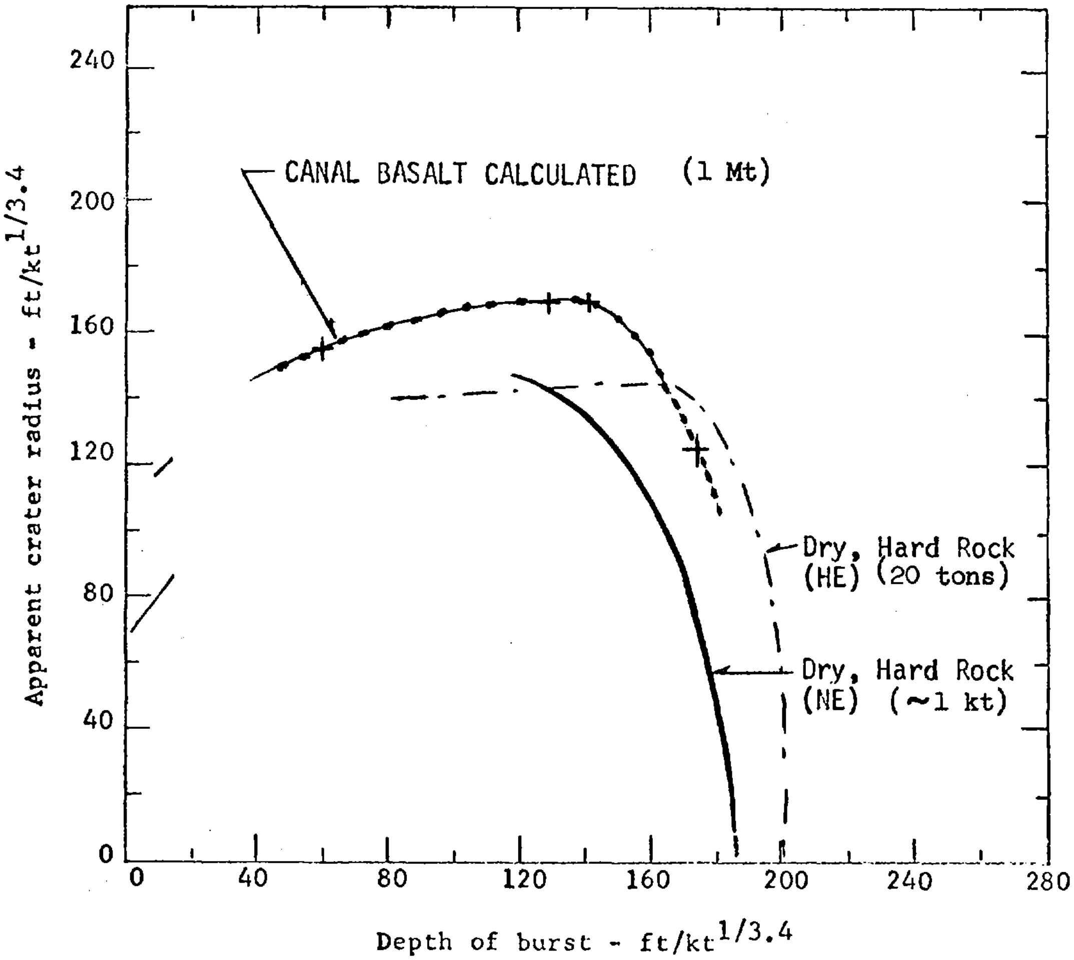


Fig. 10. Further refinement of the correlation of apparent crater radius with depth of burst.

CONCLUSIONS

Examination of past research developments permits one to speculate about the next steps that are likely to be taken in understanding nuclear explosion phenomenology. It is apparent that the application of nuclear explosives to oil shale retorting, minerals recovery, and gas stimulation all depend rather critically on the permeability of the chimney and the fractured region. Although it is now possible to calculate the extent of the fractured region, there is no satisfactory way now available to assess its permeability. There are experimental observations in which no apparent change in permeability follows fracturing. There are other cases in which the permeability seems to vary nonlinearly from a high value near the boundary of the chimney to the value of the preshocked rock at approximately the limit of fracturing. Other possibilities can be imagined, and considerable field and research work will be necessary to determine the parameters that govern permeability.

Practical application of nuclear explosives to gas stimulation depends on detonations at considerable depths of burial—10,000 to 20,000 ft. The current understanding of the effect of confining pressure on materials suggests that many materials will not fracture from explosions at these great depths but the explosions will cause only in spherical cavities surrounded by plastically deformed rather than fractured rocks.

It is also known that pore pressure in rock mitigates the effect of increased confining pressure, causing fractures to occur at a greater than expected depth. No tested method for including the effect of fluid in pores is yet available in the material models used for calculating induced fracturing. Understanding this has particular significance both in understanding the extent of fracturing at great depth applied to gas stimulation and, perhaps, in an increased understanding of the causes of deep-focus earthquakes.

The application of nuclear explosions to construction of harbors and canals is limited by safety considerations of the effects produced by ground shock or air blast. Each of these, in turn, is related to the amount of explosive energy required to create a given excavation. The gas that does the work of excavation in a nuclear explosion is created by shock vaporization. The larger the amount of gas for a given explosive energy, the more work can be accomplished with the same yield. The details of the vaporization process of rock after it has been subjected to high pressure are presently unknown. Limited experience suggests that considerably more gas is produced than is presently assumed. If so, estimates of crater dimensions at larger explosive energies may be underestimated, and unnecessarily conservative safety restrictions may be imposed. These are but a few ideas; as new applications are examined in greater detail, other research questions will undoubtedly arise.

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