UNDERGROUND PHENOMENOLOGY: SUMMARY AND CONCLUSIONS  
Second Protective Construction Symposium

Compiled by
Chairmen of Special Sessions  
(Harold L. Brode, General Chairman)

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PREFACE

The summary and conclusions contained in this research memorandum will also appear in RAND Report R-341, *Proceedings of Protective Construction Symposium*. They are presented in this form as a convenience to the reader who is concerned primarily with the findings of the sessions on underground phenomenology.
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I. SUMMARY AND INTRODUCTION

In conjunction with the Second Symposium on Protective Construction, held at The RAND Corporation (24-27 March 1959), a relatively small group of technical people met to explore the present status and the probable future of research into the underground phenomena associated with air or surface burst nuclear explosions. Emphasis in the main symposium was on construction techniques and practical problems, while the small working group was principally concerned with the physical phenomena related to the survival or failure of deep underground structures.

This effort was prompted by the need for a review of present knowledge of the basic phenomena, and more importantly by the need for suggestions as to how the physical understanding of these phenomena could be improved. The range of pertinent phenomena, extending from the earliest phases of cratering, through the propagation of various waves and including the interaction of these waves with underground structures, is very broad. For this reason, and also to facilitate productive discussion, the group was arbitrarily divided into three sessions, meeting separately at least part of the time, to concentrate on specific portions of the phenomena. The groups, with their chairmen are listed below:

CRATERING GROUP

Dr. Curtis W. Lampson, Chairman--Ballistic Research Laboratories

Mr. Donald Anderson--Armour Research Foundation

Dr. Robert Bjork--The RAND Corporation

Dr. Harold L. Brode--The RAND Corporation
Dr. Nancy Brooks--The RAND Corporation

Commander W. J. Christensen--Bureau of Yards and Docks, USN

Dr. J. E. Hill--The RAND Corporation

Dr. M. Kornhauser--General Electric

Dr. John G. Lewis--Armed Forces Special Weapons Project

Dr. J. L. Merritt--University of Illinois

Dr. B. F. Murphey--Sandia Corporation

Dr. Gene Pelsor--University of California Radiation Laboratory

Mr. Beauregard Perkins--Ballistic Research Laboratories

Dr. John S. Rinehart--Colorado School of Mines

Dr. Donald Sachs--Stanford Research Institute

Dr. Ted Schiffman--Armour Research Foundation

Dr. Richard Skalak--Columbia University

Dr. Fred Smith--Colorado School of Mines Research Foundation

WAVE PROPAGATION GROUP

Professor Daniel C. Drucker, Chairman--Brown University

Dr. Douglas Anderson--The RAND Corporation

Dr. Millard F. Barton--Space Technology Laboratories

Professor Hans Bleich--Columbia University

Dr. Chi-Chang Chao--Stanford University

Professor J. W. Craggs--Brown University

Dr. Frank L. DiMaggio--Columbia University

Mr. Wilbur Duvall--U.S. Bureau of Mines

Dr. Samuel Genensky--The RAND Corporation

Dr. B. F. Howell, Jr.--Pennsylvania State University

Dr. Carl Kisslinger--St. Louis University
Mr. Robert Loofbourow—Mining Engineer

Dr. E. L. McDowell—Armour Research Foundation

Professor Julius Miklowitz—California Institute of Technology

Professor Nathan Newmark—University of Illinois

Dr. Blaine R. Parkin—The RAND Corporation

Professor John Rinehart—Colorado School of Mines

Dr. Fred Sauer—Stanford Research Institute

Professor Werner E. Schmid—Princeton University

UNDERGROUND STRUCTURES GROUP

Mr. Paul Weidlinger, Chairman—Weidlinger Associates

Dr. Lawrence Adler—Michigan College of Mining and Technology

Dr. Melvin L. Baron—Weidlinger Associates

Professor Stefan Boshkov—Columbia University

Mr. William Brown—The RAND Corporation

Mr. Albert Cahn—The RAND Corporation

Professor Freeman Gilbert—University of California, Los Angeles

Professor Niles Grosvenor—Colorado School of Mines

Dr. John D. Haltiwanger—University of Illinois

Mr. William R. Judd—Geotechnical Consultant

Mr. John Lynch—Office of Civil and Defense Mobilization

Mr. Hubert Moshin—The RAND Corporation

Mr. Thomas Morrison—American Machine and Foundry Company

Mr. David Singer—Armour Research Foundation

Dr. R. B. Vaile, Jr.—Stanford Research Institute
Mr. Eric Wang--Air Force Special Weapons Center

Dr. Merit P. White--University of Massachusetts

The body of this report consists of the separate conclusions of each of the three sessions as prepared by each chairman. Although the summaries and conclusions of each of the sessions were arrived at separately, and on most points represent the consensus of that session, the present form of this report was reviewed by the entire working group.
II. COMMITTEE REPORT ON CRATERING AND RUPTURE

1. The Committee is tremendously impressed with the hydrodynamic model crater calculations of Drs. Brode, Bjork and Brooks and urges that:
   (1) the calculations be carried to a level of pressure at least equal to the detonation pressure of an HE charge and as far beyond as seems reasonable to the group; (2) a similar calculation be carried out for the case of a nuclear charge at two or more depths below the surface, of which one, at least, is deep enough so that surface effects are negligible; and
   (3) the same calculations be repeated for an HE charge to assist in the scaling process between HE and nuclear charges underground.

2. The Committee urges that additional calculation and analytical work be instituted to investigate the region between the crater and the limit of permanent deformation of the material. It is essential that such analytical work be coordinated with experiments designed to check the validity of the calculations. The Committee is cognizant of the difficulties of the task but believes that as many avenues of approach and skilful uses of approximations as can be found should be applied to this difficult problem.

3. The Committee believes that developments of the exploding wire technique for the production of explosive pulses and controlled media, such as plaster of paris, should be utilized for the laboratory investigation of the cratering and rupture zone formation. These results should be compared with micro-explosive charge experiments in the same medium.

4. The Committee believes that methods of investigation of the stress-strain curves of materials such as rock in situ at appreciable depths can
and should be developed in order to provide useful input data for the
analytical and computational approaches to the problems.

5. The Committee urges that pressure, and material motion data
directly underneath a surface-detonated charge be acquired. There appears
to be a great gap in our information concerning this region. This gap,
which has occurred because of the difficulty of making such measurements,
must be filled as soon as possible.

6. The Committee suggests that developed geophysical prospecting
methods such as refraction shooting and resistance survey methods, in
addition to the sand column technique, be exploited in order to delimit
the zone of rupture and permanent deformation as accurately as possible.

7. The Committee urges that refraction information and whatever
other underground measurements seem practical be incorporated in the
forthcoming Plowshare operation.

8. The Committee believes that an excavation of the Jangle "S"
crater should be conducted (if it still exists) with the objective of
determining the rupture zone and true crater size.

9. Addressing ourselves to the problem of desirable courses of
action in the three postulated situations, viz, (1) no future nuclear
tests, (2) deep underground tests only, and (3) possible future nuclear
surface tests, we arrived at the following conclusions:

a. No future nuclear bursts:

A series of tests, similar to the U.E.T. series in Utah,
using moderate-sized explosive charges of special shapes,
should be conducted in a rock site, with the express objective
of measuring the effects directly beneath a charge on the
surface and at various heights close to the surface. This test series should utilize the results of the RAND calculations and whatever other analytical approximations are developed as a mutual check and guide for the instrumentation.

b. Deep underground shots only:
We believe that drilling and refraction techniques should be explored with the objective of delimiting the zone of rupture and permanent deformation, if possible, in order to compare with the planned RAND calculations of the radii of these zones. Measurements of acceleration, pressures, and pulse arrival times are assumed to be a part of such experiments in any case.

c. Nuclear surface burst:
The same suggestions as for no testing or limited testing, with emphasis on measurements directly under the charge. Crater sectioning the sand column techniques should be applied in addition. A great need was expressed for the development of a small, self-recording pressure gauge to be buried in the sand column and later recovered when the sand column is excavated.

**ADDENDUM:**
Considerable interest was expressed on the applicability of high-speed-impact cratering information to the nuclear cratering problem. The advantage of this method of crater formation, if it proves to be
applicable, is that the energy density at the impact point can be varied over wide ranges in contrast to the use of HE for this purpose. RAND calculations should shed light on the problem of applicability.
III. COMMITTEE REPORT ON WAVE PROPAGATION

The Underground Wave Propagation Group attempted to establish the information which is presently available on the free field problem* and to determine the direction in which present and future research should go. As the discussion progressed it became apparent that definitive conclusions on the problems of immediate interest could not be formulated, because much of the necessary basic information has never been determined.

We started, therefore, with an analysis of the types of problems to be studied. Most attention was devoted to two special cases, the near miss and the direct hit, Fig. 1.

Fig. 1—Schematic diagram showing relative positions of underground shelters and surface burst crater for a near miss at A or a direct hit at B

NEAR MISS PROBLEM:

In Fig. 1 the point A would correspond to the relative position of the target structure with respect to the crater from a surface burst. In this case the majority opinion was that the important loads on the

*The term free field wave propagation is defined to include the study of underground wave motions in regions of the medium which are not influenced by man made structures or, in a medium which contains no such structures.
structure would be induced from the expanding air blast. Others felt that important loads on the structure may also be transmitted through the earth directly from the crater zone. Rayleigh waves in particular may cause trouble. It was concluded that both possibilities should be examined.

A number of competent investigators are studying linearly elastic wave propagation in connection with this problem. Work is being carried out for the isotropic homogeneous elastic half space, and some plan to include the effects of variation of properties with depth and also to solve layered systems.

The wave propagation group recognizes the need to consider inelastic bodies as well, but feels that the elastic solutions will be an extremely useful guide for design and are a necessary first step in the problem of the near miss. A second step would be to assume a visco-elastic or a perfectly plastic material, but the mathematical difficulties are overwhelming.

**DIRECT HIT PROBLEM:**

The point B of Fig. 1 shows the position of the underground target with respect to the crater after a direct hit. The wave propagation group also considered the case in which the shelter was located off the vertical axis of symmetry. They could not find any simple problems which might aid the designer but looked forward to the axially symmetric elastic wave solution considered above.

In the case where the target is centered directly under the crater it appears that there are some relatively simple idealized problems which one may study in order to gain a physical feeling for the effects of real materials and the inhomogeneities which are present in the earth's crust.
The actual problem has pressures applied to a cavity at the surface of a half space (Fig. 2). The replacement, which is far simpler, is a cavity in an infinite body (Fig. 3). Interaction between the waves and the actual free surface are thus ignored.

Fig. 2—Pressures acting on a spherical cavity in a half space

Fig. 3—Problem reduced to one of spherical symmetry by omitting the presence of the ground surface
When results from the cratering study become available they should be used in the formulation of the boundary conditions on the spherical cavity. Also, as shown in Fig. 4, the center of the cavity may be displaced upward from the ground surface position when interpreting the meaning of the solution, if the results from the cratering study make this step seem desirable.

![Diagram of cratering study](image)

**Fig. 4 — Center of cavity displaced from ground surface**

The range of problems to be considered should include inhomogeneous as well as homogeneous media. Examples are the propagation of spherical waves through a medium whose properties vary continuously with radial distance, a medium composed of homogeneous spherical layers, and perhaps also a medium containing inhomogeneous layers. Various idealized materials should be assumed which under appropriate conditions simulate the salient
features of the behavior of actual materials in the earth. A list of such materials together with schematic stress-strain diagrams follows:

1. Linearly elastic

2. Elastic perfectly plastic

3. Elastic work hardening

4. Linear visco-elastic

5. Locking material

6. Perfectly inelastic locking material

7. Visco-plastic

Although the plane-wave problem is not much simpler than the spherical and is farther from physical reality, the group felt that much of value could be learned from its solution as well. An intuitive understanding of what is likely to happen to a complex wave requires as much of this background information as possible.

The group turned its attention next to the question of what experiments should prove valuable and how they might be performed. Possible experimental work was divided into three groups:

1. Laboratory determination of stress-strain relations from intermediate to very high rates of loading and with little
to very high lateral restraint. The suggestion was made that explosive charges be used and that both the plane strain case (thin disk) and the long bar be employed. Tests in situ are then required to establish the correspondence between laboratory and field.

2. Comparison of experimental results with the theoretical predictions which are now known and those which will become available. Stress-strain relations established by (1) are to be employed for simple one-dimensional problems of plane wave propagation and spherical symmetry discussed previously.

3. Predictive experiments should be attempted to provide direct design information. This is the last step in the sequence of experiments and both in situ and laboratory experiments should be considered. The group as a whole felt that the possibility of modeling on a laboratory scale was remote but should not be discouraged. They also pointed out that valuable basic design information could be obtained from specific tests in situ which were not necessarily model tests, nor full scale.

A considerable discussion was held on the matter of instrumented field tests designed for some immediate purpose unconnected with the free field problem and for which little time could be spent on planning for this purpose. It was felt very strongly that money should not be spent in this manner. Well planned and instrumented free field tests are essential and should be carried on simultaneously and with equal priority.

Although much time was spent on the question of instrumentation, and the enormous difficulties of measurement in the free field were the subject
of repeated comment, it was felt premature to suggest appropriate instrumentation at this time. Stress measurements in the free field are especially difficult and seem to be impossible at present.

Mr. Wilbur Duvall brought to the attention of the session some experimental results, obtained by means of high explosive charges, on the propagation of waves in rock. These measurements were made on the materials in situ and most observations were carried out at stress levels which one might have expected to be within the elastic regime for the rock. However, it was found that stress pulses decayed with distance nearly as \(1/r^2\). Had the medium behaved elastically the attenuation with distance would have been proportional to \(1/r\), so that these results show a marked deviation from linear elasticity. Moreover in one sandstone layer it was found that the wave front steepened to form a shock.

Several times during the two-day meeting, attention was turned to the influence of the expanding air pressure pulse applied to the surface, on the stresses induced by a direct hit. The feeling of the Chairman was that an order of magnitude calculation demonstrated that significant stresses could not arise from these pressures. Two figures were compared. One, Fig. 5, showed the impulse induced by the air pressure, which Dr. Brode* has computed to be in the neighborhood of 500 psi-seconds. The other was obtained from extrapolation of results for water as given in the monograph edited by Glasstone, *The Effects of Nuclear Weapons*, 1956, Government Printing Office, page 217 Fig. 5.48. At a distance of 0.2 mile from

Fig. 5—Space plots for blast wave from a 20 megaton surface burst at various times after detonation

(A) Very intense pressures produced at very early times after detonation
(B) Pressures in blast wave at later times
surface zero a one kiloton explosion in deep water is said to produce 30 psi-seconds impulse and over 2000 psi. Using the scaling factor $W^{1/3} = 27$ for a 20 megaton burst, 810 psi-seconds at 5.4 miles is indicated. The impulse in water varies approximately as $1/r$ so that the impulse at 0.2 mile should be at least 20,000 psi-seconds. A comparison of the 20,000 with the 500 for the air pressure indicated to the Chairman a strong probability that the air pressure could be ignored. Furthermore, the pressure which scales to 2000 psi at 5.4 miles would be over 50,000 psi at 0.2 mile as compared with mean air pressures of the order of 1000 psi on the surface and more than one psi static stress for each foot of depth. It did appear correct to assume that the impulse transmitted to the water in a deep burst would be of the same order of magnitude as the impulse transmitted to the soil or rock in a surface or sub-surface burst. Attenuation in soil or rock would be likely to be much greater than for water but the chairman felt that stresses of 10,000 psi at a depth of 3000 feet were a strong possibility.

The group, however, felt that this question was a very difficult one which required much additional study, and it suggested that the comparison be made for an elastic solution in an effort to obtain an answer.

It is worth noting, in closing, that, although there are so many unsolved problems of great difficulty and so little is known about the physical properties of rock and of soil, the group felt optimistic about the successful accumulation of sufficient information for a rational design of underground structures. All were especially pleased by the report of Mr. Robert Loofbourow on available geological formations. Once it becomes clear that a particular geological configuration is desirable for the given application, it appears to be true that the site can be found in nature.
IV. COMMITTEE REPORT ON STRUCTURES RESPONSE

In this session four informal, but previously prepared papers, were given. Discussions were then directed to the topics of the papers. A portion of the remaining sessions was concerned with the discussion of a series of questions which were previously prepared by the chairman.

The first two papers discussed the responses of a cavity in an elastic space which is subjected to an incident elastic wave.

The first paper, by Dr. Baron, deals with a cylindrical cavity subjected to a constant-amplitude, incident stress wave carrying bi-axial stresses. The problem is solved by superposition of the stress field without a cavity and the stress field required to produce a traction-free cavity boundary. Computations are carried out by using the mode approach. Numerical data for the n = 0 mode are given for an incident wave of constant amplitude. The general method for higher modes is also given.

The second paper, presented by Professor Freeman Gilbert, considers an approximate solution of elastodynamic diffraction and scattering problems. This method is an extension of the geometrical theory of diffraction by Keller, 1958, and an extension of the first motion hypothesis (Knopoff and Gilbert, 1959). It depends on a modification of the usual laws of geometrical optics. From ray theory, modified to account for diffraction, the first term in the asymptotic series representation of the total solution to a problem can be determined even if the boundary shape of the scatterer is not a member of a separable coordinate system.

The solution gives sufficiently accurate results for high frequency components near the wave front. To obtain solutions of the field behind the front additional terms of the series are required, and the method may
lose some of its advantageous features. On the other hand, a special advantage of the method is that it is suitable for the solution of diffraction problems around smooth convex cavities of shapes which are not coordinate surfaces of the system.

The discussion of these papers centered around two main issues. First: can the proposed computations lead to useable numerical data in the near future? Both authors were able to assure the group that numerical calculations can be executed without extraordinary technical difficulties in relatively short time.

The second question was whether the assumption of an elastic medium as representing rock is tenable and realistic.

It was agreed that the elastic assumption will lead to a first approximation and that this problem must definitely be solved before other media can be considered. While some doubt was expressed regarding the feasibility of finding solutions for nonelastic cases, Gilbert suggested that his approach may be adopted with modification to visco-elastic media.

The third paper, by Mr. Singer, gave a summary of a study of the vulnerability of deep underground shelters in rock which had been prepared for the Office of Civil and Defense Mobilization. Free field data and crater dimensions are obtained by assuming spherical wave propagation, due to the application of a pressure pulse to the surface of a spherical cavity in an infinite homogeneous, isotropic elastic medium, (Selberg 1952). It is assumed that if the center of the sphere is located at an appropriate distance above the free boundary of an elastic half space, the spherical waves in an infinite medium might approximate the actual free field phenomena in the elastic half space. The effect of the resulting stress
waves on the cavity itself is obtained from the static stress concentration factors obtained by loading of an elastic plate containing a circular hole. Dynamic photo-elastic methods are discussed, but the speaker stated that while these experiments produce fringes similar to those of static tests, no estimates were currently available regarding the intensity of the principal stresses from the dynamic loading due to an incident plane wave.

Numerical computations have indicated that openings of about 35 feet diameter, placed at a depth of 800 feet below ground zero in strong rock, may be damaged by a surface burst in the kiloton range.

During the discussions, the consistency and the appropriateness of the methods were questioned. The speaker stated that these computations are at best approximate, yielding only order of magnitude information. It was brought out, however, that a similar classified investigation conducted a number of years ago by American Machine and Foundry led to results which were comparable to the data presented.

The next paper, by Dr. Vaile, concerned itself with the problem of repeated shots. He stated that most structures will be of such nature that pressure ranges, under which they suffer no damage or total damage, differ at most by a factor of two. He further pointed out that the probability of experiencing loads within a factor of two of the collapse load, considering CEP's and overpressure decay rates, is small for multiple shots. A structure which will survive a single shot is very likely not to be affected by a number of equal or sufficiently lesser intensity load applications. He concluded, therefore, that design for single shot survival was a reasonable procedure.
The discussion brought out that these computations are directly confirmed by the inspection of the usual formulas which give the probability of kill assuming a standard distribution of the individual shots, but that the conclusions are realistic only if none of the shots is of such intensity that it will produce residual stresses, that is, no yielding will occur. However if yielding should occur the stresses produced by further load applications will be additive to previous residual stresses. This is always the case in statically indeterminate structures, and since the cavity itself must be considered as highly indeterminate, it may be advisable to set the vulnerability of such tunnels at a level which will insure that elastic stresses only will be produced. On subsequent discussions by the three groups it was expressed that it may become difficult under these assumptions to design underground tunnels which may be located directly under ground zero because of the estimated high intensity of the incoming stress waves.

Further discussion ensued on the problem of failure mechanisms and failure initiation. It was the consensus of the group that at the present time there is no sufficient theoretical or practical background to conjecture regarding the most realistic strength theory to be applied. There was some feeling that direct tension failures may be of significant importance. It was also proposed that a realistic lower bound may be obtained by neglecting the tensile strength of rock. This assumption is especially justified if the presence of closely spaced and scattered tensile cracks exist initially in the rock. During further discussion within the three groups it was proposed that it may be proper to design on the assumption that net tension around the opening would be zero. That is, the super-
position of gravity, tectonic and dynamic stresses due to the incident wave should, at most, produce zero tension around the cavity.

The remaining parts of the session were devoted to a series of specific questions. The first set of questions were concerned with the effect of discontinuing nuclear tests. It was the opinion of the group that if nuclear tests are not to be conducted in the future the resulting loss of information can at least partially be replaced by intensified theoretical work, laboratory tests, and high explosive tests. It was also agreed that if nuclear tests are to be conducted, the selection of a more suitable test site more pertinent to the problem at hand, together with the explosion of multimegaton weapons should lead to the most desirable type of experiments. On the other hand, it was felt that small-yield kiloton tests or high explosive tests must be interpreted with a great deal of caution and should not be extrapolated to high yields by the usual and rather crude scaling methods. The group also felt that the greater difficulties which are usually encountered in the instrumentation of such tests and the impossibility of conducting repeated explosions make the carefully controlled and measured laboratory experiments seem quite attractive, and sufficient attention should be paid to these. The second group of questions considered the type of theoretical investigation which should be practiced. Intensified investigations should be conducted both in elastic and nonelastic media to determine: stress and velocity fields in the neighborhood of the cavity; failure criteria and failure mechanisms; effects of an elastic boundary in the cavity (i.e. linings); and shock effects on the contents of tunnels.
It was suggested that these investigations, if possible, should be carried out numerically for an entire range of assumed peak pressures, and that this theoretical work should ultimately lead to a simplified engineering method, or at least to the extensive tabulation of data suitable for design purposes.

The group also felt that while no specific consideration was given to phenomena occurring in soil these should not be neglected, and it has recommended that similar or parallel investigations should continue for this medium also. It was also agreed that in order to give maximum meaning to numerical computations it will be essential that these be accompanied by laboratory and field tests to test the reliability of the proposed theories. At the same time it was pointed out that currently a greater need exists for the development of more suitable instrumentation.

The next set of questions concerned itself with a series of design problems. The group has attempted to express its preliminary opinion or feeling at least on a number of questions which are very essential for engineering and current planning decisions, but which can only be accurately answered after all previously proposed theoretical and experimental investigations have been concluded. With these qualifications the group was able to give only some very general guidance regarding these problems.

It was felt that although theoretical investigations initially indicate that the intensity of the stress field around the boundary of a cavity in an infinite medium is independent of the size of the cavity itself, in practice it will be preferable to keep at least one dimension as small as practicable; i.e., in order to provide a required amount of floor space it will be preferable that this be provided in the form of an essentially
long tunnel, or several such tunnels instead of large dome-like excavations. This approach is also specified by certain geological considerations, inasmuch as it appears likely that the type of construction suggested above will be more easily located in horizontally bedded sound rock strata.

The next question considered was the depth of these proposed tunnels or cavities. It was felt, as expected, that deep tunnels will be preferable to shallow ones, provided that gravity pressure and tectonic stresses are taken into consideration. These seem to put a definite limit on the depth at which these structures can be built. It was also felt that the effect of shock will less likely be of importance at greater depth. On the other hand, it was felt that the shock effects could be dealt with by suitable shock mountings. The trade-off between the use of shock mountings and greater depth of overburden is probably one of economy. In connection with these two problems, the group felt very strongly that each installation should be custom built, and consequently the preparation of standard plans should be avoided. Each site needs to be carefully and separately investigated, and the size and depth of each tunnel and cavity should be determined individually.

The next question was that of the spacing of tunnels. Since the only information currently available was that of static fields around openings it was suggested that, based on this evidence alone, the spacing of tunnels should be at least one diameter and preferably more, especially if the material around the tunnels is expected to be subjected to stresses which exceed yield strength.

Considerable attention was paid to the cross sectional shape of tunnels. The group essentially felt that the evidence of certain static tests seemed
to indicate that the actual shape of the tunnel doesn't have a great influence on the intensity of the stresses around the boundary. On this basis it was felt that generally rounded cross sections should be preferred. During further discussion within the three groups the opinion was expressed that, due to effects of reflection and refractions from layers below the bottom of the tunnel, it may become advisable to provide a round cross section around the bottom of the cavity itself, and the use of round or elliptical tunnels with the major axis vertical seems to have found favorable reception. On the other hand, considerations of static stresses and residual tectonic stresses again indicate that individual decisions must be made in each instance.

The next question concerned itself with the usefulness of tunnel linings, either independent of the tunnel wall or directly connected to it. The group felt that at the present time it is not able to determine the advantages and disadvantages of this type of construction, and this problem needs to be investigated in detail. It was felt that since the solution of a cavity with an elastic boundary in an acoustical medium has been worked out already (Baron, 1958) an extension of this work to an elastic medium appears to be feasible.

The group was unable to give specific guidance regarding the preferred type of medium in which tunnels should be placed. There was even disagreement regarding the advantages which may be obtained in either one of the two extreme cases considered, namely that of strong rock or soft soil.

It was felt that in connection with construction of large underground cavities, specific attention should also be paid to the vulnerability of
utilities and that the engineering problems connected with construction methods should also be carefully considered. There seems to be a need for the consideration of special and ingenious methods of construction and imaginative design solutions which may alleviate some of the problems that show up in the consideration of structures protected by rock.