A Numerical Analysis of the Mechanics of Gas Outbursts in Salt

M. A. Mahtab,[1] B. Trent[2] and T. M. Yegulalp[1]
[1]Henry Krumb School of Mines
Columbia University
New York, New York, USA
[2]Department of Civil and Mineral Engineering
University of Minnesota
Minneapolis, Minnesota, USA

ABSTRACT

This paper describes the results of a numerical approach used to study the mechanics of gas outbursts in salt, with particular reference to Louisiana dome salt mines. An example problem is analyzed using the two-dimensional STEALTH code, mining configuration based on the Belle Isle mine, and material properties extrapolated from data on the Weeks Island mine. The analyses consider the intact salt, a weakened salt ahead of the heading face, and a burst-prone, pressure pocket beyond the weakened salt. The results of the analyses are plotted, showing regions of burst rock ahead of the face. Recommendations are provided for further analyses of the mechanics of gas outbursts and for controlling their occurrence.

INTRODUCTION

This paper is concerned with the mechanics of gas outbursts in salt, but with particular reference to the dome salt mines in Louisiana. Gas outbursts in Louisiana dome salt are sudden eruptions of salt and gas from the face or roof of a mine opening. They accompany routine blasting in certain areas of the mine. The outburst cavity may be hemispherical or an elongated cavity with elliptical cross section. The diameter of these cavities may range from 1 to 30 m and their height or length may range from 1 to 50 m or more. The outburst may suddenly expel a few tons to tens of thousands of tons of salt and large volumes of gases. Prediction and prevention of gas outbursts in Louisiana salt mines (see location in Figure 1) is important to the industry for two main reasons:

1. As mining proceeds to deeper levels and through burst-prone salt on any level, the potential risks involve safety of personnel, damage to equipment and loss of production or even part of a mine. The potential risks from gas outbursts take on greater proportions when viewed against the background of storing hydrocarbons or nuclear waste in salt domes at depths of the order of 1,000 m.

2. The present classification of three of the four operating salt mines in Louisiana (Avery being excepted) as "gassy mines" introduces severe restrictions on productivity. Demonstration of a capability by the industry in predicting and preventing gas outbursts should help in removing the necessity for applying this classification.

The geomechanical aspects of gas outbursts are poorly understood and no satisfactory explanation of their mechanics and no methods for predicting and preventing their occurrence are available. The objectives of this paper are to summarize the important geotechnical considerations leading to the phenomenon of gas outbursts in salt, construct a numerical model for analyzing the mechanics of gas outbursts, report the results of preliminary analyses using the numerical model, and recommend areas for further study of this important phenomenon.

GEOTECHNICAL CONSIDERATIONS

Several major features of gas outbursts are common to various mines and minerals in various parts of the world (see Mahtab, 1982). Rice (1931) describes a gas outburst in coal as "the phenomenon of gas held in circumscribed areas under very high pressure and as a mining face or heading approaches such a place and the mining excavation sufficiently weakens the natural surrounding dam or shell, this is burst by the pressure." Gimm and Pforr (1964) discuss the nature of gas outbursts in potash mines of East Germany as follows: "Typically, a gas outburst cavity shows a conspicuous, thinly leaved, bed separation on its surface, the scale-like fissures or splinters being convexly curved to the axis of cavity. The salt thrown out

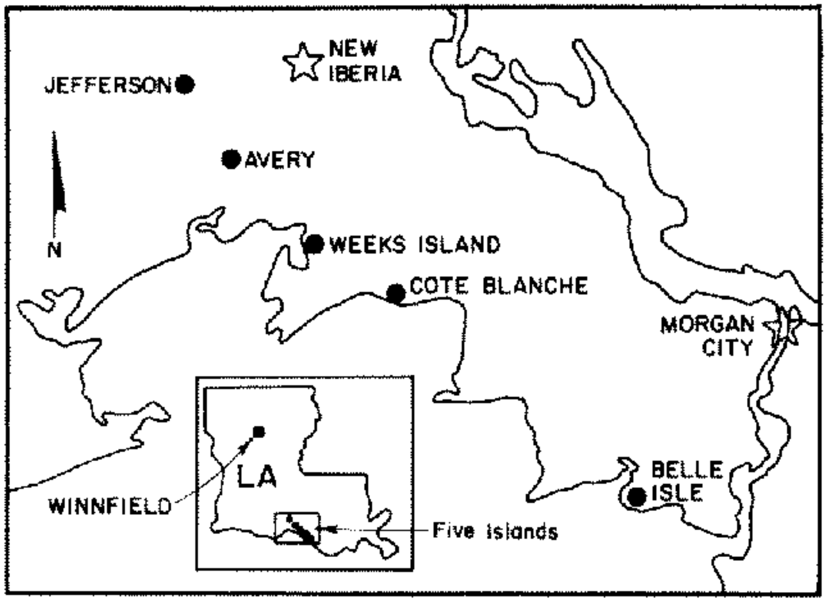

Figure 1. Index map of Louisiana dome salt mines.

is greatly broken up and, to some extent, pulverized. Gas outbursts occur when a room with a large free area approaches near enough to a horizon of rock geologically prone to outbreaks. At this distance the stress state in the 'active' rock changes from triaxial to biaxial or uniaxial, resulting in sudden failure of the rock and release of gas. The method of excavation (drill and blast, cutting, etc.) is unrelated to the occurrence of gas outbursts. Gas outbursts take the form of a chain reaction in which the characteristics of the gassy rock are significant. For instance, gas outbursts in Werra district occur in gassy zones that are located in proximity to young tectonic disturbances."

Both general and specific descriptions of gas outburst in Louisiana are given by Mahtab et al. (1979), Thoms and Martinez (1978), Kupfer (1978), and Plimpton et al. (1980).

Louisiana domal salt, according to Kupfer (1978), is medium-grained, vertically-bedded, and occurs in spines surrounded by inclusion-bearing anomalous salt. The anomalous zones (herein referred to as shear zones) are characterized by extensive shearing and tectonic lensing of the (included) sediments and by folded, black, impure salt. The inclusions, consisting of sediments, petroleum, brine and various gases, are of both primary and secondary origin.

The geometry of the shear zones is highly variable, but most shear zones are vertical and tubular. A typical shear zone may be from 3 to 100 m wide, of very long horizontal extent, and probably of large vertical extent (Kupfer, 1978, p. 121). Distribution of inclusion features within a shear zone is discontinuous and, in places, almost random.

In general, the burst-prone volumes of dome salt, to be referred to as "pressure pockets," are associated with the inclusion features in the shear zones and increased depth of mining. An illustration of a small gas outburst in a Louisiana salt mine is given in Figure 2. The outburst has occurred in the top left corner of a 7.5-m-high heading in a shear zone. The cavity is a semi-ellipsoid with its axis inclined up from the horizon at about 30°. The surface of the outburst cavity has those same conspicuous, scale-like fissures which were referred to earlier.

A survey of the geomechanical aspects of gas outbursts in Louisiana salt is given elsewhere (Mahtab, 1982). A summary of this survey is provided below.

The relative movement of spines in salt domes sets up nearly vertical zones or "pipes" of impure salt containing inclusions such as sediments and gas (Kupfer, 1978). The entrapped gas in the pipes is at least under the lithostatic pressure that corresponds to the depth of the mine (Kupfer, 1978; Baar, 1975 and 1977). Within a pipe, the distribution, shape and extent of a pressure pocket (with potential for generating gas outburst) is probably random, as evidenced by a clustering or complete absence of outbursts within short distances.

When an excavation approaches a pressure pocket containing heterogeneous and anisotropic material, there will be a preferential transfer of stress, thus increasing the level and anisotropy of stresses in the stiffer inclusions (Goodman, 1966; Leeman, 1964). In addition, the stored strain energy in the pressure pocket (containing sediments) will be higher than that in the surrounding salt, thus increasing the specific capacity of the pressure pocket for outbursts (Gimm and Pforr, 1964).

The concept of effective stress (Terzaghi, 1945) is of

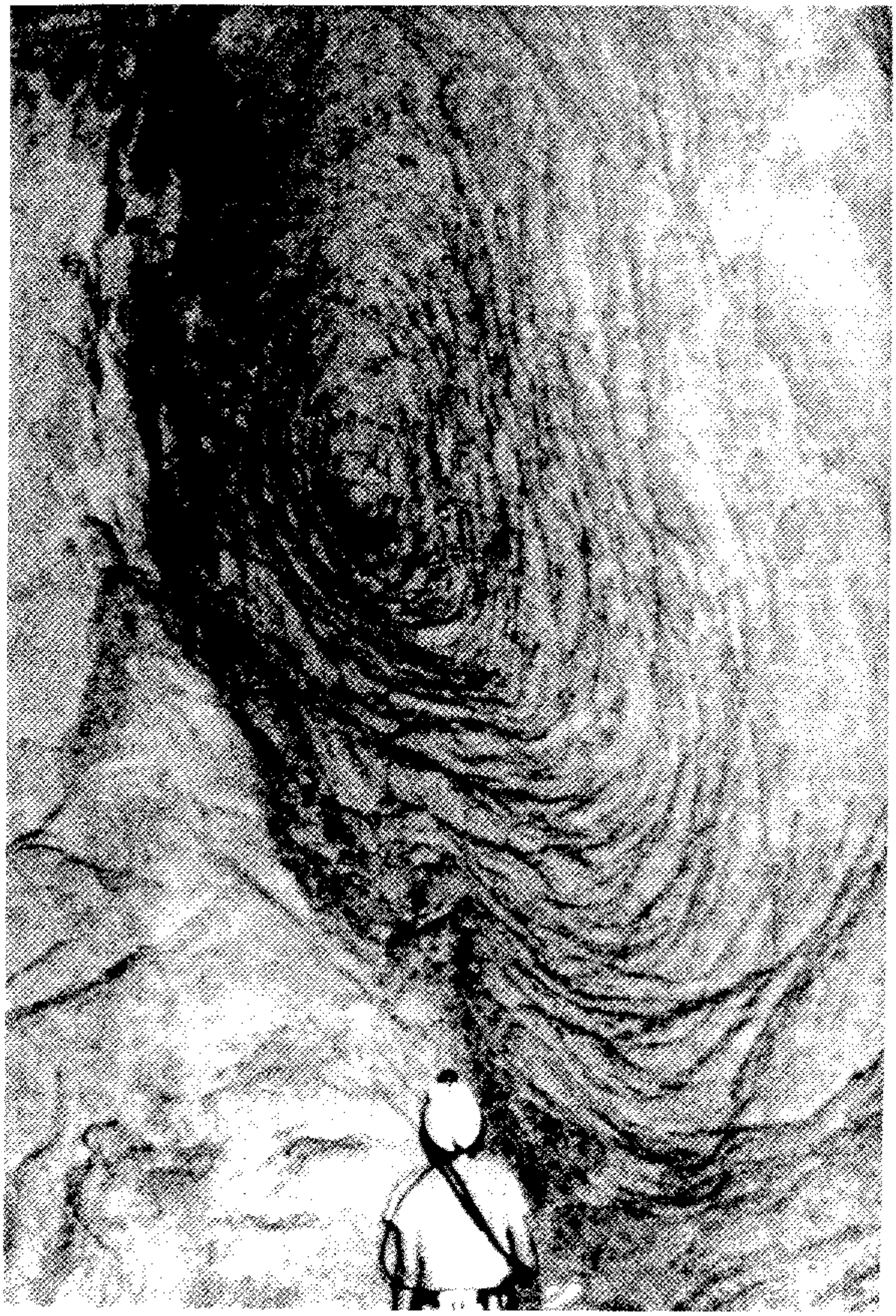

Figure 2. Typical gas outburst cavity in a Louisiana salt mine.

direct significance in studying the failure of rock containing interstitial fluids and may be interpreted in a criterion of failure by replacing the principal stresses σ_1, σ_2, σ_3 by the effective stresses $\sigma_1 - p$, $\sigma_2 - p$, $\sigma_3 - p$, where p is the pressure of the fluids. However, for pore pressure to be fully effective in reducing the stress, the fluid must completely permeate the pore space. In a low permeability rock, such as dome salt (see Mahtab, et al., 1979), the law of effective stress should hold under certain conditions, i.e., at low confinement when the rock is brittle and when some cracking has increased permeability (Brace and Martin, 1968).

The phenomenon of core "disking" is of great relevance to a study of gas outburst. Core disking is encountered in burst-prone areas (Gimm and Pforr, 1964) when the core breaks up into thin disks normal to the core axis. Jaeger and Cook (1963) subjected cylindrical rock specimens (containing a drill hole in which a stub of core was left) to biaxial compression, σ_r, normal to the axis of the hole. The core stub broke off at a value of σ_r of the order of, but less than, the uniaxial compressive strength. The fracture occurred at the bottom of the hole, was convex toward the solid, and had an appearance intermediate between that of an extension and a shear failure.

We note that the limited scope of this investigation allowed us to pursue the above-mentioned, broad, geomechanical considerations to a first level of understanding of the gas outburst phenomenon. Further investigations are continuing and their results will be reported in the near future.

ANALYSIS OF AN EXAMPLE PROBLEM

The problem selected for this investigation is largely a conceptual problem based on the typical configuration of a heading face in Louisiana salt mines and on strength of salt reported by Van Sambeek, et al. (1979). Several assumptions have been made in idealizing the problem for analysis. These are discussed in a subsequent section.

For numerical modeling and analysis of the problem, a Lagrangian, explicit, finite-difference code: STEALTH (Hofmann, 1976) was used. The problem was modeled as a quasi-static problem and solved by using density scaling and dynamic relaxation procedures (Hofmann, 1976; Trent and Langland, 1981).

Problem Idealization. The geometry of the problem is based on the room-and-pillar mining configuration used in the Belle Isle mine (Plimpton, et al., 1978, Appendix J), where the 19-m-wide rooms are supported by pillars that are 23-m-wide and 49-m-long. The total 25 m height of the rooms is achieved by first driving a 7-m heading and later blasting the 18-m bench. The heading face (19-m-wide and 7-m-high) is undercut by a 0.2-m-high and 3.7-m-deep kerf. The salt is then drilled to a depth of 3.7-m and blasted, using the typical "round" shown in Figure 3.

The problem is idealized for a numerical solution by making the following assumptions and approximations:

1. The room is considered to be sufficiently wide to permit a 2-dimensional, plane-strain idealization of the problem. A longitudinal section through the center of the room is discretized into a grid of 30 × 36, finite-difference zones, as shown in Figure 4.

2. The room is located at a depth of approximately 305 m (1000 ft). The in situ stress in the salt at this depth is assumed to be hydrostatic, with the principal stresses being $\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = 6.9 \times 10^6$ Pa, where x parallels the axis of the room and y parallels the vertical bisector of the heading face (see Figure 4).

3. The elastic moduli (Lame's constants K, bulk modulus; and G, shear modulus) for the salt are derived from the values reported for the Weeks Island salt (Van Sambeek, et al., 1979, Figure 2 and Table 3).

4. The unconfined compressive strength of four salt specimens (of diameter 0.152 m) as determined from the laboratory tests is given in Table 2 of Van Sambeek, et al. (1979). For the purpose of this study we have assumed the laboratory strength to be the average of the two lower values ($=10.5 \times 10^6$ Pa). For extrapolating the laboratory strength to in situ strength values, we used the formulation (Weibull, 1951):

$$\text{Strength Reduction Factor,} \qquad R = \left(\frac{V_l}{V_i}\right)^{1/m}$$

where

V_l = volume of laboratory specimen of diameter 0.152,

V_i = volume of representative in situ element (we selected a typical finite-difference zone, Figure 4, of side = 1 m),

m = shape parameter for Weibull equation (we selected m = 10 in the limiting range of the values suggested by Jaegar and Cook, 1979, p. 201).

Substituting the various values selected for V_l, V_i and m, we arrived at an initial, in situ, unconfined compressive strength of salt, C_0, of 5.8×10^6 Pa. We recognize that some of the assumptions made in arriving at the above value of C_0 may appear to be arbitrary. Nevertheless, the assumed strength is of the same order of magnitude as the reported laboratory strength and we believe that our assumptions are reasonable for the purpose of performing the preliminary analysis of the gas outburst problem.

(5) The criterion for failure of the salt used in this study is the von Mises criterion (Jaeger and Cook, 1971, p. 229):

$$(3J_2)^{1/2} \geq C_0$$

where J_2 is the second invariant of the stress deviators.

In presenting the results of the analyses (Figures 5 to

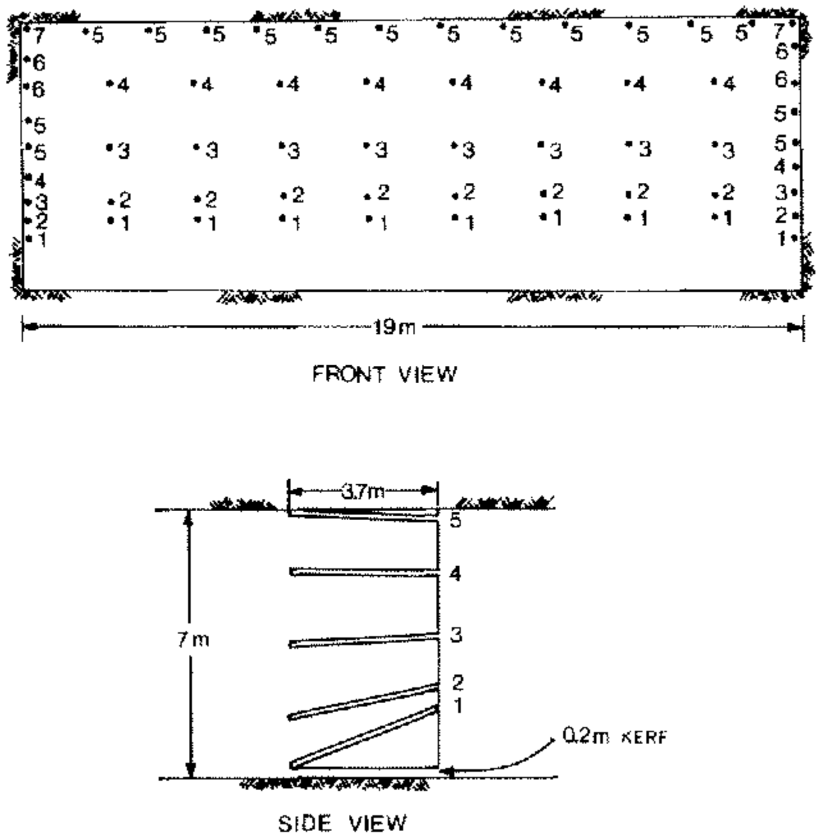

Figure 3. Typical face round for blasting a heading in Belle Isle salt mine (after Plimpton, et al., 1980, Appendix J).

9), we use the term "effective stress," σ_e, for the left-hand side of the above equation. Note that this terminology is used for convenience only and is not to be confused with the generally accepted definition of effective stress (Terzaghi, 1945) mentioned earlier.

Analyses and results. The properties of the different materials (types 1 to 6) used in the numerical analyses are listed in Table 1. The room and kerf (undercut) are modeled as air. Only the salt and the pressure pocket ahead of the face are allowed to further weaken after yielding according to von Mises criterion: $\sigma_e \gtrsim C_0$. This weakened region, where the strength of salt is reduced, or where the strength and shear modulus of the material in the pressure pocket are reduced, is called the burst zone.

A summary of the principal parameters studied in the various analyses is given in Table 2 and the results of the analyses are plotted in Figures 5 to 9.

DISCUSSION OF RESULTS

A comparison of the σ_e contours of Figures 5 and 6 shows the shift in the stress concentrations caused by the kerf (Figure 6). The plastic zones, as could be expected, will first develop near the edge of the kerf and the top of the face (Figure 7). However, for a situation where the plastic salt is not allowed to further weaken, or a weakened pressure pocket is not present near the face (as in Figures 8 and 9), the progress of the plastic zone is limited by the in situ strength of the homogeneous salt.

When a weakened salt zone (see Table 1) is modeled (Figures 8 and 9) ahead of the face, together with a vertical pressure pocket extending from the edge of the kerf to several meters beyond the kerf, plastic zones develop ahead of the face as well as in the roof and floor of the room. In addition, the properties of the material ahead of the face are changed subsequent to its yielding under von Mises criterion, using the initial strength, C_0. The strength of the weakened salt is now $1/10\ C_0$ and it is considered to be "burst salt."

When a volume element in the pressure pocket first yields according to von Mises criterion, using the initial strength C_0, the pore pressure in the element is presumed to have been mobilized. The strength of this element is reduced to $1/1000\ C_0$ (or nearly zero) and its shear modulus is reduced to $1/1000$ G. This reduction in G is assumed to correspond to a situation where pore pressures cannot dissipate rapidly and no shear stresses are allowed to develop. This technique (of reducing G) has been used with good results to model the behavior of saturated clays under pile-footings in a sea bed (Cundall, et al., 1980).

The weakened volume elements in the pressure pocket,

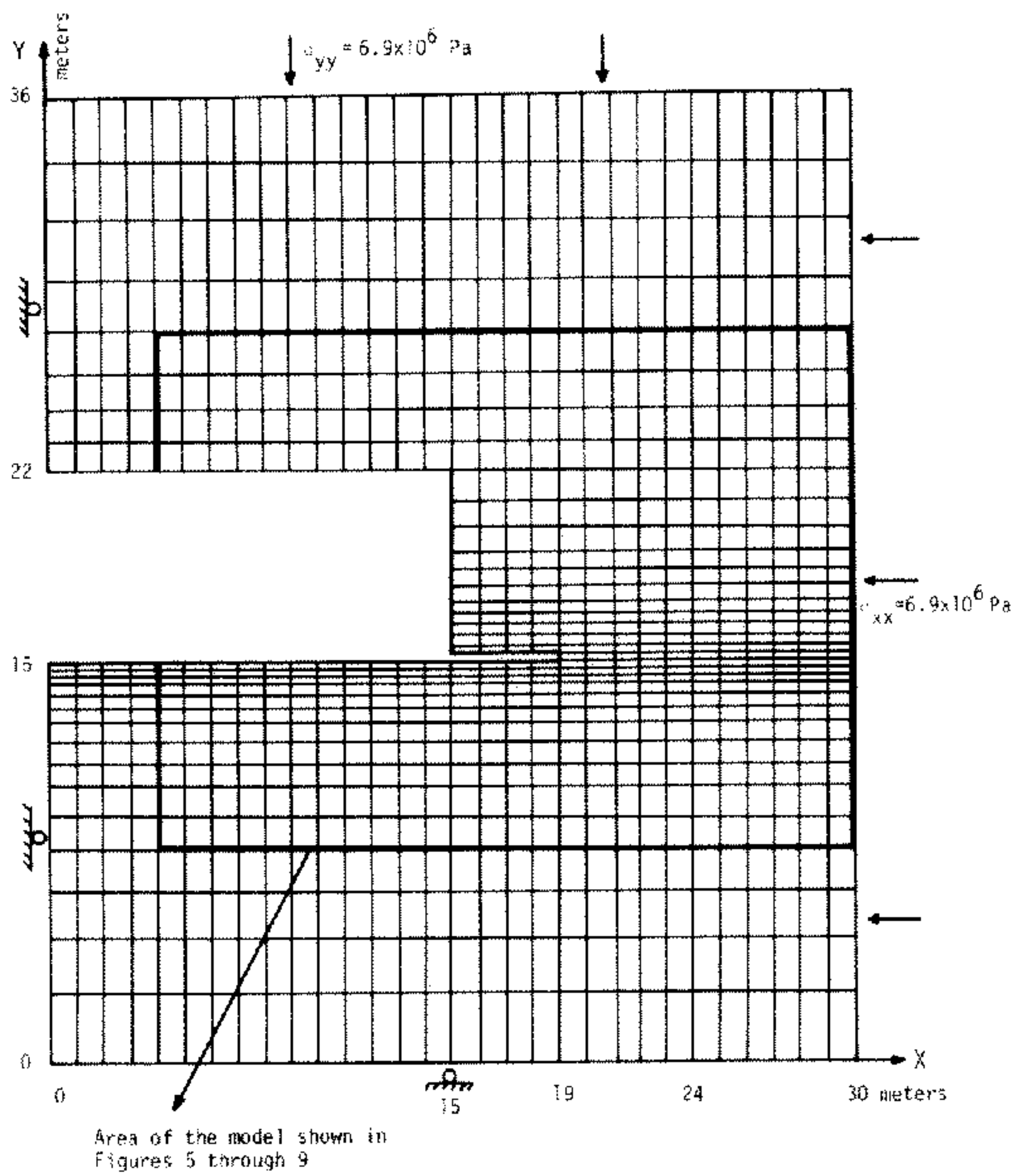

Figure 4. Finite difference model for the idealized problem.

together with the burst salt, in Figures 8 and 9, are our preliminary estimates of the zones involved in a gas outburst when using the numerical model presented here. The results presented in Figure 9 are based on the assumption that subsequent to blasting the face, or as a result of an outburst, the broken salt covers the floor of the room, thus increasing the strength of the salt below the kerf. The results, as could be expected, show that the confined salt below the kerf is now not burst-prone.

CONCLUSIONS AND RECOMMENDATIONS

The numerical analysis of the phenomenon of gas outbursts in salt presented here is to be considered a first-level approximation of the real situation. The results indicate that weakening (fracturing) of the salt and the material in the pressure pocket located a small distance beyond the face of a mine heading is a necessary condition for the occurrence of a gas outburst.

In our analyses, we have not removed any volume element of the "burst rock" from the finite-difference grid or model. We conjecture that future analyses, involving removal of burst rock, may show a progression of the outburst in a direction that is normal to the "advancing" boundary of the burst zone shown in Figure 9. Further, if in addition to the floor, the walls of the cavity were assumed to be confined by the broken salt, future analyses may show a generally upward progression of the outburst.

In our discussions we have assumed that all material in

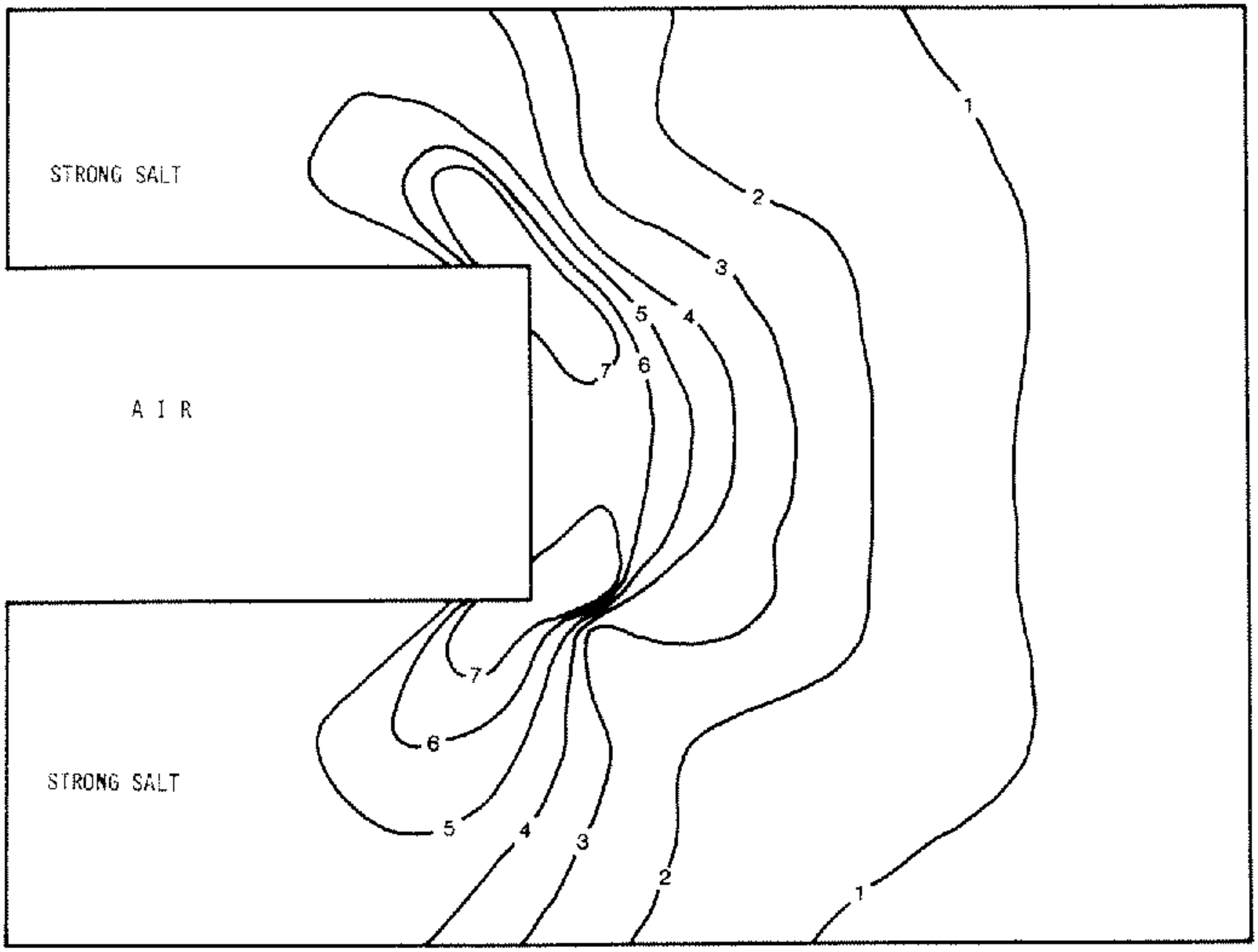

Figure 5. Contours of effective stress around a mine heading (without a kerf) in a strong, homogeneous, elastic salt.

the pressure pocket in our model has an equal chance of containing gas (or liquid) under pressure. The real situation, as far as we know, is that the pressure pockets of various shapes and sizes may be randomly located in advance of the heading face. Further analyses need to be performed using site specific data and, perhaps, back-calculation type of techniques.

For controlling and preventing gas outbursts in Louisiana dome salt mines, two important approaches are suggested: identification of burst-prone areas (pressure pockets) in advance of mining and destressing and degassification ahead of the heading face.

Because, in Louisiana domes, pressure pockets generally tend to be associated with other anomalous features and inclusions found in the edge or central shear zones, mapping of these features on a regular basis should be considered essential for identifying potential gas-outburst areas.

Drilling-exploration of the face should be carried out to obtain the following data:

1. identification of anomalous features
2. information on core disking
3. pressure and flow-rate of gas
4. detection of microseismic activity or change in stress, if required, in highly-suspect areas. The methodology for application of microseismic technique to study of geologic structure and changes in stress is described by Hardy (1975) and Blake et al. (1974).

The most important element in control and prevention of gas outbursts appears to be the degassification of the pressure pocket in advance of the heading face. Degassification reduces the pore pressure in the rock, thereby increasing its strength.

One promising method of degassification that needs to be studied is (1) drill one or more large, but safe, diameter drainage holes (Barr, 1975, recommends a 25-cm-diameter hole) into the pressure pocket; (2) drill smaller holes in the face around the drainage holes; and

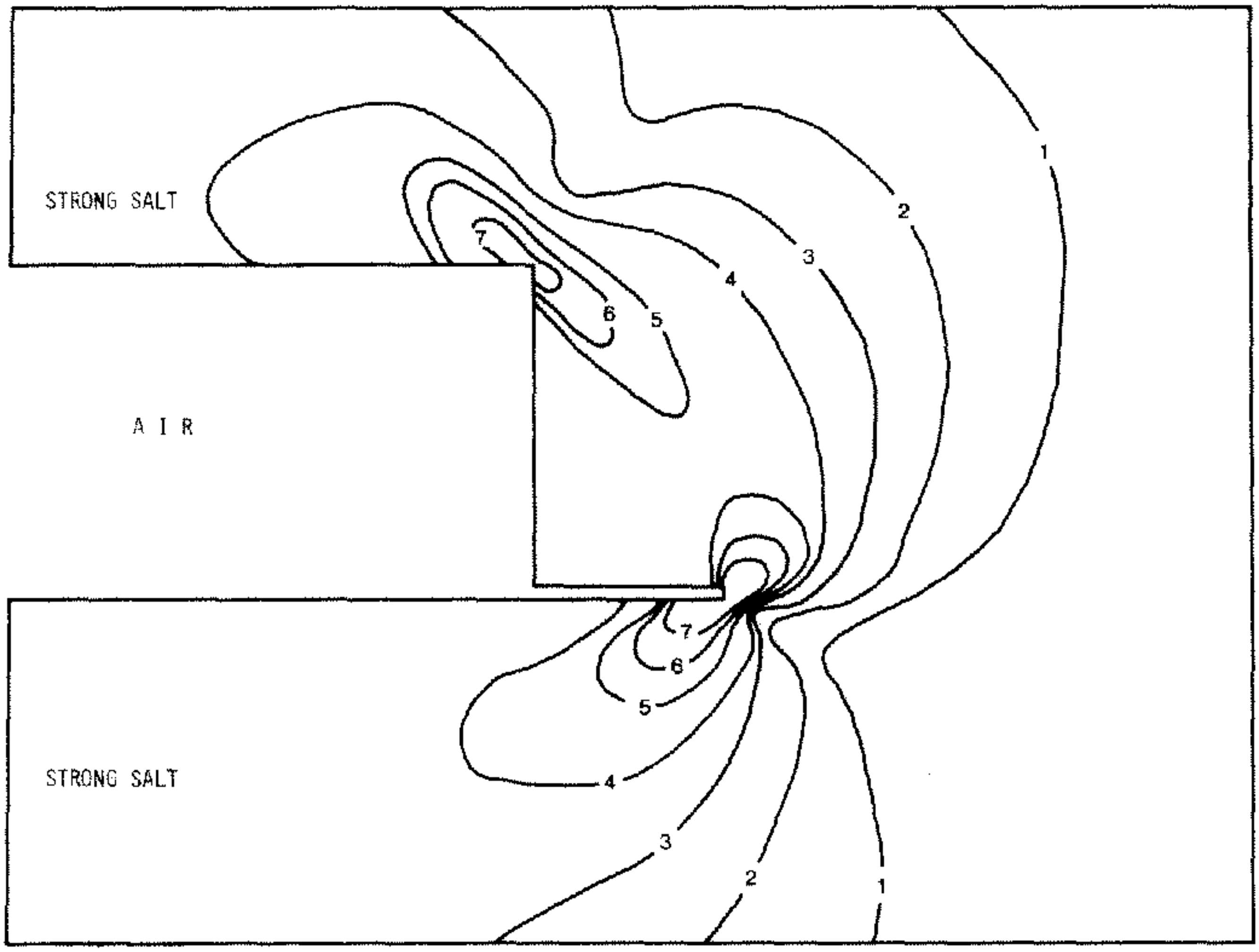

Figure 6. Contours of effective stress around a mine heading (with a kerf) in strong, homogeneous elastic salt.

(3) load and blast the back ends of the smaller holes, a procedure to be called "shock blasting." Because this procedure may trigger a gas outburst, due precautions and methodology must be used during drilling, blasting and degassification.

Shock blasting, though not practiced in Louisiana salt mines, has successfully reduced the number of accidents resulting from gas outbursts in coal and salt mines outside the U.S.A. (Ignatieff, 1954; Hargraves, 1958; Baar, 1975). Results of shock blasting (or destressing) hard rock for controlling rock bursts have been described by Hill and Plewman (1957) and Blake (1971).

TABLE I

Properties of Different Material Types Used in the Numerical Model

Material No.	Material Name	Unconfined Compressive Strength, 10^6 Pa	Bulk Modulus K, 10^9 Pa	Shear Modulus G, 10^8 Pa
1	Salt	5.8	1.148	5.3
2	Pressure pocket	5.8	1.148	5.3
3	Air	0.0	0.000	0.0
4	Weakened salt	5.8	1.148	5.3
5	Burst salt	0.58	1.148	5.3
6	Burst pressure pocket	0.0058	1.148	0.0053

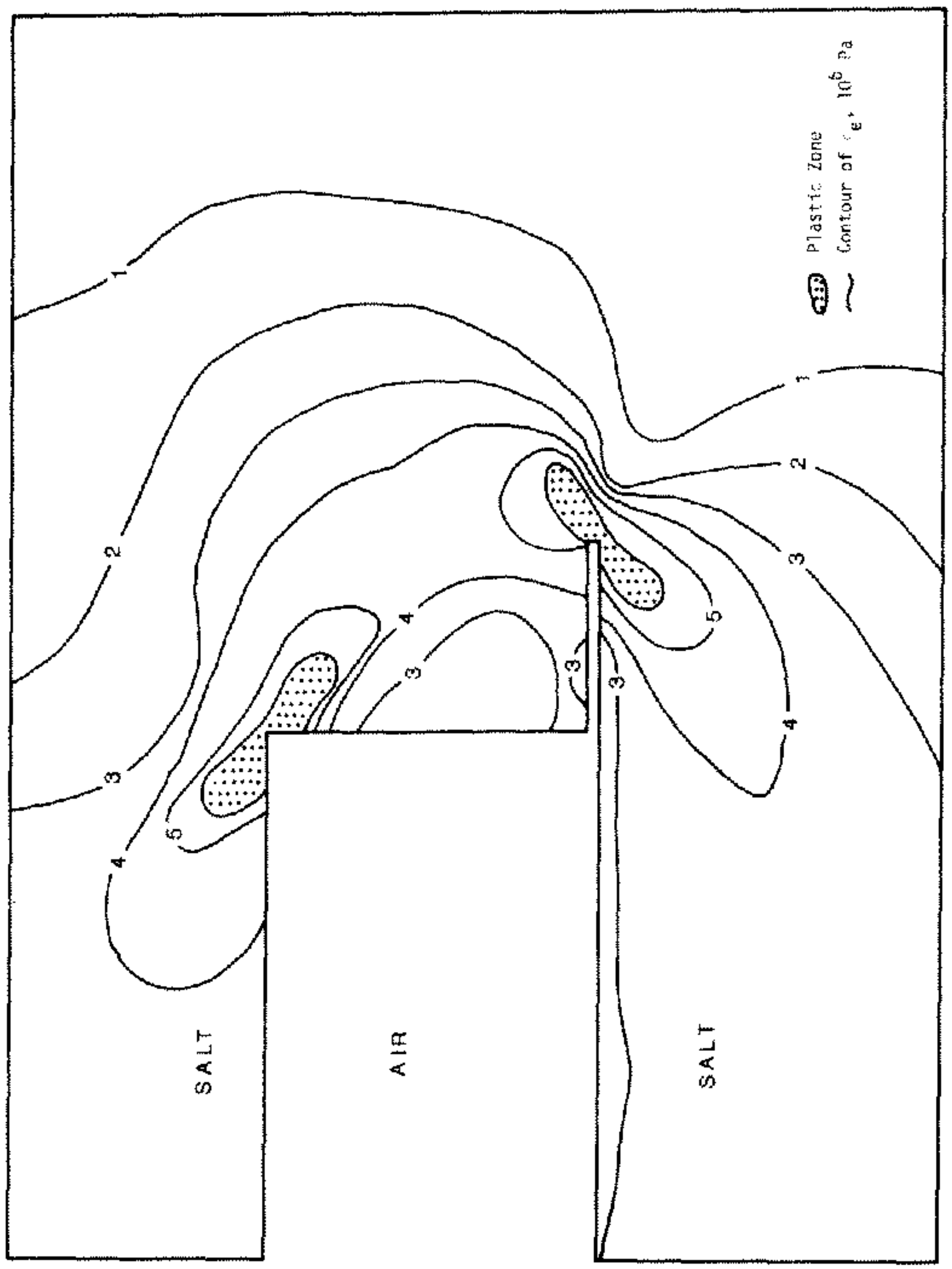

Figure 7. Effective stress contours and plastic zones around a mine heading in a typical salt (for material properties, see Table 1).

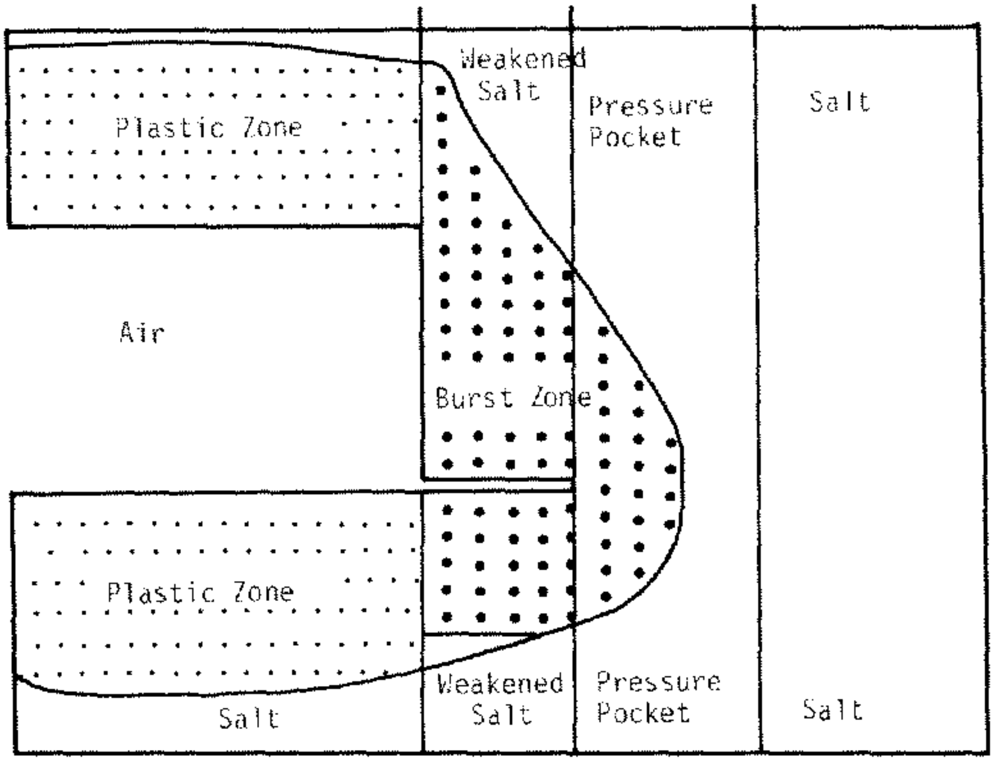

Figure 8. Plastic zones and burst zones around a mine heading near a pressure pocket with unconfined floor (for material properties, see Table 1).

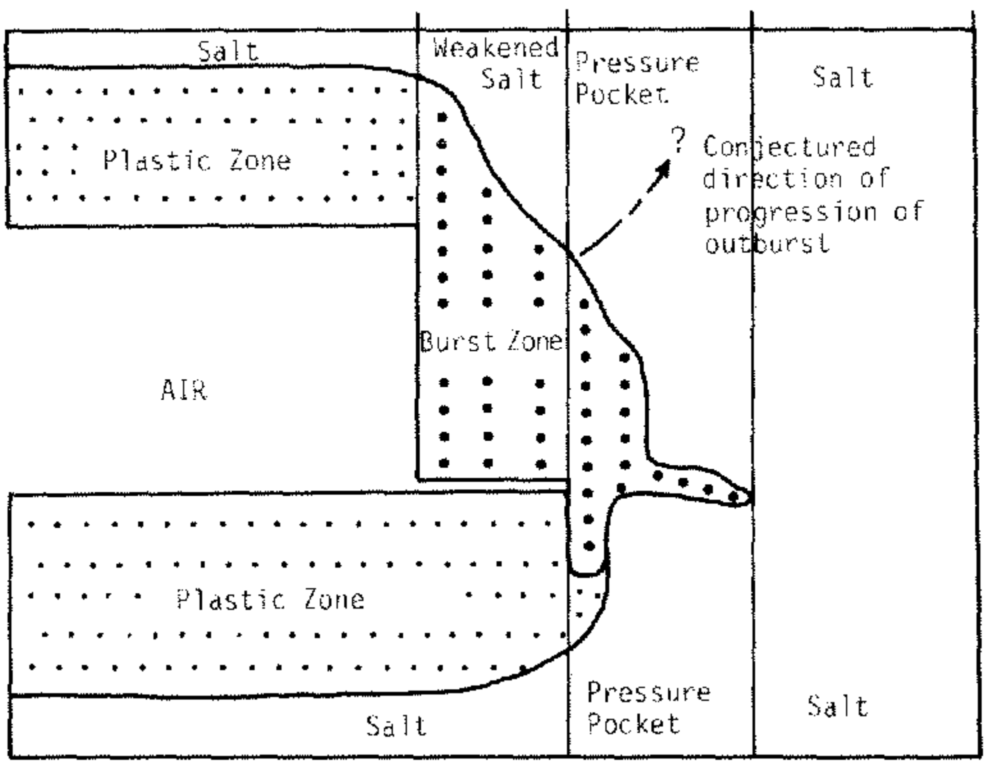

Figure 9. Plastic zones and burst zones around a mine heading near a pressure pocket with the mine floor confined by broken salt (for material properties, see Table 1).

TABLE 2

Summary of Various Analyses

Ref. Fig. No.	Configuration of Model	Material Characteristics	Results shown
5	Mine heading without kerf	Infinitely-strong, homogeneous, elastic, salt	Contours of effective stress, σ_e
6	Mine heading with kerf	Same as above	Same as above
7	Same as above	Salt, mat. no. 1, Table 1	Contours of σ_e and plastic zones
8	Mine heading with kerf, pressure pocket ahead of end of kerf	Weakened salt (mat. no. 4) ahead of heading face, above and below the kerf (no confinement of floor after blasting of face round)	Plastic zone and burst zones
9	Same as above	Weakened salt ahead of face but only above the kerf (salt broken by blasting of face confines the salt below the floor)	Same as above

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