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Gas Releases from Salt

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Gas Releases from Salt

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Underground Storage Technology

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ABSTRACT

The occurrence of gas in salt mines and caverns has presented some serious problems to facility operators. Salt mines have long experienced sudden, usually unexpected expulsions of gas and salt from a production face, commonly known as outbursts. Outbursts can release over one million cubic feet of methane and fractured salt, and are responsible for the lives of numerous miners and explosions. Equipment, production time, and even entire mines have been lost due to outbursts. An outburst creates a cornucopian shaped hole that can reach heights of several hundred feet. The potential occurrence of outbursts must be factored into mine design and mining methods. In caverns, the occurrence of outbursts and steady infiltration of gas into stored product can effect the quality of the product, particularly over the long-term, and in some cases renders the product unusable as is or difficult to transport. Gas has also been known to collect in the roof traps of caverns resulting in safety and operational concerns.

The intent of this paper is to summarize the existing knowledge on gas releases from salt. The compiled information can provide a better understanding of the phenomena and gain insight into the causative mechanisms that, once established, can help mitigate the variety of problems associated with gas releases from salt. Outbursts, as documented in mines, are discussed first. This is followed by a discussion of the relatively slow gas infiltration into stored crude oil, as observed and modeled in the caverns of the U.S. Strategic Petroleum Reserve. A model that predicts outburst pressure kicks in caverns is also discussed.

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INTRODUCTION

The occurrence of gas in salt mines and caverns has presented some serious problems to facility operators. Salt mines have long experienced sudden, usually unexpected expulsions of gas and salt from a production face. These are commonly known as outbursts. Outbursts can release over one million cubic feet of methane and fractured salt, and are responsible for the lives of numerous miners and explosions. Equipment, production time, and even entire mines have been lost due to outbursts. An outburst can create a cornucopian shaped hole that can reach heights of several hundred feet. The potential occurrence of outbursts must be factored into mine design and mining methods. In caverns, the occurrence of outbursts and steady infiltration of gas (methane, carbon dioxide, and others) into stored product can effect the quality of the product, particularly over the long-term, and in some cases renders the product unusable as is or difficult to transport. Gas has also been known to collect in the roof traps of caverns resulting in safety and operational concerns.

The intent of this paper is to summarize the existing knowledge on gas releases from salt. The compiled information can help provide a better understanding of the phenomena and gain insight into the causative mechanisms that, once established, can help mitigate the variety of problems associated with gas releases from salt. Outbursts, as documented in mines, are discussed first followed by a discussion of the relatively slow gas infiltration into stored crude oil, as observed and modeled in the caverns of the U.S. Strategic Petroleum Reserve. A model that predicts outburst pressure kicks in caverns is also included.

DEFINITIONS

An outburst is defined as an unexpected, nearly instantaneous expulsion of gas and rock salt from a production face, normally resulting in a cavity in the salt. Outburst cavity shapes are generally described as conical, cylindrical, hemispherical, or elongated with an elliptical cross section (Molinda, 1988), (Gimm, Thoma, and Eckart, 1966). In U.S. Gulf Coast domes, the smaller outbursts tend to be conchoidally shaped with symmetrical dimensions, whereas the larger ones tend to be cornucopian in shape. Figure 1 shows typical small and medium sized outbursts. After an outburst, a distinct lamination of the faces is observed, and the dish-shaped cracks are arranged symmetrical to the longitudinal axis to form a characteristic shingle-like joint pattern. The exfoliated faces look like an onion skin. The salt thrown from the cavity is always greatly broken up, and to some extent pulverized. The risks associated with gas outbursts include loss of life, equipment, and the mine itself.

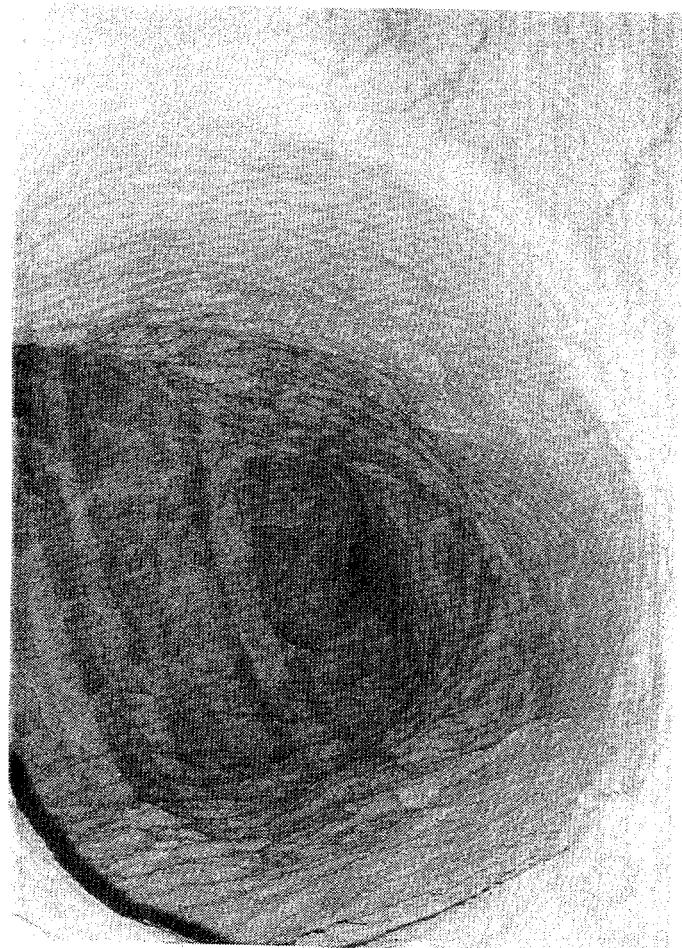
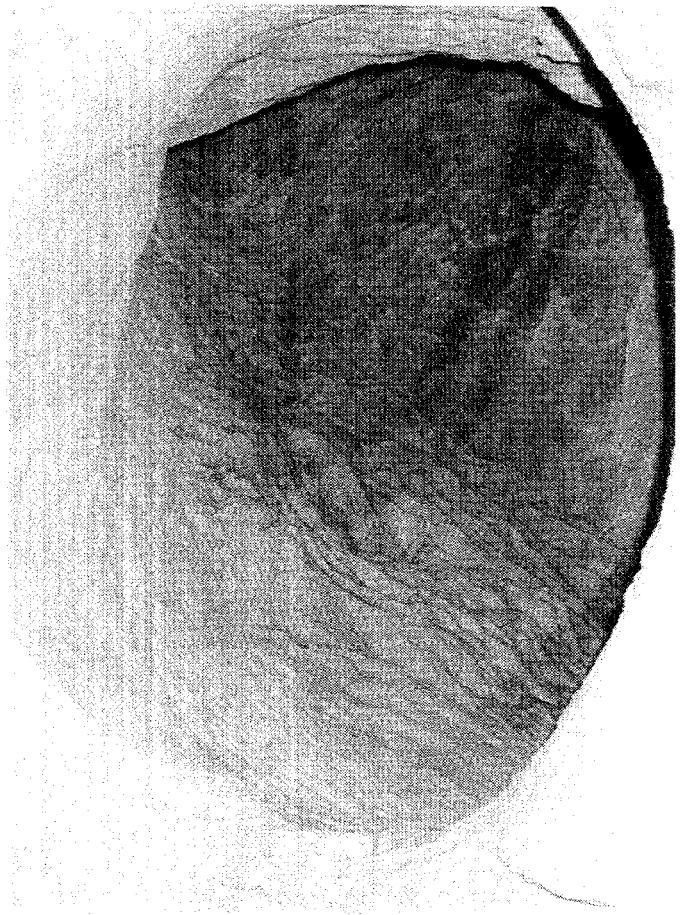


Figure 1. Typical Outbursts in the Weeks Island Salt Dome (Acres, 1978)

In some cases mines have been abandoned due to outbursts and in many cases, the layout of a mine is largely determined by the occurrence of outbursts and the planned avoidance thereof.

In the literature, outbursts are also commonly referred to as blowouts by various authors. However, some investigators distinguish outbursts from blowouts by differences in the gas storage and release mechanisms in salt-- a topic discussed later on. For our purposes, outbursts and blowouts are synonymous. Outbursts are distinguished from rockbursts as experienced in deep hard rock mines (ex. South Africa gold mines) and in soft rocks (ex. U.S. coal mine bumps). These phenomena are related to relatively high rock stresses. The presence of gas separates an outburst from a rockburst (Cruickshank, Mahtab, and Wane, 1986). In most salt mines, both outbursts and the free flow of gas (without ejection of salt from a cavity) have been observed (Bakowski, 1966). In some cases gas flows are violent without any explosion of rock or important mechanical occurrences (Brendiaux, 1966; Kupfer, 1976) and therefore are not considered outbursts.

CASE HISTORIES OF OUTBURSTS

Outbursts have occurred in the U.S., Canada, and throughout northern Europe in salt and potash mines. The salt domes of northern Europe are loaded with pockets of abundant gas inclusions, and at the beginning of the century, several potash mines were abandoned because of problems caused by outbursts (Gimm, 1968). In the early history of salt mining (prior to the current practice of evacuating the mine prior to blasting), many fatalities resulted from outbursts. A large portion were due to secondary factors, such as a methane explosion, suffocation, and poisoning (Dorfelt, 1966). Even with the practice of mine evacuation, outburst gases have in some cases filled the mine, blown out of the mine shafts, and caused fatalities at the surface. In one case, the heavier-than-air gas (CO_2) gas blew out of the mine shafts for 25 minutes, flowed down a hill into a populated area, and killed 3 people. Several potash mines were abandoned due to a high number of casualties (Baar, 1977).

Perhaps the most frequent and largest occurrences of outbursts have been recorded in the Werra mining district in former East Germany. Gimm and Pforr (1964) report that outbursts occurred every day in the Werra region. Including the potash mines in the Southern Harz region, more than 10,000 outbursts have been recorded (Dorfelt, 1966). Menzengraben (Potash Mine No. 3) reported an outburst of 100,000 metric tons of fractured rock salt

(approximately 1.6 million ft³) in 1953. This may well be the world's largest outburst in terms of cavity size (Gimm, 1968). Extensive roof falls are frequently associated with large outbursts (Baar, 1977). Another occurrence given in Baar (1977) is a mine shaft which ejected brine, H₂S, CH₄, and N₂ from depths of 1000 ft to the height of houses for two hours, resulting in abandonment of the shaft (Baar, 1977).

Less severe examples of outbursts are found elsewhere in the world. Over 200 gas dynamic events with ejected rock salt volumes up to 4500 tons occurred in the Upper Kama potash deposits of Russia (Laptev and Potekhin, 1989). Baltaretu and Gaube (1966) reported sudden outbursts in potassium salt deposits in Rumania. Outbursts in Polish mines were noted by Bakowski (1966). Brendiaux (1966) reported outbursts in the floor of Alsace potash (France) and a further discussion is provided by Baar (1977). The potash mines in England and Canada also exhibited outbursts (Head, 1997; Schatzel and Dunsbier, 1988).

Major outbursts have been documented in Louisiana salt mines in the 5-Island chain of domal salts (Belle Isle, Cote Blanche, Weeks Island, and Jefferson Island) with the exception of Avery Island. Outbursts have also occurred at the Winnfield mine (domal salt). Outburst diameters ranged from a few inches up to over 50 ft. The heights ranged from several inches to several hundred feet. The small ones are ordinarily overlooked (Kupfer, 1978). The larger outbursts tended to be cornucopian in shape, whereas the shorter ones were conchoidally shaped with symmetrical dimensions. Outbursts approaching several hundred feet high have occurred at the Jefferson Island and Belle Isle mines. The outburst disaster at Belle Isle mine in 1979, in which five miners died, proved that high-pressure methane in large quantities can be released from an outburst. It was estimated that more than 600,000 ft³ of methane was instantaneously emitted from the outburst (Plimpton, et al., 1980). At the new Morton mine at Weeks Island, an even larger gas emission apparently occurred in connection with an outburst. It was estimated that as much as 36,100 ft³ of salt was released from the outburst and 50 million ft³ of gas filled the Morton mine (MSHA, 1983). If the limited number of sample points represented a well mixed mine atmosphere, the gas alone would occupy approximately 600,000 ft³ in the salt at lithostatic pressure.

Outbursts have occurred during mining of all three of the mines at Weeks Island-- the old Morton mine (now the U.S. Strategic Petroleum Reserve), the Markel mine, and the new Morton mine. Perhaps the largest outburst at the new Morton mine occurred on October 6, 1982 in the southwest corner of the 1200-ft level, close to the edge of the dome. A balloon with an attached measuring string is typically used to estimate the height of large vertical

outbursts. A balloon went up more than 100 ft into an outburst some 35 ft wide (MSHA, 1983). Outbursts in the old Morton mine occurred only in the larger lower level (-800 ft) of the two level mine outside the vertically projected boundary of the upper (-6000 ft) level. A similar trend was noted at Jefferson Island where no outbursts occurred in the upper level of the mine. The outbursts observed at the Jefferson Island mine were in the same relative position at both the 1300-ft and 1500-ft levels. This is attributed to the near vertical orientation of a very gassy zone of salt (Iannacchione, et al., 1984). Structural continuity (banding) is nearly vertical in salt dome diapirs, except where the top of the dome has mushroomed. As a result, horizontal runs of outbursts have reportedly been small, and unlikely to connect caverns separated by 100 ft or more (Thoms and Martinez, 1978.).

Outbursts are not limited to domal salt. High pressure pockets of inert gas, such as nitrogen, have been found in bedded potash mines (Carlsbad, NM), and combustible gases (methane) and fluids (brine and oil) in bedded potash mines in Utah (Djahanguiri, 1984). The Cane Creek potash mine (Utah) in the bedded formations of the Paradox Basin had extensive equipment damage and fatalities as a result of an outburst (Westfield, et al., 1963). No outbursts have been reported to date at the Waste Isolation Pilot Plant in the bedded salts of southeastern New Mexico. Routine drilling ahead of the roadheader checked for gas, but found very little (Munson, 1997).

The above limited literature sampling does not preclude the possibility that outbursts may also have occurred in other countries. It is not intended to be a complete list of mines or regions experiencing outbursts.

OUTBURST CAUSATIVE FACTORS

The abrupt, explosive release of gas and crushed salt from the working face of a mine are the two main characteristics of an outburst. This section investigates the type of gases, their concentrations and pressures, along with the association of outbursts with anomalous zones and different types of mining.

Types of Gases

The relationship of outbursts with gas is unavoidable by definition. The obvious evidence of gas is observed when one walks over the ejected grains of salt from an outburst cavity. They are known as crackle or popcorn salt as they contain gas under high pressure and make a popping sound as one walks over them.

Kupfer (1978) states that inclusions in U.S. domal salt can be of primary origin (from decomposition of trapped organics during the original salt deposition) or of secondary origin (during the movement process gases penetrated either the sediments or the salt itself). Some suggest that the origin of the gas can be important in determining outburst potential. Baar (1977) suggests a relationship between gas related reaction minerals that are formed during intracrustal processes of solution metamorphism and the potential for outbursts in Germany.

As a result of different depositional environments, many different gases are found in salt. However, all are believed to have the potential to outburst. U.S. domal salts contain 90 to 99 percent methane, and lesser amounts of other hydrocarbons and other gases (Iannacchione and Schatzel, 1985). The methane is found in localized discrete pockets and the content is directly related to the likelihood of outbursting (Schatzel and Dunsbier, 1988). Gas chromatograms taken of domal salt show salt from outburst areas contain significantly more methane than the normal mine salt. There are also traces of ethylene, ethane, and propane in the salt (Molecke, et al., 1996). The 5-Island salt domes also contain brine, CO₂, oil, ethane-pentane, nitrogen, and H₂S. Djahanguiri (1984). Of the 5-Island mines, only Avery Island is classified as non-gassy and has had no outbursts (Molinda, 1988). Outbursts observed in the Winnfield mine in Louisiana were predominantly CO₂ and water (Kupfer, 1978) with lesser amounts of N₂, O₂, SO₂, H₂, CH₄, Ar, S₂H₂, other hydrocarbons (Thoms and Martinez, 1978). The character of gas in outbursts generally varies between salt deposits and even between sites within a dome. In Germany, the frequently reported gases are CH₄, CO₂, and N₂ as the main components of gas mixtures (Baar, 1977). Gases in the Werra region consist of CO₂ and N₂, while the Southern Harz area contains CH₄ (Dorfelt, 1966). The Alsace potash mines of France show the gases are principally a mixture of methane (and higher gases-- ethane, propane, butane) and carbonic acid gases (Brendiaux, 1966). Gases noted in Polish mines included methane, nitrogen, hydrogen sulfide, with small amounts of heavier hydrocarbons, carbon dioxide, and noble gases (mainly helium) (Bakowski, 1966). Outbursts and gases in a Canadian potash mine contained CO₂, N₂, CH₄, and higher hydrocarbons (Iannacchione and Schatzel, 1985).

Concentrations of Gases

Schatzel and Dunsbier (1988) describe two methods used by the USBM to measure gas content based on dissolving a sample of salt and 1) acoustically monitoring by a sound meter the amplitude made by the gas bursts, as found to be directly related to the gas content of a sample, and 2) directly measuring the STP volume and composition using a gas

chromatograph. The gas contents of normal and outburst salt were measured in several mines in Louisiana salt domes during the 1980's. The shallow levels in domal salt mines were found to be generally low in methane; however, no general trend of methane increase with depth could be seen from 200 samples tested at 4 mines with depths ranging from less than 750 ft to 1425 ft (Schatzel and Hyman, 1984). Over 90 percent of the samples contained less than 0.0032 ft³ methane per ton of salt. Routine use of the USBM acoustic technique at Cote Blanche, measured sample methane content ranging from 0.0045 to 2.78 ft³/ton from outburst areas, while normal salt ranged from 0.0001 to 0.1 ft³/ton (Molinda, 1988; Grau, 1990). Similarly the methane gas measured in outburst salt at Belle Isle ranged up to 2.6 ft³/ton, with concentrations up to 200 times as much methane as in normal salt (Molinda, 1988). The gas, measured from salt samples using the acoustic method, represents to a large degree entrained intragranular gas. Gases released during mining are dominantly located along grain boundaries (intergranular), and therefore are not accounted for the sample analyses.

Recognizing that gas can be trapped along grain boundaries and located within salt crystals, gas releases have been measured on the mining face. The emission rate for normal salt has been measured underground at 5.65 ft³/ton, whereas core taken from the same location had an average entrained gas content of only 0.004 ft³/ton (Schatzel and Hyman, 1984). Anomalous zone salt had mine emission rates measured from 16.6 to 77 ft³/ton. These measurements in Gulf Coast domal mines show that anomalous zones can contain and emit much higher levels of methane than normal salts (<5.6 ft³/ton, Hyman, D, 1982). Based on these limited data, it would appear that for normal salt, the volume of entrained gas content is quite small and the intergranular gas content is relatively large in comparison to entrained gas content (up to several orders of magnitude). The ratio of intergranular to entrained gas appears to be much smaller for anomalous salt (the emissions rate was 83 times greater than the entrained gas content in a Belle Isle drift, Iannacchione, et al., 1984). For both normal and outburst salts in the Gulf Coast salt domes, the intergranular gas volume appears to be many times larger than the intragranular gas volume.

Similarly, the Upper Kama potash deposit of sylvanite, carnalite, and rock salt beds contain gas in both a free form or in micro-inclusions (Laptev and Potekhin, 1989). Dorfelt (1966) mentions a gas measurement technique used in German potash mines that appears similar to the USBM acoustic method called the Sondershausen crackle-probe. Gimm and Pforr (1964) believe that a large part of the gases found in German potash mines is bound to the interstices between individual crystals (intergranular), and a smaller amount bound to the

pores in the crystals (intragranular). Actual measurements showed that over 90 percent of the gas is included in the microscopic cavities between crystals through intergranular binding, and the rest of the gas within the crystals themselves (Gimm, Thoma, and Eckart, 1966).

Wolf (1966) reports measurements at two different German mines where outburst salt had an average gas content of 375 to 625 ft³/ton. Therefore, gas concentrations in German potash mines appear to be much higher than those measured in U.S. salt mines.

Gas Pressures

One of the driving forces of an outburst is the pressure of the gas. Pore pressures are generally believed to range from hydrostatic (standing water pressure) to lithostatic (the ground pressure). In salt, as long as a connected pore system exists, pores will continue to close by creep until the porosity becomes so low that the salt is virtually impermeable and the remaining pores are no longer interconnected (Fokker et al., 1992). The remaining gas or fluid volume will be stored as small bubbles at the intercrystalline boundaries, as can be observed under the microscope (Urai, 1983). The entrapped gas is believed to be at lithostatic pressure that corresponds to the depth of the mine (Kupfer, 1978; Baar, 1975 & 1977). Measurements of in situ pressure in domal and bedded salts in the U.S. tend to support pressures in excess of hydrostatic and approaching lithostatic (Iannacchione and Schatzel, 1985; Lappin and Hunter, 1989). At Belle Isle, gas pressures have been measured at 1200 psi in an exploratory borehole at the 1200 ft level (implying gas pressure at lithostatic) (Molinda, 1988). In situ pore pressures in the bedded salt at the Waste Isolation Pilot Plant were also measured close to lithostatic pressure (Beauheim, 1997). In contrast to the U.S. and German salts, the pore pressure in French deposits is assumed to be hydrostatic (Berest, et al., 1996; Durup, 1994).

Mining causes a pressure drop in the rock as it is extracted from the working face. The pressure drop can change the phase of a fluid. Carbon dioxide, in particular, is susceptible to a phase change because its critical point is close to some ambient mining conditions. As long as CO₂ is present above 1070 psi and below 88 °F (critical point), it will be in a liquid phase. Such conditions are atypical in the U.S. because of the existing geothermal gradient. However, included CO₂ generally exists as a liquid in German potash mines (Gimm, Thoma, and Eckart, 1966). When mining drops the pressure (from lithostatic to near atmospheric) the phase will change to a gas causing abrupt expansion. The sudden change also results in a 5 to 6 °C cooling as measured in regions near large outbursts Wolf (1966). The solubility

of gases in liquids also changes when mining. For example, the solubility of methane in brine is extremely low at atmospheric pressure and its release from brine upon mining has been observed (Iannacchione and Schatzel, 1985). The effect of phase changes and changes in solubility on outburst potential has not been fully quantified.

The pressures released during an outburst result in velocities at the outburst throat which should be very large and approach the local sonic velocity. Velocities of more than 500 ft/s have been recorded in vertical airways away from outbursts in Germany. Velocities at the outburst would be higher. The narrow throat characteristic on some outbursts can also result in a throttling effect. However, pressure waves are not strong enough to cause observed equipment destruction since they are of a magnitude similar to those found in blasting. Rather, observed damage is due to flying debris as the quantities of rock thrown out have a high kinetic energy (Wolf, 1966).

Anomalous Zones

In the U.S., outbursts are generally associated with anomalous geologic features (Kupfer, 1978 and Thoms and Martinez, 1978). Outbursts are commonly observed in areas that Kupfer (1990) classifies as shear or anomalous zones, such zones being usually vertically orientated due to the movement of the dome. Kupfer (1978) describes the movement of individual salt splines arising out of an older pillar of salt to collectively form a salt stock. Anomalous zones are formed at the edges and between splines. Unusual features are presumably associated with these shear zones, such as natural-gas seeps, oil and gas pockets, increased impurity content, and a tendency for salt to exfoliate (Kupfer, 1976). In general, domal salt mines show enhanced permeability in continuous zones of impure salt in clastic or argillaceous material (Iannacchione and Schatzel, 1985). At the Winnfield mine, where internal shear zones are not evident, the outbursts were most frequently at the edges of the dome (likely anomalous areas) ranging up to 30 ft in diameter and 1.1×10^5 ft³ of salt (Kupfer, 1976). Djahanguiri (1984) provides a summary of the 5-Island and other U.S. salt and potash mines that have had outbursts along with their associated geologic anomalies.

The frequency and magnitude of outbursts depends strongly on the particular salt dome under consideration, and the correlation between anomalous zones and outbursts is not perfect. For example, although Avery Island has anomalous features, no outburst has been associated with them. Further, Cote Blanche has no real evidence of any shear or anomalous zones, yet more than 80 outbursts have been mapped (Molinda, 1988). The outbursts at Cote Blanche are related to large rock crystals (larger than $\frac{1}{4}$ in size) which are usually

methane enriched Molinda (1988). The presence of large crystal size and gas in salt is not enough to characterize a region as an anomalous zone. Generally three or more anomalous and dissimilar features or properties are required for an anomalous zone to be declared (Kupfer, 1990; Neal, 1993). Coarse-grained salt in Gulf Coast stocks is generally not in veins, but in irregular masses associated with brine inclusions (Kupfer, 1978). At Weeks Island, outbursts are specifically associated with sandstone impurities and areas of darker, coarse-grained, jointed, moist, gaseous salt (U.S. FEA, 1977; Magorian, 1997). Other mines include such features as various salt impurities, disrupted or sheared salt, incorporating rock fragments or sediment, brine, and petroleum. Bakowski, et al. (1966), noted a correlation with outbursts in Polish mines and a zone of strong tectonic disturbances which is characterized by gas-enriched salt, contaminated by petroleum.

Mining

The salt in U.S. salt domes is typically mined by first creating a development level, and then benching the floor. Conventional mining techniques (blasting) are typically used and the rooms are commonly undercut prior to blasting. The mine development at Weeks Island was typical of the neighboring domes. Outbursts have always been associated with mining of the development drifts, and never encountered at any other time. The outbursts usually occurred within 10 ft of the upper corners of the development drifts. No outbursts were observed in the floors or in the lower half of the ribs of the development headings at Weeks Island (Mirza, 1979).

A number of noticeable trends emerge. The outbursts normally occur in the mine roof during initial development, and only rarely extend downward from the floor of mines (Molinda, 1988). Exceptions are noted at Cote Blanche, where outbursts have also been experienced during bench mining-- in one case an outburst extended diagonally across the drift, measuring up to 200 ft in total length. Although outbursts consistently are associated with blasting, one presumably occurred spontaneously, overnight at Belle Isle (Kupfer, 1978). There are reports of outbursts occurring in conjunction with solution mining (no explosive force and gradual relaxation of stresses) (Thoms and Martinez, 1980). Despite these exceptions, the relationship with mining is pervasive. For example, in one mine after driving the entry face, an outburst occurred and the face was abandoned for 10 years; immediately after mining resumed, another outburst occurred Molinda (1988).

The experience in Poland is similar in that all outbursts occurred only during blasting of active faces (Bakowski, 1966). Seismo-acoustic measurements in German mines show

outbursting to start during shooting or immediately after. No delayed outbursts were found (Gimm, Thoma, and Eckart, 1966). Laptev and Potekhin (1989) report in the Upper Kama potash deposit 40 to 50 percent of events occur after one or more hours of advancing the drift or in worked-out chambers. Brendiaux (1966) reports a slight delay where the outburst explosion always occurs a few seconds after blasting the residual pillars. The outbursts are typically in the floor of Alsace potash mines which were mined by room and pillar method or by longwall shearer-loader faces. This is likely a result of the underlying bedded formations and the inherent location of the gas occlusion zones.

Although outbursting is simultaneous to or immediately follows blasting, the mining method may not be the important factor in triggering outbursts that was once thought. Gimm and Pforr (1964) state that the type of mining is irrelevant, as there can be outbursts even in the absence of blasting (ex. mechanical or dissolution mining). It makes no difference in principle whether the salt is mined by drilling, cutting, blasting, or brining as outbursts have occurred with all mining techniques (Gimm, 1968). The only activation required for occluded gases to explode is the removal of restraining salt sufficiently close to gas inclusions. The Germans report that in 1953, an outburst occurred in front of a cutting machine and two more outbursts occurred in 1959 while cutting a 3-m roadway into gas bearing salt. Minor outbursts have also been encountered in U.S. domal salt mines when undercutter blades have reportedly been "kicked" out of the face advance (Thoms, personal communication, 1992). As such, the "pulse of shooting" is not necessary to initiate an outburst (Gimm, Thoma, and Eckart, 1966). In the Werra and Southern Harz potash mines, outbursts that occurred during mechanized mining, core boring, or working with a pneumatic pick were smaller than those initiated by blasting (Dorfelt, 1966). At least one outburst occurred in an English potash mine while a room was being driven by a continuous mining machine (Head, 1997). Bakowski (1966) reports on several outbursts (3 to 800 tons) in Poland. The largest one was released from the face and the other two within 5 ft from the actual face, using brine exploitation (drifting by water sprayers).

There appears to be a relationship of outburst potential with mine depth. Kupfer (1978) states that there is some indication that outbursts increase in size and abundance with greater depth, although this is not firmly established. A cursory look at the available information on the 5-Island mines along the Gulf Coast show that the largest outbursts were recorded at Jefferson Island, Belle Isle, and Cote Blanche-- all on mining levels below 1000 ft. In contrast, the upper mining levels at Weeks Island and Jefferson Island (above 1000 ft) experienced relatively small outbursts and no outbursts have been observed in the mining

levels above 1000 ft at Avery Island. Recent mining at Avery Island is below 1000 ft and the occurrence of any outbursts remains to be reported. The experience in Germany also shows that there is some evidence (two similar mines) to suggest that increasing depth accelerates the outburst process Wolf (1966). The reason for an increase in frequency and intensity with depth may be due to an increase in gas pressure or rock stress with depth (Baar, 1977; Gimm and Pforr, 1964).

OUTBURST MECHANISMS

There are generally two schools of thought for outburst mechanisms. The first is based on gas pressure as the primary driving mechanism, whereas the second believes that rock stresses are most important. Most likely the interaction of the two can not be ignored and the dominance of a particular mechanism may be site specific dependent upon geologic and mining conditions.

Gas Pressure

Baar (1977) explains the outburst mechanism as a chain reaction, initiated at the surface of an opening, when the gas pressure exceeds the tensile strength of the occluding salt. The salt is then destroyed by brittle fracture. Baar states that the only activation required for occluded gases to explode is the removal of restraining salt and hence stress relief sufficiently close to gas inclusions. As discussed in the mining section above, it appears to make no difference in principle whether the restraining salt at the mined face is removed by drilling, cutting, blasting, or solution mining as outbursts have occurred with all types of excavation (Gimm, 1968). However, there may be a certain surface area requirement to initiate an outburst. Baar states that small-diameter exploration boreholes do not initiate outbursts. The data presented by Gimm, implies a borehole of approximately 1.6 ft or larger is needed before an outburst can occur.

Outbursts are reported to progress into the salt mass at rates of approximately 2.3 to 7.9 ft/s in German potash mines (Gimm, 1968). The process terminates in either of two ways. First, the process can terminate when the cavity reaches the natural, geologically controlled boundaries of gas bearing salt. Second, the outburst process can terminate prematurely when the volume expansion of the exploding gases when compared to the amount exiting the outburst cavity, results in a pressure buildup in the cavity that prevents further brittle fracturing at the surface of the surrounding salt.

The outburst process can take place in a number of phases. The total duration of an outburst can range from seconds to minutes with the intensity varying over time (Gimm, Thoma, and Eckart, 1966). Data from Gimm (1968) shows a seismo-acoustic record of a 3-phase outburst which finally terminated after 14 s, after having been interrupted twice for periods of 10 and 25 s according to the aero-dynamic record. The reduced gas pressure at the end of the first two phases apparently restored excessive stress differences which caused the resumptions in the outburst process. The rate of pressure build-up and pressure reductions in a cavity depend on the width of the passageway (Gimm, 1968).

Laboratory experiments support the concept that when gas pressures exceed the rock stresses fracture can occur. Although this concept is widely adopted in soil mechanics (Terzaghi, 1945), the development of effective stress laws lagged in rock mechanics because of the notion that small porosities could not affect the stress or strength in rocks. However, it can be shown that the concept of effective stress holds for crystalline rocks of low porosity (Brace, W.F. and R.J. Martin, 1968). For example, Jaeger (1963) performed experiments on unjacketed cylindrical cores of a low-porosity dolerite. Failure occurred when the pore pressure exceeded the tensile strength of the rock. The same law also appears to apply to rock salt. Laboratory tests performed by Fokker and Kentor (Fokker, 1995; Fokker, et al., 1993; and Kentor, et al., 1990) on salt show a permeability enhancement (implying the onset of damage or fracturing) when fluid pressures in salt samples exceeded the confining stresses. This suggested that salt should be treated as a Terzaghi material (its behavior influenced by pore pressure) when determining dilation or fracture criteria. The halite did not fracture until the fluid pressure was slightly above the tensile strength of salt.

In U.S. Gulf Coast salt domes, the evidence strongly implies that the dominating energy source for outbursts is entrapped gas (Kupfer, 1976). Kupfer believes that the gas release mechanism is separated from strain energy mechanisms associated with rockbursts due to high geostatic stresses in hard, strong, brittle rock at depth.

Rock Stresses

Changes in underground stresses are a direct result of excavation or blasting. When an excavation approaches a heterogeneous material with a different elastic modulus (perhaps impure salt or other anomalous characteristics) there will be a preferential transfer of stress, increasing the stress in the stiffer material (Goodman, 1966; Leeman, 1964). The stored strain energy in impure salt within a pressure pocket is higher than in the surrounding material (Gimm and Pforr, 1964) increasing the potential to outburst. In some cases, the

outburst-prone rock may be weaker than the surrounding rock in some cases. Gimm, Thoma, and Eckart (1966) state that outburst active zones differ from the normal salt rocks by a reduced bonding strength and a greater tendency to brittle fracture. Testing at the Alsace potash mines also showed that the rocks tending to outburst are mechanically weaker Brendiaux (1966). Therefore, the combination or presence of high stresses or weak strength may contribute to outbursting.

Mahtab (1981) proposed a mechanism for outbursts as initiated by disking in biaxial compression and propagating by spalling until a combination of dilatancy hardening (reduced pore pressures increase strength), increase in back pressure along the cavity axis, and enlargement to the boundaries of the pressure pocket. Aside from excavation induced stresses, outbursts may be influenced by the stress pulse generated by explosives. Explosives typically fracture rock by creating a tensile stress field. The blast-induced tensile stress field could preferentially interconnect the occluded gas bubbles to abruptly release stored energy (Head, 1977). Whether it is due to blasting or excavation, localized stress concentrations will occur around the surface of gas inclusions, and it is likely that fracture would initiate at these surfaces and interconnect the inclusions.

In general, when the sole mechanism for breakage is attributed to stress, strain, or mechanical energy, the expulsion of rock from the face is recorded as a rockburst rather than an outburst. In principle though, splintering of rock (either a rockburst or outburst) can be caused by rapid loading or by the sudden removal of stress in one direction (Gimm and Pforr, 1964). Gimm and Pforr (1964) discuss both rockbursts and outbursts in the Werra (CO_2) and Southern Harz (CH_4) potash mines. Rockbursts were found to occur only in carnallite and were caused by extending the panel too far or by incorrect working (over-extraction). The sudden release of energy (brittle) resulted in the destruction of the pillars themselves and the roof was left undisturbed. Eight true rockbursts, resulting in considerable pillar damage, were documented at magnitude 7 on the Mercalli-Sieberg scale. In contrast, outbursts occurred when a roadway, room, or very large borehole (e.g. 3 ft diameter) with a sufficiently large free area approached an area that was geologically liable to outbreak (gassy zones). The outburst cavities showed distinct lamination of the faces, where the disk-shaped cracks were arranged symmetrically to the longitudinal axis. It is interesting to note that the same lamination was observed in highly stressed gas-free pillars and was reproduced in the laboratory by rapid loading of potash core (Gimm, Thoma, and Eckart, 1966).

Core tests (with a small hemispherical pit etched in the end) showed lamination characteristics similar to those observed in outbursts, thus demonstrating outbursts can be initiated by rock mechanical processes (Gimm and Pforr, 1964). Energy releases were measured for various rocks. The energy released is a function of the rock properties and the magnitude of sudden change in the stress field. If carnallite is used instead of sylvite in the core tests, the destruction phenomena becomes more intensive. The elastic modulus and compressive strength provided no measure for the assessment of liability to rockbursts, so specific energy releases were measured in anhydrite, sandstone, carnallite, hard salt, and rock salt (ranked from largest to smallest). The energy released from rock salt was almost too small to measure, and unlike the other rocks tested, no relationship was observed between energy release and the rate of loading. The theory that rock salt may be a rockburst stratum can be rejected in view of the extremely low energy release (2 orders of magnitude below carnallite and 3 below anhydrite and sandstone). It is interesting to note that the salts were several times stronger than carnallite. In addition to the above observations and measurements, seismo-acoustic and simultaneous aerodynamic measurements in the mines showed a chain reaction in which a rise and fall in intensity is observed for both outbursts and rockbursts (Gimm and Pforr, 1964). Based on this Gimm, Thoma, and Eckart (1966) conclude that the change from a triaxial stress field (where all the stresses are equal) causes outbursts in potash mines.

Gas Pressure and Rock Stress

Thoms and Martinez (1980) suggest gas pressure as the dominating energy source for outbursts, with the possibility of coupled geostatic stresses to increase the severity of outbursts. Since practically all outbursts are observed in the roof of excavations in U.S. salt domes, a mechanism is proposed whereby the dynamic stress wave associated with blasting moves forward and upward from the face. Because rock salt is a strain rate dependent material, it behaves in a brittle manner when loaded rapidly by the stress wave. As previously discussed, outbursts consistently occur with blasting, although blasting is apparently not required to initiate them. The shape of the outburst is believed to be influenced by material anisotropy. Gas pressurized zones are nearly vertical and elongated because of the dominantly vertical flow patterns and extension strain associated with spline movements within the salt stock. The "chain reaction" and gravity unloading in vertically oriented structures seem to be the primary reasons for the vertical cornucopias seen in U.S. domes.

Although outbursts in U.S. domes are almost always observed in the roof of the excavation, case histories from Germany and France show them to be located primarily at the mining face (wall) and in the floor. In addition to blasting practices potentially effecting outburst orientation, it has been speculated that the combination of gravity and the time between undercutting and blasting allows for some stress and perhaps gas relief in U.S. mines. This hypothesis is supported by the fact that large outbursts occur at the end of a block of salt removed by blasting and commonly curve horizontally into the newly opened face before curving upward. If the outburst is too close to the previous working face most of the stress is released before blasting and a cavity may not form, or if it does, it is much smaller (Kupfer, 1978). An analysis by Mahtab, Trent, and Yegulalp (1983) of an undercut and blasted room in a salt mine show that the weight of the blasted material may provide enough confinement to limit the plastic zone (damaged) in the floor, thus encouraging upward development of the outburst. The other possibility for explaining the frequency of outbursts observed in the roof is simply that they exist in the floor but are often not noticed under the crushed salt following a blast.

Coupled gas diffusion and creep modeling was performed for the original two-level room and pillar mine at Weeks Island (Ney and Stroller, 1979). The potential for outbursts was defined as being proportional to the predicted pore gas pressure in the salt divided by the mean salt stress. In the Weeks Island mine, outbursts usually occurred within 10 ft of the upper corners of the development drifts and were never observed in the floors or in the lower half of the ribs of the development headings at Weeks Island (Mirza, 1979). The analysis predicted the greatest outburst potential to be in these same regions of the rooms. The close agreement of the predictions with observations in the mine lend credibility to a coupled gas pressure-rock stress mechanism.

Additional gas diffusion modeling (Ney and Stroller, 1979) examined the outburst potential of a new level located 300 ft under the existing level of a room and pillar mine. The results showed that it was unlikely that an outburst initiated from the new lower level would communicate with the upper level because pore pressures in the salt surrounding the upper level had bled to a low pressure. Supporting this prediction is the absence of a known case where two levels of a mine have been connected by an outburst. Mining levels in salt mines are typically separated by approximately 150 ft of salt in the Gulf Coast domes. The outbursts studied at the Weeks Island mine were all located in the lower level, outside of the vertically projected boundary of the upper level. This may have been a result of the gas bleed off mechanism since the gas in the lower level salt had over 50 years to drain into the

upper level mine prior to mining the lower level. The modeling results are not in perfect correlation with observations. A case exists where an outburst occurred immediately after mining a face that had been inactive for 10 years (Molinda, 1988).

Other analyses were performed for Weeks Island to determine acceptable working level separations. The mechanical response of a 20 ft diameter outburst propagated upward from a new lower mining level were performed by Hilton, Benzley, and Gubbels (1979) and Preece and Krieg (1984). The analyses showed no measurable effect on the upper working level until the outburst approached within 100 ft of the mine. Even at 50 ft below the room and pillar mine, the predicted stresses in comparison to the strength of the salt was adequate, and therefore, failure was not a concern. A working level separation for the mine was based on the results of these analyses and the historic data that showed outbursts up to 300 ft high.

Other Theories

It appears to be universally accepted that the crushed, pulverized salt associated with an outburst is a result of the violent nature of the outbursting process. However, the possibility that a fragmented or incohesive volume of salt could exist in situ (prior to mining) within a domal or bedded salt has not been disproven. Creep stresses would normally heal any crushed salt into intact salt over the diagenic ages where internal movement within the salt structure may have caused such conditions to come about, but the presence of impurities, gases, and liquids may prevent salt healing. As such, a gas-pressurized, incohesive mass of salt could form and demonstrate some of the same characteristics of outbursts when mined into.

In light of the aforementioned possibility that gas pressurized salt could behave as a Terzaghi material (see section on gas pressure), a new theory emerges on the interaction of gas pressure and salt strength. The limited amount of testing to date suggests that if pore pressures exceed the rock stress, the salt will lose cohesion. As the mine approaches a gassy pocket of salt, the confining stresses in the salt could be reduced below the gas pressure in the salt. The resulting loss of cohesion combined with the relatively high gas pressure could account for outbursting. These conditions are illustrated in Figure 2.

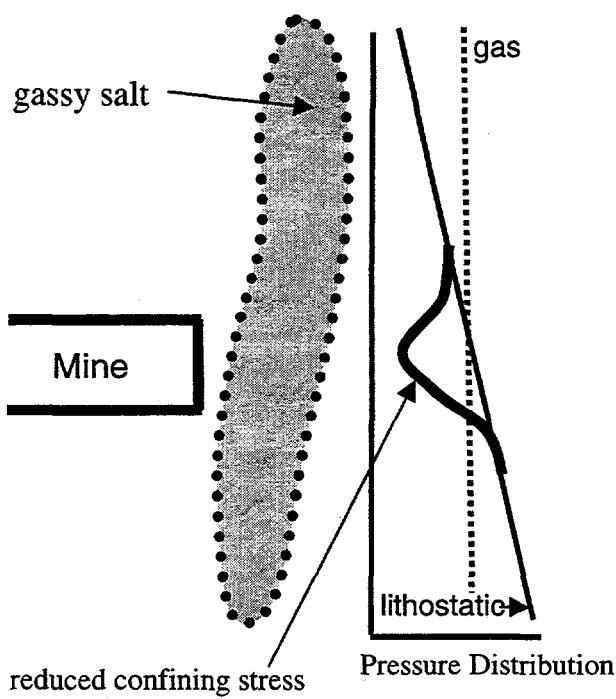


Figure 2. Outburst Process

- prior to mining, gas pressure is on average at lithostatic pressure
- mining removes the confining pressure on the salt face
- gas pore pressure remains high even though the pores may expand some due to reduction in rock stress
- gassy salt becomes cohesionless because pore pressure is greater than the rock stress
- rubbleized salt blows out unto mine
- as outburst cavity propagates, it acts as the mining face
- gas over-pressure is greater higher up in the cavity creating the tendency to propagate upward

PREDICTION AND PREVENTION OF OUTBURSTS

The historical response of mining to outbursts is described by Dorfelt (1966). The plan for dealing with outbursts evolved from no protection, to protection of the crew (initially in underground shelters, then evacuation to the surface during blasting), to later include protection of equipment, and currently prediction and control of outbursts.

To be successful, a technique aimed at either predicting or preventing an outburst must be simple to adapt underground, and be economical. Various methods have been used including mapping, sampling gas content, drilling and coring, geophysical techniques, and blasting techniques.

Mapping

Perhaps the earliest attempts to mitigate outbursts was derived from their known association with anomalous zones. Mapping anomalous features associated with outbursts and the previous outbursts themselves could potentially delineate zones where outbursting has a high potential. These areas could then be avoided. In practice, mines have been closed

because of outburst problems, and the layout of mines is often controlled to some extent by the magnitude of an outburst problem. The vertical extent of any buffer zone between a mine level and potential hazards (such as a fresh water aquifer) must also consider the potential heights that an outburst could achieve. Characterization of previous outbursts can help determine an acceptable barrier thickness. More often though, mine layouts are reactionary in nature to outbursts, rather than emphasizing planning, prediction, and control.

The potential for an outburst could be reduced by avoiding known shear and anomalous zones. Geologic mapping of these zones prior to and during mining could help in anticipating potential outbursts. Of particular use is the mapping of such features when a new mine level is planned either above or below the existing one since the inclination of geologic structure is often known. For example, in U.S. salt domes, geologic anomalous zones are vertically oriented and often extensive enough to cross multiple mine levels. However, where a potential outburst zone is being breached by mine workings for the first time (a new mine), physical associations can not be used to predict outbursting (Schatzman and Hyman, 1984; and Molinda, 1988). These authors conclude that physical features (alone) are unreliable in predicting outbursts. However, by using information collected from a number of different sources including previously mapped outbursts, anomalous zones, and measured gas emissions, it may be possible to predict the approach to potential outburst hazard areas, particularly where high methane content, large crystal size, and disturbed banding occur abruptly. Such an area could be outlined and identified as a potential outburst hazard area Molinda (1988).

When observation is coupled to core measurements, analytic techniques that predict risk can be derived. A number of potential burst indices (based in part on accumulated strain, kinetic energy, failure velocity and stress relaxation) are discussed by Cruickshank, Mahtab, and Wane (1986), but need further development before they can be applied routinely.

Sampling Gas Content

The correlation of gassy zones of salt and outbursts resulted in perhaps the first analytic attempt to predict outburst potential based on the inferred gas content of salt at the mining face. The gas content of salt samples collected during mining could be evaluated using a rather simple test. The gas content was estimated by dissolving a salt sample in fresh water and recording the acoustic noises generated as the occluded gas bubbles were released. The method may have been first used in what is called the Sondershausen crackle-probe (Dorfelt, 1966). Gimm, Thoma, and Eckart (1966) mention a method that measures the

intensity of decrepitation noises produced during salt dissolution. The noises are proportional to the gas content of the sample and provide a method to predict outbursts.

More recent, Grau (1990) developed an acoustic method for the U.S. Bureau of Mines based on sound emitted when pressurized gas occlusions are dissolved. One hundred seventy three salt samples were analyzed for gas content and noise output (dB). It was concluded that salt taken from outbursts contained more gas than normal salt and also generated louder noise when dissolved. Therefore salt samples could be classified as normal or outburst salt. Although salt taken from an outburst holds measurable quantities of methane, even after many months, the technique was intended for underground use to provide a quick assessment of outburst potential.

U.S. experience shows that at least one mining operator (at Cote Blanche) routinely used this method to check the face prior to blasting. However, the dissolution test itself has been primarily used as a research tool, and not accepted by the salt mining industry for daily use because of several inherent problems. It was viewed as a lengthy procedure, requiring special equipment, and sometimes difficult to interpret as there is some overlap in gas content values for normal and outburst salt. Also, the method may not work well for CO₂ or if the gas inclusions are not homogeneously distributed (Grau, 1990). In a test case at a Canadian potash mine, the method did not work very well as the gas pressure was too low (Iannacchione and Schatzel, 1985). In bedded formations, the method may not work because the gas content of the neighboring horizons (which are not measured) can be the major cause of outbursting.

Drilling and Coring

The other method to collect information on gas content is to drill into the face and to measure emissions from the borehole. Exploratory drilling may become an important prediction tool to provide information on methane content and salt purity (Molinda, 1988). In an effort to predict outbursts in advance of mining, drilling ahead of the working face was experimented with in the Weeks Island domal salt mine (Head, 1997). The results showed that no distinguishing criteria could be established to predict outburst prone areas based on the amount of methane emitted from the holes. A similar experience is noted by Bakowski (1966), where measuring gas outflows in boreholes at the face, and mapping salt bituminity (an anomalous feature in polish mines) did not result in the determination of outburst zones in an indisputable way. Believing that a relationship between outbursts and gas exists, it was postulated that outbursts may be associated with occluded gas, which can not be

readily relieved through drilling and that the gas contents measured in the boreholes reflected largely draining of intercrystalline gas (Head, 1997). In contrast to the above experience, Gimm, Thoma, and Eckart (1966) report that gas pressure measured in boreholes at the working face of German potash mines has been used as a predictive method for outbursts.

Boreholes located in the working face may serve another useful purpose in reducing the potential for outbursts. Holes drilled into the roof of a potash mine reduced gas pressure, stabilized the roof, and decreased the outburst potential (Schatzel and Dunsbier, 1988). The reduction in gas pressure not only reduces the driving force, but also increases the effective strength of the salt (Mahtab, 1981). However, Thoms and Martinez (1978) conclude that the success is mixed, the effectiveness of bleeder holes is questionable, and therefore considered a speculative method in reducing outbursts.

Perhaps the better use of boreholes is to obtain core for inspection purposes. Core disking is common when drilling into highly stressed hard rock where thickness decreases with increasing stress (Mahab, 1981). In deep South African gold mines (quartzite), the characteristics of core breakage is used as a prognosis for rockbursts. Similarly, characteristic differences in core breakage (relatively thin slices) is used to predict outbursts (Freiberg core prognosis) in German potash mines (Dorfelt, 1966; Gimm and Pforr, 1964). Outburst-prone salt results in watch-glass shaped core discs that are laminated in the direction of drilling, similar to those observed in the deep South African gold mines, even though the potash mines are much shallower (1600 to 2300 ft).

Duchrow and Marggraf (1966) report that in practice, core examination, inferred gas content, and measuring borehole gas pressures are used, but with none given absolute priority over the other in predicting outburst occurrence. Schatzman and Hyman (1984) and Molinda (1988) state that measurements of gas concentrations in salt can provide pertinent information to distinguish potential outbursts in salt, and exploratory holes may be useful in advance of the face to determine physical properties, disk, and salt composition. They conclude that there are no other predictive methods currently available.

Geophysical Techniques

Cruickshank, Mahtab, and Wane (1986) discuss microseismic monitoring and acoustic emission or rock noise. They conclude that, unfortunately, research has not yet reached the point where the timing of an upcoming failure can be forecast accurately. Apparently

geophysical techniques have not been developed or at least reported that can be employed to give warning of potential outburst areas (Thoms and Martinez, 1978).

Remote listening devices (microphones) have been successfully used by Schatzel and Dunsbier (1988) to investigate outburst occurrence in a Canadian potash mine. They recorded roof bolts failing in rapid succession as an outburst occurred at an intersection. In general, outbursts have not resulted in roof instabilities in U.S. mines; however, extensive roof falls are frequently associated with the much larger outbursts in German mines (Baar, 1977). As such, remote listening devices may be effective in monitoring events after a blast, particularly roof instabilities, but they are not considered a predictive tool.

Questions remain on the use of remote sensing. Although attempts have been made at this, results have been inconclusive. There is a great need for an accurate in-mine technique to sense high pressure gas zones, as well as boundaries (radar techniques have shown the most promise) (Molinda, 1988). However, experience at the Waste Isolation Pilot Plant (Borns, 1998) showed that radar penetrability is very limited (less than 10 ft) in bedded salt because of its relatively high brine content. In dry salt domes, the increased resistance could result in radar penetration up to several hundred feet. In practice, experience using radar as a means to detect geologic anomalies is limited. In one mine, radar failed to locate a breccia pipe known to exist within a potash and salt unit (Unterberger, 1981).

The difficulty in most geophysical techniques is interpreting the raw data. It may be possible with experience to distinguish the difference between gas pockets in salt and the various other anomalous features found in salt. However, the use of geophysical techniques can be costly and require training before they could be routinely used underground.

Blasting Techniques

It is possible to use special blasting techniques to control outbursting. Duchrow and Marggraf (1966) report on technically controlling outbursts as early as 1962 in German potash mines. Examination of outbursts in German potash mines has shown that in the end phase of an outburst, mostly at the cavity circumference, a secondarily deactivated protective layer is formed, behind which there remains still outburst-active, but dammed rock. This layer consists of a thin zone which is arched like the outburst lamination and possesses a considerable bonding strength. Because it is completely intact it limits the outburst growth and intensity. By using special shooting schemes, an outburst can be

prematurely terminated by inducing this secondary protective layer (Gimm, Thoma, and Eckart, 1966).

Outburst apertures ranges from 11 to 110 ft² in most cases (Wolf, 1966). Using this concept, an outburst may be controlled by making artificial outburst apertures of a small size (say 0.8 ft). By artificially shooting a hole size of less than the critical diameter, an outburst may be limited (Gimm, Thoma, and Eckart, 1966). Their data suggests that an equivalent face diameter of 0.95 ± 0.16 ft is required for an outburst. A normally large outburst, purposely triggered in front of the face, will prematurely terminate because of its small hole size. Duchrow and Marggraf (1966) outline the blast procedures. A burn cut is used with a vertical row of blast holes on each side of a drill hole to enlarge the burn hole at the toe. The size of the outburst will be limited by the size of the burn hole. In wide faces, several such cuts can be made to control outburst potential in the face of German potash mines.

The method for systematically provoking outbursts has become routine in the Werra and Southern Harz potash mines (Dorfelt, 1966) and it is reported by Baar (1977) as being extensively used in Germany. It should be noted that Gulf Coast domes mapped by Kupfer showed much smaller diameter outbursts. Therefore, controlled blasting techniques may not be practical in the U.S. as a much smaller hole size may apply. Also outbursts tend to be in the roof of U.S. domal salt mines, rather than in front of the face, making the blast technique less likely to be effective.

Another blasting technique considered for controlling outbursts is shock blasting in advance of mining Mahtab (1981). Mahtab (1981b) reports that shock blasting, though not practiced in Louisiana salt mines, has successfully reduced outbursts in coal mines and controlled rockbursts in hard rock mines (in particular S. Africa). As such, it may be a promising technique for use in salt mines. Mahtab, Boshkov, and Shirshac (1984) review procedures that could be used for controlled mining of salt under conditions of potential outbursts. In general, the methods reduce susceptibility of salt to outbursts by transferring stress away from burst-prone areas and on to the abutments of non-bursting salt. The net result of shock blasting is that a fractured zone yields gradually rather than failing suddenly. Most of the experience with shock blasting is with coal mines to date. There is at least one instance where it was ineffective and shock blasting may instead trigger an outburst. The use of yielding concepts requires specific geologic knowledge and the methods do not always result in the desired objectives and in some cases, contrary results.

Comments on Prediction and Control of Outbursts

The Germans have had the most success in predicting and controlling outbursts, undoubtedly a result of the effort put into the program and understanding the mechanisms that control outbursts. It is not obvious whether the methods and techniques used in the German potash mines would be as successful for other operators. For example, the outbursts in German potash mines can be explained by stress related mechanisms, but in contrast the outbursts in U.S. salt domes appear to be dominated by gas related mechanisms. The Germans have adopted blasting methods to prematurely trigger and hence limit or control the size of an outburst at the working face. This technique is based on a minimum critical throat size, below which outbursts do not occur. However, in U.S. domal mines there does not appear to be a minimum outburst size, in addition the outbursts are located mainly in the roof of the workings, further reducing the chances that such a technique would work. Although outbursts throughout the world tend to share certain characteristics (associated with gas and other anomalous features, abruptly generated upon excavation, similar appearance), site specific geology control their location, magnitude, and orientation. Therefore, site characterization can help, but experience shows that predictive methods are unreliable. The potential benefits must be weighed against the costs in deciding whether it is practical to pursue prediction and control techniques.

In general, the experience of others shows limited success in understanding, predicting, or controlling outbursts. Perhaps Brendiaux (1966) best expresses the state-of-art: "Although underground and laboratory studies were complete. The results are interesting, but they haven't reached valid conclusions of the mechanisms or haven't given usable indications for preventing rockbursts or gas-flows." A similar assessment is made by Mahtab (1981), "The geomechanical aspects of outbursts are poorly understood, and no satisfactorily explanation of their mechanics and no methods for predicting and preventing their occurrence are available".

It appears that no reliable method exists to predict outbursts, and the mechanisms that cause them are not well understood. The "unreliable" state-of-art in predicting rock outbursts may continue for some time, until a new technology comes forth.

OUTBURSTS INTO CAVERNS

It is not known whether or not salt caverns experience the same magnitude of outbursts as noted in mines. The absence of direct observation and limitations on sonar accuracy restrict the ability to detect and characterize typical outbursts sizes as noted in mines. Indirect evidence of outbursts may be noted during cavern leaching where pressure bumps are often recorded. The above discussions on outbursts have shown that outbursts occur regardless of the mining method used, therefore they should also occur during leaching of caverns.

Predicted Pressure Kick

The magnitude of a pressure kick in a cavern due to an outburst can be estimated analytically. The solution assumes that the gas in the outburst cavity is at a higher pressure than the fluid in the cavern and upon release into the cavern compresses the cavern fluid causing a pressure increase in the cavern. Dynamic impact forces are assumed to be negligible at the well head due to either attenuation along the fluid column to the surface or the absence of large pressure transients in the first place. As discussed above, pressure waves measured near outbursts were only on the order of those found in blasting (Wolf, 1966). It is also assumed that gas dissolution into the cavern fluid is negligible immediately following the outburst. In general, gas dissolution into a fluid is a slow process where the gas molecules slip between the fluid molecules resulting in a net volume loss, and hence slow depressurization following the gas release into the cavern.

The cavern equilibrium pressure following an outburst is dependent upon the size and depth of the cavern and outburst. Since pressure kicks due to outbursts are expected during leaching of caverns, the cavern fluid is dominantly brine. Predicted cavern pressures following an outburst are presented in Figure 3 for two different cavern sizes (1 and 10 MMB), two different depths (1000 and 5000 ft), and over a wide range of outbursts sizes, since outbursts can vary in size from essentially small pockets up to perhaps 50 million ft³ of gas. Note that the convention used throughout this paper is to reference gas volume at atmospheric pressure or standard cubic feet of gas (SCF). For very small outbursts, the cavern pressure after an outburst is essentially equal to the hydrostatic pressure during brining (0.5 psi per ft of depth). As the size of the outburst increases, the cavern pressure tends to increase towards its maximum possible value of lithostatic gas pressure (1 psi per ft of depth). The 1 MMB cavern at 1000 ft deep almost attains lithostatic pressure for relatively large outbursts (greater than 10 million ft³). The volume of the 1 MMB cavern (5.6 million ft³) is smaller than the gas volume in the outburst at standard conditions (1 atm).

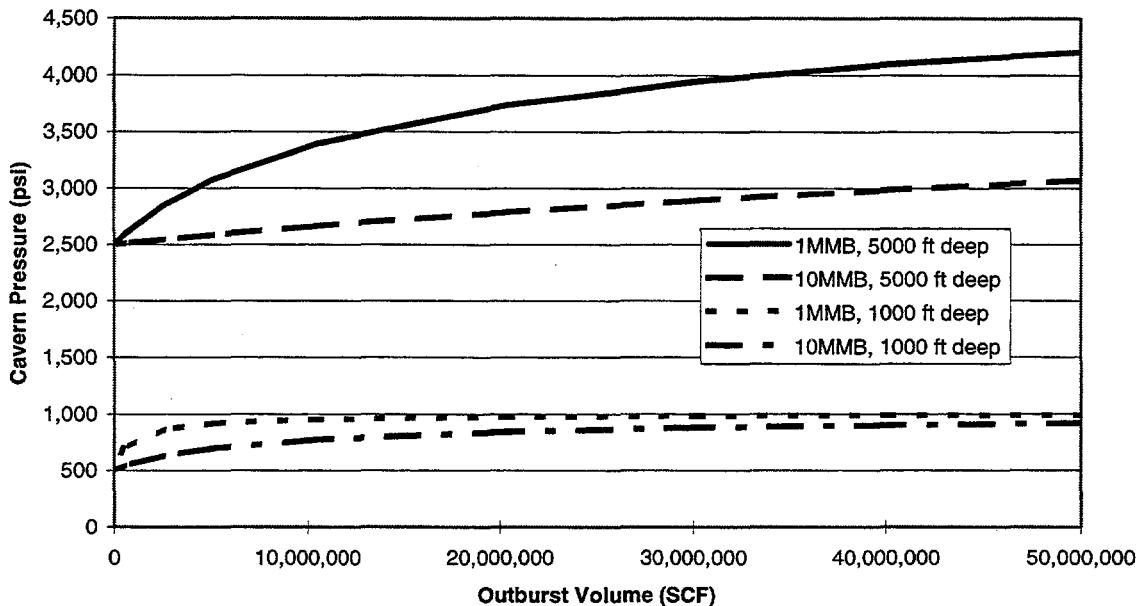
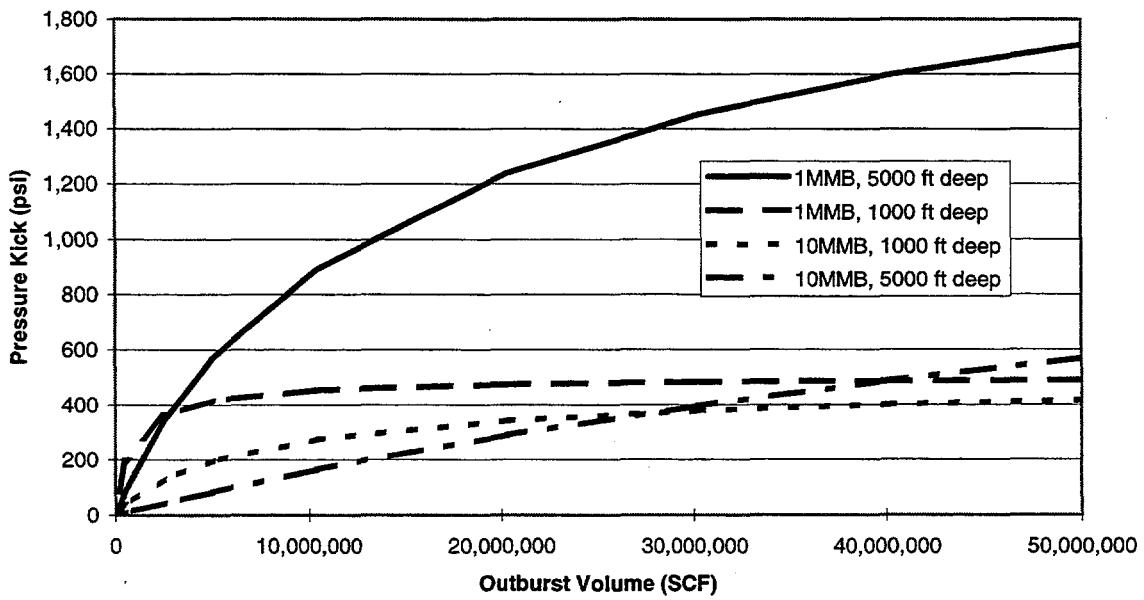
Figure 3. Cavern Pressures Following an Outburst**Figure 4. Rise in Cavern Pressure Following an Outburst**

Figure 4, shows the predicted pressure kick or increase in cavern pressure following an outburst. In most cases, the magnitude of the pressure kicks would manifest as less than a few hundred psi pressure bump at the wellhead. The smaller, deeper cavern (1 MMB, 5000 ft deep) is most susceptible to a large pressure kick.

Gas Caps

Gas intrusion into caverns may result in distinct phases or a gas cap forming on top of the cavern fluid. Not all gas caps in caverns are a result of gas being released from the salt. Some gas caps represent intentionally stored product, while others may have been created to control leaching or a result of entrained air in the leach water, and still others may have resulted from accidental overfill of nitrogen during testing of cavern wells. There is however, the possibility that a gas cap may form as gas migrates from the salt into a stored liquid. This could occur abruptly as in an outburst, or slowly over time.

The rate of gas intrusions ranges from near instantaneous (outbursts) to very slow infiltration or percolation. Gas can be released abruptly, without the ejection of salt. For example, Molinda (1988) reports that exploratory holes in the Belle Isle mine emitted 49,000 cubic feet of methane abruptly. The duration of gas releases from boreholes or wells varies. At Big Hill, gas pressurized the newly completed cavern wells at a constant rate of 0 to 8 psi/day over an 800 day observation period (Hinkebein, et al., 1995). The variability in release rates showed that within a salt structure, gas intrusion rates can vary significantly. In some cases, the duration of flow is limited. In one Gulf Coast salt mine, a continuous methane out-gas from a anomalous zone was measured over 47 days at flow rates as high as 88,000 ft³/day (Iannacchione, et al., 1984). Regardless of release rates, durations, and magnitudes, the presence of a gas cap and/or the accumulation of gas in the stored product in a cavern can result from gas inflows.

An abrupt release of a large quantity of gas may not entirely dissolve into the cavern fluid. This release would form a distinct phase or cap on top of the liquid. If, on the other hand, the release rate is small enough, the gas could dissolves into the cavern fluid and no cap would form unless the liquid were completely saturated. For water, the solubility of natural gas varies from 5 to 16 ft³/B at pressures from 500 to 2500 psi for typical 100 °F cavern temperatures (Bradley, 1987). For brine, the maximum dissolved gas content is reduced by up to one-fourth that found in water. If a petroleum product is present as a blanket oil for leaching, the affinity of gas for petroleum is much greater than water or brine. These values show that a very large gas release is required to saturate the cavern fluids, particularly

during brining where the fluid are constantly being circulated and removed. In practice, saturation of an entire cavern is unusual, but has been noted in at least one brine cavern at the Weeks Island site. In the absence of overall saturation, localized saturation could occur, especially if the liquid is static. During product storage, in a static fluid, localized saturation along the entire flow path from the release point to the top of the cavern may cause a gas cap to form. Such conditions are more likely to occur in bowl-shaped caverns of small height. The geometry and lack of a thermal gradient inhibits fluid circulation.

Two examples of gas caps are at Carresse (Berest, et al., 1997) and at Bryan Mound (Ehgartner, 1996). Gas caps were noticed in both of these caverns in sonar surveys and their presence analytically verified by the low compressibility of the caverns.

GAS INTRUSION INTO SPR CAVERNS

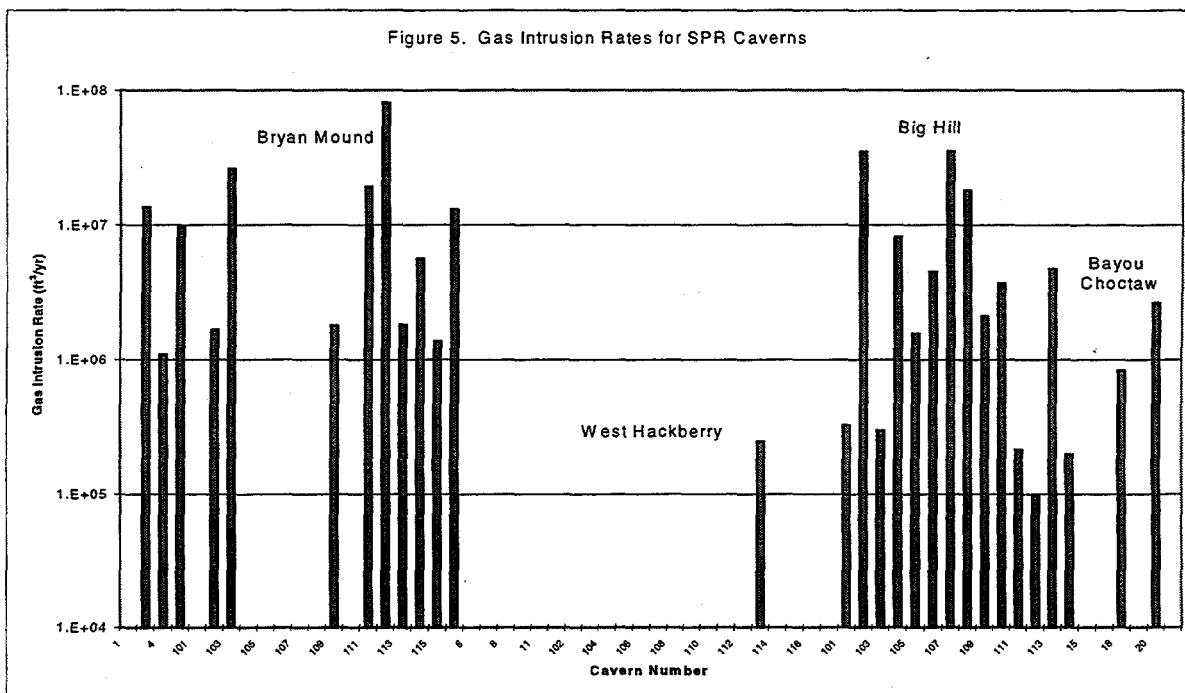
Although gas releases from salt occur, in many cases they are not noticed or measured because the products are stored for only a short time before being used. This is particularly true for commercial caverns. However, the U.S. Strategic Petroleum Reserve (SPR) is a good case history to examine since the product has been stored long enough to allow detectable measurements of the gas accumulation rates in the oil.

Gas Intrusion Rates

The SPR currently stores approximately 560 million barrels of crude oil in 62 caverns located in 4 salt domes along the Gulf Coast. Most of the oil has been in storage since the early 1980's when the majority of the caverns were leached. Over time the gas content of the oil has increased and in some caverns may exceed the EPA emission standards for tanks and safety limits for handling (Hinkebein, et al., 1995). The gases are approximately 80 percent methane, with the remained comprised of nitrogen and some light hydrocarbons.

The typical SPR cavern is approximately cylindrical in shape with a roof at 2500 ft below surface, a diameter of 190 ft, and a bottom depth of 4500 ft. This results in a cavern volume of about 10 MMB. Initial gas concentrations were obtained in the early 1990's using two methods-- analysis of pressurized samples and data from a skid-mounted gas separator on the surface. Although some discrepancies existed in the measurements, gas intrusion rates significantly varied between sites and caverns in a particular dome. As shown in Figure 5, only 29 of the 62 caverns had a measurable gas content. Of the caverns with measurable gas contents, the average gas intrusion rate was 10 million ft³/yr and the maximum rate was 81

million ft³/yr. The volumes of gas accumulated in the oil reserves in a year are on the same order as some of the largest outbursts and sudden gas influxes noted earlier for mines.



As such, it was not known whether the gases were accumulated over time or were a product from leaching. Two major gas migration concepts were examined and evaluated against the available data and analyses. The first assumed that the gas was liberated from the leached salt during brining of the cavern, absorbed into the leach blanket (oil), then later redistributed into the oil upon filling of the cavern. Although enough gas could potentially exist in the salt to account for the measured gas contents in the oil, the equilibrium concentration in the blanket oil (which has a much greater affinity for gas than brine) is too low to account for the measured gas to oil ratios. It was concluded that this mechanism is a minor effect, perhaps accounting for 0.01 of the typical 4 ft³ of gas per B measured.

Modeling gas percolation through salt

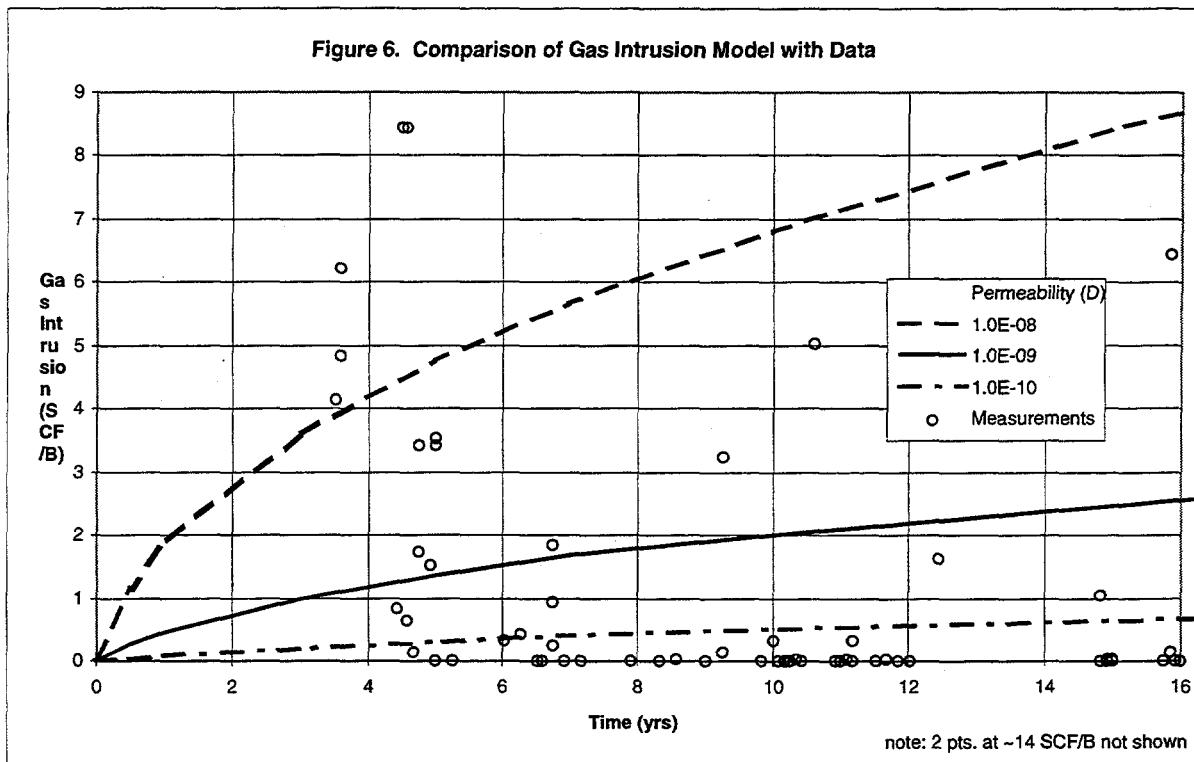
The second mechanism that could potentially account for the measured gas contents in the SPR crude was based on a permeability model for the salt. Transient gas flow through a porous media using Darcy's law predicted gas inflows into the cavern over time. One of the major assumptions in most hydrologic analyses is that Darcy's law is applicable for fluid flow through salt. Darcy's law was originally developed for water flowing through soil. It is well known that porosities of salt are typically much smaller than soil values. However,

field and laboratory data suggest that Darcy's law may be appropriate for modeling flow through salt. Cosenza, et al. (1996) performed a gas and brine injection test in a borehole located in a relatively pure salt and percolation was simulated by a model based on Darcy's law. The flow of kerosene through rock salt also appears to obey the same laws as developed for flow of water through soils (Lai, 1971). It was originally thought that capillary action may prevent fluid flow where two different fluids are present. For salt, capillary action was theoretically estimated in the range of 1 to 300+ MPa (Cosenza, et al., 1995), but measurements suggested the capillary pressure does not exceed about 1 MPa. The analysis of the long-term hydraulic fracture tests by Durup (1994) also showed the absence of significant capillary pressure and use of Darcy's law to simulate brine percolation through salt. The use of Darcy's law and absence of significant capillary action greatly simplifies the modeling of fluid flow through salt.

Assuming a typical salt porosity of 1 percent and permeability of 1 nanoDarcy for intact salt (Sutherland and Cave, 1980; Stormont, 1990; SNL, 1996), gas intrusion was predicted to be 2 ft³/B over the initial 10 years, and decreases by approximately 50 percent over the second 10 years. This intrusion rate approximates the actual gas intrusion for many SPR caverns. Geomechanics analyses of the caverns predicted no potential damage to the salt surrounding the cavern, even during low pressure operations such as workovers. As such, the salt surrounding the caverns can be represented by the properties of intact salt (undamaged). The sensitivity of the salt permeability was evaluated by examining an expected range in permeabilities for intact salt--an order of magnitude greater and less than 1 nanoDarcy (Berest and Brouard, 1995). The results of the permeability model show the low permeability intrusion and high permeability intrusion rates to approximately bound the measured intrusion rates. The measured gas contents of SPR caverns are compared to the model results in Figure 6. This implies that the differences in gas intrusion rates could be a result of permeability variations both within and between salt domes

Anomalous zones in the salt could result in localized permeability variations and are also likely to contain a higher content of gas. Because gas samples taken from the caverns were largely petrogenic in origin, it was logical to associate geologic features with the occurrence of gas. As such, an attempt (Hinkebein, et al., 1995) was made to correlate the rate of gas intrusion with proximity to known anomalous zones at the three SPR domes exhibiting the largest gas inflows. The exercise showed that correlations at Bayou Choctaw and Big Hill were not intuitively apparent. Similarly at Bryan Mound, definitive correlations could not be

made. The lack of any specific correlations may be due in part to the difficulties in defining and mapping geologic features and postulated anomalous zones in salt domes.



The permeability model for gas intrusion is expected to predict a decrease in gas concentration when cavern operating pressure is increased. The expected value for SPR caverns is small, because of the narrow operating range in caverns. For example, a 200 psi decrease in well head pressure results in approximately a 15 percent decrease in driving pressure. The driving pressure is defined as the difference in pressure between the cavern fluid and the pore pressures in salt. Given the typical SPR operating pressures and a lithostatic pore pressure, gas is predicted to flow into the caverns. As discussed earlier, pore pressures in some salts are assumed to be much lower than lithostatic pressure--at hydrostatic in some cases (Berest and Brouard, 1995). If this were the case for SPR domes, gas migration would be in the opposite direction (into the salt), and the problem of gas intrusion into the crude oil would not exist because the caverns are operated above hydrostatic pressure. A study of five gassy caverns at Bryan Mound, supported the permeability model. A correlation was derived between gas content and the average historic operating pressure of the caverns, where lower operating pressures resulted in higher gas contents in the oil.

Degassing of SPR Caverns

The potential problems associated with gas in SPR crude oil prompted degassing of the oil. Caverns in the first scheduled round have now completed de-gassing. With time, gas regain rates will be measured and compared to model predictions to better understand the intrusion mechanisms and assist in planning any future de-gassing of SPR caverns.

CONCLUSIONS

Observed gas releases from salt demonstrate that salt contains pressurized gases and permits flow into mines and caverns. The types of gases vary, as do the quantities and release rates. Abrupt releases or outbursts are most evident in mines, but are also believed to occur in caverns and can be quantified by secondary means, such as pressure "kick" observations. Slow releases may require a long time before a detectable amount of gas can accumulate. In either case, gas releases have caused problems for facility operators throughout the world.

The mechanisms potentially responsible for gas-related occurrences vary as do the factors that influence them. In general, abrupt gas releases (outbursts) occur only during mining (conventional or solution). This suggests that the change in rock stresses induced by mining is a primary cause of outbursts. After mining, gas release rates are slower. Under these conditions, the permeability of the salt controls the inflow. In both cases, gas pressure is the driving mechanism and the permeability of salt is effected by rock stress, particularly if fracturing develops.

Methods to predict and control gas releases have met with limited success in both mines and caverns. Despite having been studied and investigated by many experts, the state-of-art in gas releases from salt is considered to be in its infancy-- not having past the terrible twos in age.

References

Acres American Inc. Photographs of the Weeks Island Mines. Courtesy of Stewart Thompson. Contract DEA-121-75, Gulf Interstate Engineering Co. for U.S. Federal Energy Administration. Buffalo, NY, 1978.

Baar, C.A. Measurements of Rock Pressure and Pillar Loads in Deep Potash Mines, 2nd Symposium on Salt, Vol. 2, The Northern Ohio Geologic Society, Cleveland, Ohio, 1961

Baar C.A. Applied Salt Rock Mechanics, I. Elsevier Sci. Pub. Co., NY, NY, 1977.

Bakowski, J., M. Dialy, A. Litonski, J. Poborski. Concurrence, Investigation and Forecasting of Sudden Outbursts in Polish Salt Mines. International Congress on Problems of Sudden Outbursts of Gas and Rock. Leipzig, German Democratic Republic, October, 1966.

Baltaretu, R. and R. Gaube. A Sudden Outburst of Gas and Rock in Particular Conditions. International Congress on Problems of Sudden Outbursts of Gas and Rock. Leipzig, German Democratic Republic, October, 1966.

Beauheim, R. Recent Pore Pressure Measurements at WIPP. Personal communications, Sandia National Laboratories, Albuquerque, NM, October 1997.

Berest, P. and B. Brouard. Behavior of Sealed Soution-Mined Caverns. Solution Mining Research Institute, Spring Meeting, New Orleans, 1995.

Berest, P., B. Brouard, J. Bergues, J. Frelat, and G. Durup. Salt Caverns and the Compressibility Factor. Technical paper presented at the Fall Solution Mining Research Institute meeting, El Paso, TX, October 5-8, 1997.

Berest, P., B. Brouard, and G. Durup. Behavior of Sealed Solution-Mined Caverns. Proc. ISRM Int. Symp., Eurock '96, Bakema, Rotterdam, 1996.

Borns, D. J. Personal communications, Sandia National Laboratories, Albuquerque, NM, March, 1998.

Brace, W.F. and R.J. Martin. A Test of the law of Effective Stress for Crystalline Rocks of Low Porosity. International Journal of Rock mechanics and Mining Sciences, V. 5, 1968.

Bradley, H.B. (Editor-in-Chief). Petroleum Engineering Handbook. Society of Petroleum Engineers, Richardson, TX, Third Ed., 1987.

Brendiaux, J. Investigations of Foot-wall-bursts and Gas-effusions in the State Potash-mines of Alsace. International Congress on Problems of Sudden Outbursts of Gas and Rock. Leipzig, German Democratic Republic, October, 1966.

Cosenza, P., M. Ghoreychi, and B. Bazargan-Sabet. In Situ Gas and Brine Permeability Measurements in Salt. Proc. 4th Conf. Mechanical Behavior of Salt, Trans. Tech Publications, Montreal, 1996.

Cosenza, P., M. Ghoreychi, and B. Bazargan, S. Telandro, and A. Cournut. First Results and Interpretation of In Situ Permeability Measurements in Salt to Gas and to Brine. Proc. 5th Progress meeting PEGASUS (Project on Effects of Gas in Underground Storage Facilities for Radioactive Waste) Office for Official Publications of the European Communities, EUR16796, Rapolano Terme, June 1995.

Cruickshank, N.M., M.A. Mahtab, and M.T. Wane. Methods for Predicting Gas Outbursts in Salt and Coal Mines. Trans. Amer. Inst. Mining, Metall., and pet. Engr., Vol. 280, 1986.

Djahanguiri, F. Critical Aspects of Mining Technology in Excavation of a Nuclear Waste Repository in Salt. International Society of Rock Mechanics, Symposium on Design and Performance of Underground Excavations, paper 39, 1984.

Dorfelt, H. Sudden Outbursts of Gas and Rock in the Mining of the GDR in Relation to the Safety in Mines. International Congress on Problems of Sudden Outbursts of Gas and Rock. Leipzig, German Democratic Republic, October, 1966.

Duchrow, G. and P. Marggraf. State of the Control of Sudden Outbursts of Salt and Gas in the Werra Area of the GDR. International Congress on Problems of Sudden Outbursts of Gas and Rock. Leipzig, German Democratic Republic, October, 1966.

Durup, J.G. Long Term Tests for Tightness Evaluations with Brine and Gas in Salt. SMRI Research Report 90-0002, Fall Meeting, Hanover, 1994.

Ehgartner, B.L. Bryan Mound Cavern 2 (Gas Cap). Internal report. Sandia National Laboratories, Albuquerque, NM, January 19, 1996.

Fokker, P.A. The Behavior of Salt and Salt Caverns. PhD Thesis, Technische Universiteit Delft, 1995.

Fokker, P.A., C.J. Kentor, and H.P. Rogaar. The Effect of Fluid Pressures on the Mechanical Stability of (Rock) Salt. 7th Symposium on Salt, Elsevier Science Publishers, Amsterdam, 1993.

Kentor, C.J., S.J. Doig, P. Rogaar, P.A. Fokker, and D.R. Davies. Diffusion of Brine Through Rock Salt Roof of Caverns. SMRI Fall meeting, Paris, 1990.

Fokker, P.A., C.J. Kentor, and H.P. Rogaar. The Effects of Fluid Pressure on the Mechanical Stability of Rock Salt. Publication 1087, Shell Transport and Trading Company, Rijswijk, The Netherlands, March 1992 and in the 7th Symposium on Salt, Elsevier Science Publishers, Amsterdam, 1993.

Gimm W. and H. Pforr. Breaking Behavior of Salt Rock Under Rockbursts and Gas Outbursts. 4th International Conference on Strata Control and Rock Mechanics, Columbia University, NY, May 4-8, 1964.

Gimm, W., K. Thoma, D. Eckart. Organization and Scientific Results of the Work of the "Mineralgebundene Gase" Research Group. International Congress on Problems of Sudden Outbursts of Gas and Rock. Leipzig, German Democratic Republic, October, 1966.

Gimm, W. Kali- und Steinsalzbergbau. VER Deutscher Verlag Fur Grundstoffindustrie, Leipzig, 1968.

Goodman, R.E. On the distribution of Stresses Around Circular Tunnels in Non-Homogeneous Rocks. Proc. Of the 1st congress, International Society of Rock Mechanics, Vol. II, 1966.

Grau III, R.H. and T.E. Marshall. Analysis of Acoustic Responses of Domal Salt Mine Samples. Report of Investigations 9295, U.S. Bureau of Mines, 1990.

Head, J. H. personal communications. Harding Lawson Associates, Oak Brook, Illinois, February 13, 1997.

Hilton. P., S. Benzley, and M. Gubbels. Structural Analysis of Weeks Island Mine/Petroleum Repository. SAND79-0595, Sandia National Laboratories, Albuquerque, NM, August, 1979.

Hinkebein, T.E., S.J. Bauer, B.L. Ehgartner, J.K. Linn, J.T. Neal, J.L. Todd, P.S. Kuhlman, C.T. Gniady, H.N. Giles. Gas Intrusion into SPR Caverns. SAND 94-0023, Sandia National Laboratories, Albuquerque, NM, Dec. 1995.

Hyman, D. Methodology for Developing Occulded Gas Contents in Domal Rock Salt. Bureau of Mines Report of Investigations RI- 8700, U.S. Dept. of the Interior, 1982.

Iannacchione, A.T. and S.J. Schatzel. Characterization of the Occurrence of Methane in Gulf Coast Domal Salt Mines. 2nd U.S. mine Ventilation symposium, Reno, NV, 1985.

Iannacchione, A., R. Grau, A. Sainato, T. Kohler, and S. Schatzel, Assessment of Methane Hazards in an Anomalous Zone of a Gulf Coast Salt Dome. Bureau of Mines Report of Investigations RI-8861, U.S. Dept. of the Interior, 1984.

Jaeger, J.C. Extension Failures in Rocks Subject to Fluid Pressure. Journal of Geophysics Research. V 68, 1963.

Kupfer, D.H. Shear Zones Inside Gulf Coast Salt Stocks Help to Delineate Spines of Movement. Am. Assoc. Pet. Geol. Bull. 60: 1434-1447, 1976.

Kupfer, D.H. Problems Associate with Anomalous Zones in Louisiana Salt Stocks, USA, 119-134, Fifth International Symposium on Salt, The Northern Ohio Geological Society, Cleveland, Ohio, 1978.

Kupfer, D.H. Anomalous Features in Five Island Salt Stocks. Trans. Gulf Coast Assoc. of Geol. Soc., 40:425-437, 1990.

Lai, C-S. Fluid Flow Through Rock-Salt Under Various Stress States. PhD Thesis, Michigan State University, 1971.

Lappin, A.R. and R.L. Hunter, ed. Systems Analysis, Long-Term Radionuclide Transport and Doe Assessments, Waste Isolation Pilot Plant (SIPP), SAND89-0462, Sandia National Laboratories, Albuquerque, NM 1989.

Laptev, B.V. and R.P. Potekhin. Burst Triggering by Zonal Disintegration of Evaporites. Soviet Mining Science, Vol. 24, No. 3, March 1989.

Leeman, E.R. The Measurement of Stress in Rock. Part 1, J. So. African inst. Min. and Met., pp 45-81, Sept. 1964.

Magorian, T. personal communications. Amherst NY, February 4, 1997.

Mahtab, M.A. Considerations of Gas Outbursts in Using Salt Mines for Storage of Oil and Nuclear Waste. Ground Control in Mining. Proceeding, 1st Conference, West Virginia University, 1981.

Mahtab, M.A. Occurrence and Control of Gas Outbursts in Domal Salt. First Conference on the Mechanical Behavior of Salt, The Pennsylvania State University, Nov. 9-11, 1981b.

Mahtab, M.A., S. Boshkov, and A. Shirshac. Controlled Mining of Salt Under Gas Outburst Conditions. World Mining Congress, 12th Proc., Nov. 19-23, New Delhi, 1984.

Mahtab, M.A., B. Trent, and T.M. Yegulalp. A Numerical Analysis of the Mechanics of Gas Outbursts in Salt. Sixth International Symposium on Salt, Vol. 1 Toronto, Canada, 1983.

Mirza, Mahmood B. Underground Mining Practices in Salt Dome at Morton Salt, Preprint No. 79-103, Society of Mining Engineers of AIME, Littleton CO, presented at annual meeting in New Orleans, Feb 18-22, 1979.

Molecke, M.A., K.R. Carney, W.J. Autin, E.B. Overton. Near-Surface Gas Mapping Studies of Salt Geologic Features at Weeks Island and Other Sites, SAND96-2502, Sandia National Laboratories, Albuquerque, NM, October, 1996.

Molinda, G.M. Gas outbursts Studied at Domal Salt Mines. Geotimes, Vol. 33, p 12-14, January, 1988.

Molinda, G. Investigation of Methane Occurrence and Outbursts in the Cote Blanche Domal Salt Mine, Louisiana. Bureau of Mines Report of Investigations RI- 9186, U.S. Dept. of the Interior, 1988.

MSHA (Mine Safety and Health Administration). Report of Nonfatal Outburst of Flammable Gas, Morton Salt Division of Morton Thiokol, Inc., Weeks Island Mine, New Iberia, Iberia Parish, Louisiana, Accident Investigation Report, report 16-00970, October 6, 1982. Published, January 31, 1983.

Munson, D.E. Personal communications. Sandia National Laboratories, Albuquerque, NM, Dec. 2, 1997

Neal, J.T., T.R. Magorian, R.L. Thoms, W.J. Autin, R.P. McCulloh, S. Denzler, K. Byrne. Anomalous Zones in Gulf Coast Salt Domes with Special Reference to Big Hill, TX and Weeks Island, LA. SAND92-2283, Sandia National Laboratories, Albuquerque, NM, July 1993.

Ney, J.F. and H.M. Stoller. Systems Integration and Engineering Support Study for the Strategic Petroleum Reserve (SPR) Program- Final Report. SAND79-0637, edited by SPR Project Division 4701, Sandia National Laboratories, Albuquerque, NM, June 1979.

Plimpton, H. R., Foster, J. Risbeck, R. Rutherford, R. King, G. Buffington, and W. Traweek. Final report of Mine Explosion Disaster, Belle Isle Mine, Cargill, Inc., Franklin, St. Mary Parish, Louisiana. MSHA Accident Invest. Report, 1980.

Preece, D. and R. Krieg. Finite Element Study of Working Level Separation at the Weeks Island Salt Dome. SAND84-1021, Sandia National Laboratories, Albuquerque, NM, July, 1984.

Sandia National Laboratories. Waste Isolation Pilot Plant Shaft Sealing System Compliance Submittal Design Report. Volume 1 of 2: Main Report & Appendices A,B, C, and D. SAND96-1326/1. Repository Isolation Department, Sandia National Laboratories, August 1996.

Schatzel, S.J. and M.S. Dunsbier. Roof Outbursting at a Canadian Bedded Salt Mine. U.S. Mine Ventilation Symposium, 4th proceeding, Reno, NV, 1988.

Schatzel, S.J. and D.M. Hyman. Methane Content of Gulf Coast Domal Rock Salt. Bureau of Mines Report of Investigations RI- 8889, U.S. Dept. of the Interior, 1984.

Stormont, J.C. Gas Permeability Changes in Rock Salt During Deformation, Ph.D. Dissertation, University of Arizona, Tucson, AZ, 1990.

Sutherland, H.J. and S.P. Cave. Argon gas permeability of New Mexico rock salt under hydrostatic compression, Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 17, 1980.

Terzaghi, K. Stress conditions for the Failure of Saturated concrete and Rock. Proc. Of the American Society of Testing Materials. V45, 1945.

Thoms, R.L. and J.D. Martinez. Blowouts in Domal Salt, 405-411, Fifth International Symposium on Salt, Vol 1, The Northern Ohio Geological Society, Cleveland, Ohio, 1978.

Unterberger, R.R. Final Report on Subsurface Radar Application in the Delaware Basin, Covering the Period June 1, 1980 through January 31, 1981. College Station, TX: Texas A&M University, Dept. of Geophysics, 1981.

U.S. Federal Energy Administration. National Strategic Oil Storage Program, Weeks Island Mine, Geotechnical Study. Contract FEA-1251-54 Gulf Interstate Company, Houston, Texas, November, 1977.

Westfield, J. et al. USBM Report District H, Final Report of Major Mine- Explosion Disasters, Cane Creek Mine, Potash Division, Texas Gulf Sulphur Company, Grand County, Utah, August 27, 1963.

Wolf, H. Aerodynamics of Sudden Outbursts of Salt and Gas. International Congress on Problems of Sudden Outbursts of Gas and Rock. Leipzig, German Democratic Republic, October, 1966.