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Joint Oil/Gas and Trona Development Industry Group

Policy Committee

Report on Concurrent Development of Mineral Resources in the Known Sodium Leasing Area of the Greater Green River Basin

INTRODUCTION

The Joint Oil/Gas and Trona Development Industry Group was created in May 1995. The industry participants are: FMC Corporation, the Gas Research Institute, General Chemical Soda Ash Partners, OCI Wyoming LP, Petroleum Association of Wyoming, Rock Springs Royalty Company, Solvay Soda Ash Joint Venture, Tg Soda Ash Inc., Union Pacific Resources Company, and Wyoming Mining Association.

The Group's mission was to develop technical information about the interactions of trona mining and oil/gas exploration and production. The information developed would be used as a basis for the resolution or prevention of conflicts that might occur related to the coincidental development of the trona and hydrocarbon resources in that portion of the Greater Green River Basin in southwest Wyoming described as the Known Sodium Leasing Area ("KSLA").

The Joint Oil/Gas and Trona Development Industry Group established a Policy Committee ("JIC") made up of industry and government participants to implement the purposes of the Group and direct technical investigations. The technical investigations were undertaken by a Technical Subcommittee which included members from the State of Wyoming ("State"), the United States Department of Interior ("BLM"), the Petroleum Association of Wyoming ("PAW"), the Wyoming Mining Association Trona Subcommittee ("WMA") and other stakeholders and qualified specialists as requested by the Technical Subcommittee. The JIC also established additional subcommittees to evaluate Safety, Economics, Well Completion and Abandonment, Gas Migration, and Shallow Gas Drilling.

The intention of the JIC was at all times to have a balance of members from the government and private sectors and from the trona and oil/gas industries. The information gained has been used to formulate fair and equitable co-existence strategies, while protecting both resources. All decisions related to the investigations conducted under the direction of the JIC as well as the recommendations and report(s) that follow were agreed to by consensus of the JIC.

EXHIBIT
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POLICY COMMITTEE SUMMARY

The task of the JIC was to identify technical problems that might be associated with concurrent development, evaluate the potential for problems, and recommend mitigating actions. Primary concerns were: the safety of the underground miners and the economic implications associated with contemporaneous development. The safety concerns were the effects of mining induced stresses upon a well bore in or near the underground workings and the potential for gas and/or fluid migration from a well and the impacts it might have on an operating mine in terms of loss of life. The economic concerns centered on the possible sterilization of the trona resources, loss of capital investment in the mines and soda ash plants, loss of jobs, loss of tax revenue, loss of royalty revenue, and loss of economic viability of the trona industry.

The committee identified three areas that should be evaluated relative to concurrent development of the hydrocarbon and trona resources: (1) the Mechanical Mineable Trona Area ("MMTA") that lies within the KSLA, (2) the KSLA outside of the MMTA, and (3) hydrocarbon production areas within and outside the KSLA that are in close proximity to existing underground trona mining.

Technical investigations were conducted in several areas of concern utilizing the members of the Technical Subcommittee and third party consulting firms. The JIC members shared the $790,000 cost of third party consulting arrangements. The final report of the Technical Subcommittee concluded that casing deformation in the well bore was substantial and is a function of the proximity of the well to the underground mining and subsequent post mining subsidence. Gas and/or fluid migration from a well bore was identified through an independent study as a potentially catastrophic occurrence.

In parallel with the technical investigations, the JIC considered business, regulatory, and legal solutions to mitigate potential conflicts associated with concurrent development. Union Pacific Resources (UPR), the largest private landowner in the KSLA, has offered to lease the oil/gas rights within the MMTA to the individual trona operators that hold sodium leases from UPR. The UPR proposal provides a business solution, which puts oil and gas development on private trona leases under control of the trona lessee. Regulations adopted by BLM and the Wyoming Oil & Gas Conservation Commission relative to drilling, completion and abandonment would provide an extra measure of safety to the underground miners. Pursuing a legal resolution was considered the least attractive approach, as all participants wished to avoid a protracted and expensive litigation exercise.

MINING INDUCED STRESS ON A WELL

The JIC technical investigations evaluated the potential hazards of concurrent development of the trona and hydrocarbon resources. Two primary hazards were found: (1) the loss of control of a well due to mining-generated subsidence slippage within the overburden, and (2) the migration of high-pressure gas, oil, or water into the mines with catastrophic consequences.

The initial thoughts on co-existence centered on a "drilling island" concept that would cluster wells in a specific "island" area similar to the patterns used in the offshore drilling platforms. A test program was formulated to investigate the size of the island necessary to provide a protective barrier around a well so that its integrity would not be compromised by mining activities.

The interdisciplinary study involved drilling two cased wells ahead of an FMC longwall-mining unit. These wells were then approached, each in turn, and mined through using a machine which cuts away a 500 ft. wide by 10 ft. high section of the main trona seam, known locally as Bed 17. Longwall mining yields the highest extraction of trona and this approach generated the most severe regional deformation pattern of any trona mining method currently employed using workers underground.

Nine slip planes strongly influenced the potential for casing damage in the two test wells drilled near the longwall workings of FMC. The location and spacing between these slip planes influenced the amount of horizontal slip. The most severe horizontal displacements occurred on slip planes of depths of about 300 ft., 600 ft., 690 ft., and 900 ft. All of the nine significant slip planes were found at depths of less than 1100 ft.; however, additional slip planes developed below 1100 ft. when the mine workings and test wells were in close proximity.

A finite element model (FEM) was developed for the KSLA utilizing local geology, local physical properties, and mine geometry parameters. The model relates the magnitude and direction of horizontal slip on nine bedding planes to the distance from a longwall mining system operated by FMC. A similar model was also developed to define the basic relationships for bedding-plane slippage anticipated in the vicinity of partial-extraction mining techniques in more common use for trona mining. The FEM models were used to predict the stress-strain field surrounding the mine workings and the rock-cement-casing deformations.

The models show that very little lateral displacement would occur at distances beyond 1250 ft. from the edge of longwall trona mining at a depth of 1600 ft. In consideration of geologic discontinuities and the vagaries of numerical modeling, the consensus of the JIC was that an island with a radius of one mine-depth would provide sufficient protection from casing deformation to allow a well to be drilled. The models and field measurements show that if a barrier size of less than this distance is selected well integrity is compromised.

Additional analytical studies were conducted to define the relationships between bedding plane slip and allowable casing deformation. Due to crushing of rock and cement, not all horizontal movement is converted to pipe body strain. This work concluded that, ignoring threaded connections, an 8 5/8-inch casing would deform about 2 inches when the longwall was within about 1000 feet horizontally. Additional deformation of the casing would not allow re-entry to the well for repair of work-over.

Methane samples from the five trona mines and several deep gas wells were chemically and isotopically analyzed to determine if the gases from these two sources were distinctly different. The analyses indicated that the shallow (mine level) methane samples were enriched in the lighter isotopes of hydrogen and carbon relative to the deeper (Cretaceous) methane samples. Mixtures of shallow and deeper gases were also analyzed. It was determined that such mixtures could be identified using isotopic analysis and a proportional mixing model.

FLUID/GAS MIGRATION

The JIC retained the services of Dr. Craig W. Van Kirk of the Colorado School of Mines to conduct a study to analyze the potential for fluid flows from oil and/or gas wells and the effects on trona mining in the KSLA. The study focused on two major tasks, (1) a literature survey to identify situations and examples of case histories demonstrating where oil and/or gas has migrated from wells and, (2) computer simulation models were developed to demonstrate if and how fluids could leak from wells within the KSLA of the Green River Basin.

The major conclusions of the study are, (1) case histories in other areas of the world do document the consequences of uncontrolled fluid migration and some examples demonstrate that the potential exists for leakage from wells within the KSLA and illustrate that the potential for such leakage is significant, (2) computer models simulated the lithology and geology of the Green River Basin in the KSLA and clearly demonstrated that dangerous uncontrolled fluid flows could occur in a variety of ways, resulting in a range of damaging effects on mining operations from a minimum of increased water influx into the mines, to a maximum of life threatening gas blowouts into a mine, (3) high pressure gas could fracture the rocks and flow out of control laterally a distance of two miles and break into a working trona mine in a matter of 1.5 to 3 days.

SAFETY

The trona mines employ over 1,000 miners with approximately 200 miners working underground at any point in time. The health and safety of these men and women is the primary concern of the Joint Industry Committee (JIC). A considerable amount of time, money, and effort has been expended by the JIC over the last few years investigating the feasibility of contemporaneous development of the oil/gas and trona resources in the Green River Basin. The investigations have shown that co-development of both resources is not without risk. History has demonstrated that, despite the best applications of technology and operating practice, mining and oil/gas extraction operations can, at times, exhibit unpredicted and unprecedented behavior. The interactions between the oil/gas and trona industries increase the likelihood of an unexpected event.

In brief, the issues relating to interactions between the oil/gas and trona industries can be broadly grouped into two general areas:

1. The effects upon an operating well due to mining induced stresses.
2. The effects upon an underground mine due to gas and/or fluid migration from a well(s).

Engineering studies performed by the JIC clearly show that a well located within the stress envelope of an active mine will suffer varying degrees of deformation dependent upon the distance from the mine workings, the type of mining employed, and the extraction ratio in the area. The deformation tends to become more severe as the distance the mining area to the well bore is decreased or the extraction ratio is increased. In the situation where the well is in close proximity, (i.e., within one mine-depth radius) to an area of high level extraction, several inches of horizontal and vertical displacement can be expected resulting in severe damage to the well.

Assuming significant damage to a well in close proximity to a mine(s), there are at least two conceivable scenarios that could severely impact the mining operation(s).

1. High-pressure gas inundations of mine workings resulting in an explosive, oxygen deficient, or possibly toxic atmosphere.
2. High-pressure gas invasion of the trona and/or strata surrounding the trona leading to rockbursts or unexpected cave ins.

In the case of gas and/or fluid migration, computer simulations and historical information supplied to the JIC by Dr. Van Kirk, a recognized authority in petroleum extraction, demonstrate that the potential does exist for such processes to occur within the KSLA, particularly if the wells are not completed properly.

There are several conceivable adverse effects of gas/fluid migration that could impact a mining operation including those listed above. The most likely of these would be the slow, chronic leakage from a well(s) toward mineable portions of the trona reserve. Should this phenomenon occur, it is likely that large undetected gas or fluid filled fractures would be created in the trona seam. Miners who inadvertently breach such an area undoubtedly would not survive the encounter.

An equally likely impact of gas/fluid migration would be the slow invasion of gas or fluids into the strata surrounding the trona seams. In this case, the gas/fluids would tend to saturate and weaken these strata leading to incompetent roof and floor in the mine workings. At the very least, an increase in the occurrence of roof failures and floor heave would be expected, both of which present serious hazards to miners. In the worst case, the weakened strata could propagate a violent, large-scale collapse of the mine workings.

Although the probability of such events is difficult to assess, the fact that a 1994 study of gas and water wells in a 20 square-mile area around Granger, Wyoming determined that 30% were leaking fluids or gas warrants serious consideration of these issues.

ECONOMICS

The trona and hydrocarbon resources in the area have a great value and are significant contributors to the economy of the local communities. An economic comparison between the trona and oil/gas industries clearly shows that the trona industry has a significantly greater impact on the economy of Southwest Wyoming within the study area. The government royalties, production taxes, and number of jobs associated with the trona production exceed that of the oil/gas industry by a ratio of fifty to one over a fifty-year time frame.

COINCIDENTAL DEVELOPMENT

The productive life of both resources presents problems. The production life of a conventional underground trona mine is at least 100 years. The production life of a hydrocarbon well is 20-50 years, based on existing gas fields in the area. The findings of the JIC suggest that:

> If the hydrocarbon reserves within the MMTA are produced prior to mining, development of the leased and permitted trona reserves would be delayed as long as a well or series of wells is producing, making the development of the sodium within the MMTA uneconomic at this time.
>
> If the trona reserves are produced first, the hydrocarbon reserves would be unrecoverable for an extended period, but conserved for future development.

If the resources were concurrently developed, a protective island of one mine-depth would be required to protect a well bore from damage due to mining. To adequately protect amine from the potential effects of fluid migration from a deep gas well, a separation of one to two miles is required.

RECOMMENDATIONS

The JIC has deliberated for four years on the complexities of coincidental development. The technical analysis, studies, safety, and economic comparisons show that the conventionally mineable trona within the MMTA should be completely developed before development of the deep gas resource. The JIC recommends the following approach as a compromise between the oil/gas and trona industries:

1. Extension of the existing moratorium on oil and gas development within the MMTA for an additional three months.

2. Expansion of the MMTA boundary to include a one-mile lateral safety buffer.

3. Adoption of special drilling, completion, and abandonment standards within the KSLA and the MMTA..

4. Shallow gas drilling would be allowed within the MMTA subject to special rules for drilling operations, well completion, production, and abandonment procedures.

5. In that area of the KSLA lying outside the MMTA, drilling of deep gas wells would be allowed utilizing special rules for drilling operations, well completion, production, and abandonment procedures as proposed to the Wyoming Oil & Gas Conservation Commission for the Special Sodium Drilling Area.

6. Modification of the BLM Land Use Plan to close the MMTA to oil and gas leasing and development for drilling of deep gas wells. Drilling would be prohibited until after completion of conventional underground trona mining and abandonment of the underground trona mines. The hydrocarbon resources in the MMTA will be conserved for future development.

7. The area of the KSLA outside the MMTA boundary may be developed concurrently, but it is the consensus of the JIC that drilling procedures and well completion practices require modification to ensure that uncontrolled releases of fluids (gas or liquid) does not occur. The JIC, in conjunction with the Wyoming Oil & Gas Conservation Commission,

has drafted rules for a Special Sodium Drilling Area that encompasses the KSLA. These rules were adopted by the Commission on April 13, 1999.

Due to the existence of Federal and State oil and gas leases that have been issued within the MMTA, the adoption of the above recommendations may be somewhat problematic. There are several options for addressing this problem:

1. Existing Federal and State lessees could be given a preferential right to trade leases within the MMTA for other Federal or State leases of equal or greater appraised value.
2. The current suspension of leases could be continued on a long term basis until the conventional underground mining of the trona is completed and miners are no longer working underground.
3. The existing Federal and State leases could be purchased from the lessees. Funding for a repurchase could take several forms:
   - A. Give the leaseholder a royalty credit against future oil and gas production on other leases held by the lessee.
   - B. Allocate a portion of future sodium royalties to purchase leases from the lessee.
   - C. Federal budget disbursement.
   - D. Private compensation from trona producers.

The JIC recommends Option 1— trading of leases — as the preferred alternative.

CONCLUSIONS

The issue of concurrent development of the trona and hydrocarbon resources is very complex and no single avenue exists to solve the myriad of potential problems. History has shown that both mining and oil/gas operations can behave unpredictably despite the best efforts in the application of technology and operating practices. The studies performed under the direction of the JIC have proven that coincidental development of trona and oil/gas within the MMTA, could have catastrophic consequences. This finding is based on the analysis of current drilling and completion standards used in the Green River Basin and the potential for uncontrolled fluid migration from oil/gas wells into the underground mine(s). The safety and well being of 1000 underground miners employed in the trona mines is of paramount importance.

SUMMARY

Trona mining and oil & gas industry groups in the Green River Basin region of Wyoming are concerned that their operations may geographically overlap in the future. The present report is the last of a 3-part analytical study program intending to explain and quantify those mining-related ground movements which can influence the design of oil and gas wells. It is one portion of an industry and government-sponsored research program which included (a) field measurements of ground surface subsidence over a trona mine at the FMC mine near Little America, Wyoming; (b) measurements of horizontal and vertical deformations in dedicated observation wells, and (c) laboratory tests on rock samples from coreholes. Phase 1 work completed in 1995 included analyses of the effects of parameter variability, rock-layer geology and mine geometry on overburden movements within the theoretical limitations of a 2-dimensional plane-strain model. Phase 2 and Phase 3 considered those aspects of subsidence that are controlled by the 3-dimensional character of trona mining operations.

For our analysis, we created plane strain and 3-D finite element models which analytically represent horizontally-lying, laterally-continuous layers of (predominantly) shale and sandstone rocks with a 10-ft thick trona bed at 1570 ft below the ground surface. The present 3-D model represents a volume of sediments that is 4100 ft long, 2300 ft wide, and 1700 ft thick. Because of symmetry assumptions in the model, this is a "real width" of 4600 ft. The trona layer is analytically "mined" by simulating a long-wall method which completely excavates a tabular ore body 500 to 1500 ft wide, 2850 ft long, and 10 ft thick. We also created a plane strain model which is representative of a large regional longwall mine with panel extraction widths greater than 1500 ft. Relatively weak, horizontally-oriented slide surfaces were placed between rock layers to model bedding planes in the rock. Material engineering properties such as weight, elastic modulus, Poisson's Ratio, shear strength, etc. were estimated from tests on rock core samples, by downhole logging measurements, and from published literature. In addition to the regional finite element models, we developed a 3-D model to study the relationships between rock movements and the resulting displacements of a casing which is cemented in a borehole.

Results of Phase 3 studies are in basic agreement with the results of the previous phases of the investigation wherein we had concluded that the major design problems for oil and gas wells which are located in native rock adjacent to active longwall trona mines are (a) bedding plane displacements that can occur great distances from the mine works, and (b) vertical compression of rock layers immediately above and below the trona bed. However, results of tests on rock core samples from one of the borings at the test site suggest that creep deformations are not a significant factor in regional subsidence phenomena.

Numerical calculations performed with the 3-D and plane strain models show good agreement with surveying measurements of ground surface movements. Also, numerical calculations agree very well with the measurements of mining-induced sliding on bedding planes that were obtained from the two observation wells installed at the site. In particular, they confirm measurements in well COEX2 suggesting that bedding plane movements can be initiated when the face of the longwall is between 1200 and 1700 ft away from the well.

Numerical calculations were performed to estimate the effects that a steel casing and borehole cement might have on localized rock deformations in the immediate vicinity of the observation wells. They indicate that bedding planes must slip about 1 inch before the center axis of the casing will be offset significantly. Once the initial bedding plane offset motion is achieved, the casing offset increments will equal the bedding plane slip increments.

The numerical models indicate that a small, single panel longwall mine can create bedding plane slip of 0.1 ft as far away as 600 ft from the face of the mine. For larger longwall panels, bedding plane slip of 0.1 ft or more may be felt more than 2000 ft from the mine boundaries.

1. INTRODUCTION

Green River Basin trona beds are mined at depths ranging from 850 ft to 1700 ft by underground excavation methods and may eventually be mined at greater depths by solutioning techniques. Oil and gas is also produced in the Green River Basin, and gas potential may exist beneath the trona beds in some areas. Since trona mining can sometimes cause subsidence of the overlying rock layers, the subsidence-related movements of overburden rocks must be analytically predictable if wells are to be designed to withstand these movements without significant damage.

The Joint Oil/Gas and Trona Development Industry Group (the "Group") was formed to develop methods for the extraction of both hydrocarbon and trona minerals in the Green River Basin. To this end, the Group created a program of field, laboratory and analytical studies that would be carried out in conjunction with trona mining at the FMC facility near Little America, Wyoming. Boreholes were cored and cased at two locations close to an active mine, and rock properties were tested in a laboratory using samples from the borehole. Starting in May, 1995, vertical and horizontal movements of the ground surface above the mine were surveyed and movements of rock strata were measured by downhole logging tools during underground mining operations.

The ground surveys were performed by William H. Smith and Associates, Green River, Wyoming. Results of the field measurements will be detailed in a report by the Technical Subcommittee of the Joint Oil/Gas Trona Development Industry Group (The Technical Subcommittee). Results of laboratory measurements of rock properties are in a report by TerraTek (1996). The Project Operator is the FMC Corporation, Green River, Wyoming, and the Project Manager is Mr. William G. Fischer, Trona Associates, Green River, Wyoming.

This is the third and final report in a three-phase numerical study. Phase 1 results were presented in a meeting in Green River on November 13, 1995, and Phase 2 results were presented in a meeting in Rock Springs on October 24, 1996. The Phase 1 and Phase 2 studies were primarily concerned with the analytical development of plane strain and 3-dimensional finite element models, including the investigation of those physical parameters which significantly influence subsidence-related rock movements. In Phase 3 we used rock engineering parameters measured in laboratory tests in the numerical model, and we calibrated the response of the model to measured surface and downhole rock movements. Specific attention was given to those types of rock deformations which are important for the design of oil and gas wells in regions of mining-induced subsidence.

The purpose of this investigation is to elucidate highly complex interactions between trona mining-induced subsidence and rock movements around well casings that are installed near the mine. Numerical results presented in the report are specific to the FMC test site, but they also provide a basis for more generalized conclusions concerning the risks of locating oil and gas wells in the vicinity of mining operations throughout the Green River Basin. However, final design details for a well near an operating mine should always be based on the specific geology and operational methods that are encountered at the site.

The results of this investigation do not apply to mining in geologic regions outside the Green River Basin KSLA. The results should not be used for predicting rock movements around wells in any geologic region other that the one described in this report.

During this investigation the Project Manager, Mr. William G. Fischer, provided invaluable aid based on his extensive experience with Green River Basin trona mining operations. We gratefully acknowledge and sincerely appreciate his assistance.

2. GEOLOGIC SETTING

The FMC mine is located in the Green River Basin region of southwestern Wyoming near Little America, Wyoming. The mineral "trona" (a crystalline source rock for soda ash) is mined here. At least 42 trona beds have been discovered in the Green River Basin Known Sodium Leasing Area (KSLA), 11 of which have thickness greater than 6 ft (Wiig, et al, 1995; Culbertson, 1966, and 1971). At the FMC test site, mining is conducted in an 11-ft thick trona layer known as Bed 17 encountered about 1580 ft below the ground surface. The ground surface elevation at the test site is about 6377 ft above sea level.

The southwestern Wyoming trona beds (Na_2CO_2 $NaHCO_3$ $2H_2O$) originated in the early to middle Eocene epoch (about 50 million years ago) in a freshwater lake by processes such as leaching of volcanic ash layers and seasonal influxes of carbonate-rich sediments. The lake went through many stages of filling and evaporation during a period of about 4 million years to create the trona beds. The trona-bearing layers are in the Wilkins Peak Member of the Green River Formation.

The Eocene Green River Formation is divided, in ascending order, into the Tipton Shale, the Wilkins Peak, and the Laney Shale Members (Wiig, 1995). The Wilkins Peak Member is up to 1350-ft thick in the southeast part of the basin, and thins to about 600 ft in the northern part of the KSLA. It consists of sharply differentiated layers of marlstone, oil shale, trona, sandstone, siltstone, mudstone, and volcanic tuffs. The Laney is overlain by fluviatile shales, siltstones and sandstones of the Eocene-age Bridger Formation to the ground surface.

In the geologic sense, a sudden change from one type of rock to another signifies there was a major change in the prevailing deposition and erosion environment in the Green River Basin. In most cases, the change occurred across a very narrow boundary between the layers amounting to fractions of an inch in thickness rather than as a gradual transition through many feet of rock. These sharply defined bedding planes can be planes of weakness which become surfaces of sliding between layers during trona mining.

Wilkins Peak sediments can be seen along the north side of the Green River valley near Green River, Wyoming as shown in the photographs on Plates 2-1 and 2-2. The reddish-brown colored sandstone atop the steep bluffs in the distance in Plate 2-1 is a sandstone in the lower part of the Laney Member of the Green River formation (known in former years as the Tower sandstone). It originated as alluvial fans which generally filled into the basin from the west covering the old lakebed. Wilkins Peak sediments on Plate 2-2 illustrate the layering in a region where the trona beds have been leached from the geologic section. These lacustrine sediments tend to be flat-lying, thin beds of uniform thickness. In the upper section of the Wilkins Peak, fluviatile sandstones of variable thickness sometimes intrude (Plate 2-2). Layers tend to thicken to the west, and fluviatile sands can become relatively thick within the Wilkins Peak Member.

At the FMC test site, the base of the Wilkins Peak (top of the Tipton Shales) is believed to be about 1780 ft below the ground surface and the top of the Wilkins Peak is at about 1270 ft. The top of Trona layer #17 was encountered at 1586.5 ft below ground level in test boring COEX1, and at 1577.5 ft below ground level in test boring COEX2. The sediments immediately above the trona are relatively weak, pliable shales and marlstones. They are overlain by much stronger, but often poorly cemented sandstones which occur from about 1070 to 1270 ft and again from 900 to 990 ft. The materials above the sandstones are even weaker shales and clay shales. The section from the ground surface to about 880 ft is believed to be part of the Bridger Formation.

The lacustrine deposits in the Wilkins Peak tend to be flat lying, and bedding planes generally dip about 1 degree or less throughout the Green River Basin KSLA. Regional tectonic shifting over geologic time has left a vague fracture network which dips at 70 to 80 degrees from horizontal throughout the Green River and Bridger formations. These fractures are "tight," low-permeability contact surfaces that tend to be short and discontinuous, normally 100 to 200 ft in length. Vertical permeability is in the order of 0.02 md; however, FMC has studied them for many years in the belief that mining induced stresses can cause them to open, which allows water to enter the mine from the sandstones of the underlying Tipton. Other mines in the KSLA might have similar problems with the overlying sandstone strata. The current model assumes these little-known fracture networks are insignificant to the overall problem.

Natural methane gas occurs in these sediments, possibly associated with highly organic oil shales in the Wilkins Peak. Methane gas was found escaping from both of the test boreholes after the casing was disrupted by mining-induced ground movements.

3. OIL AND GAS WELLS IN SUBSIDENCE ZONES

Gas wells are commonly constructed along the western edge of the KSLA by cementing a surface casing through the more prominent near-surface water-bearing zones, followed by a deeper casing which is commonly cemented from the production zone upwards for 1000 ft or more, leaving several thousand feet of uncemented casing to the surface. (No oil has been found in the KSLA, but nearby indicators are favorable based on today's technology.) The BLM has suggested and some operators have tried to cement to the surface, but high lifting pressures, tender formations, lack of cement quality in the trona horizons, and difficulty in pressure monitoring at the surface make this only a temporary measure. Smaller tubing is installed within the deep casing to carry the product to the surface.

Among other factors, the casing is designed to resist the natural tendency of the drilled borehole to squeeze inward due to failure-level stresses created by the weight of the overburden sediments, regional tectonic stresses, etc. Casing design to resist these "normal" rock-stress conditions is generally accomplished by standard methods of petroleum engineering practice. Casing stability problems can occur, however, when excessively large stresses are created in rock strata by mining-induced subsidence. Typical stress systems that have been encountered in subsidence areas include the following:

- Bending stresses can be induced in casing by differential sliding between opposing rock layers.
- Abnormally high horizontal compression stresses are created in rocks that are "arching" across the mine opening.
- Tensile stresses are created by those rock layers beneath the arch zone that move down into the mine cavity.
- Vertical compression stresses are created in comparatively weak rock layers which compact and shorten vertically. This generally occurs in those areas around the sides of the mine which carry increased loads due to the creation of the mine cavity.

Problems have been encountered with oil and gas wells that have been drilled in subsidence regions, where subsidence was caused by hydrocarbon production from deep-seated reservoirs, groundwater withdrawal, and sulfur mining by solutioning techniques.

Well casing problems at the Beldridge Oil Field (Bakersfield, California) have been described by Dale et al (1996), Hilbert et al (1996), de Rouffignac et al (1995), and Hansen et al (1993). Oil production in the field has lowered reservoir pressures, causing subsidence of a large region at present-day rates of about 0.5 ft/yr. At the edges of the affected region, near-vertical fissures have been created. Investigations have shown that the most serious problems occur near the edges of the field, where numerous wells have suffered damage as a result of differential sliding between layers of sediments. The top of the reservoir occurs near 1200 ft. and the most serious shear zones tend to be in a sequence of sand and clay-shale layers lying above the reservoir. Particularly troublesome shear zones are at about 700 ft and 900 ft. New wells are installed using larger diameter casing than used in earlier wells. The additional area in the casing allows greater differential movement before the well becomes inoperable.

Subsidence at the Ekofisk Field in the North Sea amounted to about 14 ft in February, 1989, and is presently occurring at a rate of 10- to 12-inches per year (Sulak and Danielsen, 1989). Ultimate subsidence may be as much as 60 ft. Oil well casing failure has proven to be a problem in several areas of Ekofisk (Yudovich et al, 1989; Schwall and Denney, 1994). Collapse of well casings occurs in the reservoir rock and in the sediments immediately above the reservoir (generally, within 400 to 900 ft of the top of the reservoir). Measurements in wells and mathematical modeling shows that failure-level tension loads are introduced in casing which passes through the overburden sediments, and failure-level compression loads occur where they penetrate the chalk reservoir rock. Localized deformations related to faulting does not seem to be a significant factor at Ekofisk. The most effective defense against damage to Ekofisk wells has been to avoid the high stress regions by directional drilling when possible.

Significant subsidence from reservoir depletion has also been observed in Long Beach California's Wilmington Field amounting to more than 30 ft in a 35-year period. Production from a reservoir averaging 3300 ft depth has produced an elliptically-shaped subsidence bowl about 5 miles by 2.5 miles in size. This subsidence has caused deep-seated horizontally oriented movements through thin shale layers lying between thick sand strata. These movements damage oil and gas wells, surface structures and underground pipelines. Some movements have been very sudden, creating small seismic events (Kovach, 1980). The earliest known seismicity-level bedding plane slip at Wilmington occurred in 1947. Another occurred in 1949 which damaged almost 200 wells. Measurements at Long Beach show horizontal ground movements of 11 ft, and surface strains of up to 1.4 percent in both extension and compression, depending upon the location within the subsidence bowl (Mayuga and Allen, 1969; Allen, 1971).

Offshore wells have also been damaged by subsidence in the Gulf of Mexico. Reservoir depressurization at a field about 50 miles offshore Louisiana has initiated new movements on several faults and has severed numerous oil and gas wells. Our study of the failures showed the fault was sliding at rates ranging from 0.5 to 1.5 in. per year and failures occurred when the casing collapsed inward far enough to contact the production tubing. Because of the limited space between the inside of the casing and the production tubing, some wells failed as quickly as 3 to 5 years after installation.

Failures also occur in wells that are drilled to produce liquid sulfur at the Freeport-McMoRan sulfur mine located about 20 miles east of the delta of the Mississippi River in the Gulf of Mexico. The wells are installed from production platforms in 210 ft water depth and they are drilled and cased to about 1400 ft below the seafloor. The damage appears to be caused by tensile stresses that are induced in the casing when the overburden sediments collapse into cavities that are created by the extraction of the sulfur. Sulfur wells are generally expected to have a life span of only a few years at most (this is very short compared to oil and gas wells) and the remedy is to drill a new well as soon as possible after a premature failure.

It is interesting to note that subsidence was a major design problem for the 350-ft long piles which support the 14 offshore platforms comprising the offshore sulfur mine facility. Finite element studies indicated that very high bending stresses would be created in the piles by differential sliding between several of the sand and clay layers in the overburden strata. In those high-stress areas, pile sections were constructed of 5-in. thick, 150,000 psi steel.

4. TRONA MINING AT THE FMC TEST SITE

Trona production from the #17 Bed was initiated at the FMC mine in 1949. A "room-and-pillar" pattern followed by pillar extraction on the retreat was used for many years. Small stubs of pillars were left behind when the roof collapsed, resulting in area extraction of 87 to 90% (0.87 to 0.90 of the plan area) of the trona. Mining operations were segmented into panels consisting of "blocks" of ore about 400 ft by 2000 ft, and 7 to 11 ft thick depending on the height of the seam. Adjacent blocks were mined in sequence so that the caved area of each block coalesced with the previously caved area (Morgan, et al, 1985). Later, FMC changed to a longwall mining technique which extracts trona in individual "panels", nominally 500 ft wide and up to 5000 ft long. A continuous double row of pillars is left between adjacent panels. Between-panel pillars are somewhat crushed and are punched into the floor and roof layers when the adjacent panel is mined. The regional area extraction for adjacent longwall panels is near 0.75.

Observations show that the mine roof behind the longwall breaks into rubble up to three or four seam heights in thickness. At that point, the main roof deflects, and comes to rest upon the rubble virtually intact. This roof plate remains as a laterally extensive unit although vertical separation occurs on bedding planes up to a distance of about 325 ft above the mine level. This distance corresponds to the distance upwards to the base of the strong sandstone layers near the top of the Wilkins Peak. These lime-cemented sandstones appear to resist the downward collapse and act as the keystone of an arch which is subsequently loaded by the shale layers extending to the surface. The differences in relative thickness and stiffness between the layers of sandstones and shales causes bedding plane slippage between some of the regionally extensive layers.

Both room-and-pillar and longwall methods are presently used to mine trona in the KSLA. Also, there is discussion of using solutioning techniques to mine deeper trona beds. While the analytical models that are discussed in this report are based on the stratigraphy, rock properties and field measurements at the FMC longwall test site, the technique can be applied to other Green River Basin trona mines. Stratigraphy, rock properties, etc. can be adjusted in the model to correspond to geologic conditions at these other mines, and the simulated "trona extraction" in the model can be adjusted to mimic the mining schedule. This could even include mining trona layers at several different elevations.

A plan-view drawing of the mine layout at the FMC test site is shown on Plate 4-1. A summary history of the longwall panels that are pertinent to the investigation is as follows;

- Panel 1 (500 x 4370 ft) is located east of the test wells. It was completed in October, 1994 about seven months before test wells COEX1 and COEX2 were drilled and cased in mid-May, 1995.
- Panel 2 (518 x 4970 ft) was started in November, 1994 and was carried north toward COEX1. The first successful multi-finger caliper log looking for horizontal sliding on bedding planes was run in COEX1 on August 14, 1995. At that time, the face of the longwall was about 607 ft south of COEX1. A reference multi-finger caliper log was run in COEX2 on August 25, 1995. At that time, the northwest corner of Panel 2 was about 600 ft from COEX2. Panel 2 was completed in November, 1995.
- Panel 3 (518 x 5800 ft) was started in December, 1995 and was completed in November, 1996.
- The average height of the mined layer was 10.36 ft in Panel 3.

Plate 4-2 shows the position of the longwall mining face as of April 14, 1997 when it had progressed about 2300 ft north in Panel 4. Subsidence at the north end of the longwall panels on April 14 is shown at a larger scale on Plate 4-3. Subsidence contours drawn on Plate 4-2 and 4-3 are based on measurements by FMC surveyors and are not related to the small precision survey grid shown on Plate 4-1. The contours indicate a maximum subsidence value of about 4.2 ft, centered over Panel 2. The maximum depth and width of subsidence will increase with additional mining, eventually creating a flat-bottom saucer-like shape. Based on past experience at the FMC mine, the maximum value of subsidence is expected to increase to about 8.5 ft when all of the adjacent panels are completed (estimate by the Project Manager, W.G. Fischer).

5. FIELD AND LABORATORY TESTING PROGRAMS

5.1 Program Outline

The field measurements program included both an investigation of movements of the ground surface above the mine and the deformation of subterranean rock layers. Locations of (a) the survey grid used to measure surface movements, and (b) the two observation wells COEX1 and COEX2 used to measure deformations of rock layers are shown on Plate 4-1. The movement of the ground surface near the north end of the longwall panels was measured by repeated surveys of the closely spaced grid benchmarks and this information was integrated into general regional surveys performed using wide spaced marks. Subsurface movements between rock layers were measured by downhole logging in the COEX1 and COEX2 observation wells. The field measurement programs started in May, 1995 and continued throughout the active mining of trona panels 2 and 3. Results of these measurements will be given in a report by the Technical Subcommittee.

Cores of significant rock layers encountered in observation well COEX2 were sampled by rotary core barrel and were logged by the Project Manager, W.G. Fischer. The samples were sent to TerraTek, Inc., in Salt Lake City where they were tested extensively for engineering and geologic characteristics. The results are presented in a report by TerraTek (1996). Results of the field and laboratory programs that were most significant for the numerical analysis program are summarized in the following paragraphs.

5.2 Ground Surface Subsidence; Vertical and Horizontal Measurements

Steel rods were driven into the ground to form benchmarks for the survey grid shown on Plate 4-1. Their vertical and horizontal positions were measured at periodic intervals during the mining of trona longwall panels 2 and 3. Typical results of vertical subsidence calculations are illustrated in the graph on Plate 5-1.

Line A data is taken from the line of benchmarks that is located over the centerline of Panel 2 as measured at the end of longwall Panel 2. The maximum recorded vertical subsidence shown on the Line A graph is about 1.4 ft at the survey Station 0+00 located about 1400 ft back from the end of the panel 2 longwall. After 1 month, the ground had settled an additional 0.1 ft due to secondary effects such as (perhaps) crack propagation on bedding planes due to stress redistribution and stress adjustments in the ground after mining was completed in the immediate region. Line B data was collected about a year later, at the completion of Panel 3. The survey line is located above the barrier pillars halfway between the two panels. Because of the larger excavation, the 1996 subsidence is more than twice as great as the 1995 subsidence. A survey of Line B four months later shows an additional 0.2 ft of settlement due to secondary effects.

Survey lines A and B were not long enough to capture the maximum subsidence. As shown on Plate 4-2 (taken from a regional ground survey data set), about 4.2 ft of subsidence has developed about 3000 ft back from the end of the longwall (or about 1600 ft from the rear abutment) in April, 1997. Subsidence will continue to increase as additional panels are mined in the regions that are adjacent to panels 2 and 3. Also, subterranean movements of rock layers will continue due to time-dependent phenomena such as stress adjustment and crack propagation. These movements are transmitted to the surface and add to the final ground subsidence. As noted earlier, the ultimate subsidence is expected to be about 8.5 ft based on past experience at the FMC mine.

Horizontal movements of surface benchmarks tend to be small, on the order of a few tenths of a foot, but they are highly sensitive indicators of underground mining operations. In general, these movements tend to be directed towards the active mining zone. This is illustrated by the example history of movements at Station 12+00 above Panel 2 shown on Plate 5-2 (see Plate 4-3 for the location of this station).

In the early stages of Panel 2 mining, the reference post at Sta. 12+00 moves south and east a distance of 0.13 ft from A to B on the graph as the longwall approaches from the south to within 379 ft. The eastward component of the motion is probably caused by the influence of the mined-out panel 1 region. Movements toward the face of the longwall continue from B to C (about 0.07 ft southwest) as it gets within 90 ft. The face of the longwall passes beneath Sta. 12+00 and is about 178 ft to the north when Sta. 12+00 is at D, thus causing motion in a northward direction. The panel 2 longwall was completed in November 1995, and Panel 3 started in December far to the south of Sta. 12+00. The complex movements that eventually take the benchmark to Point E on Plate 5-2, are largely a result of Panel 3 approaching from the south and then passing west of the survey station.

In general, the earliest reliable indications of horizontal movements of the ground surface occurred when the longwall panel was about 900 ft from the measurement post. However, the initial motion values are very small, and the measurements are complicated by natural phenomena such as temperature change and moisture change in the ground. These effects can cause significant variations that may mask the horizontal motions caused by underground mining.

5.3 Bedding Plane Deformations in COEX1 and COEX2.

Observation wells COEX 1 and COEX 2 were drilled in May, 1995 to depths of approximately 1660 ft. The hole diameter was about 12-1/4 in.; 32 lb. LTC R3 seamless steel casing was cemented into the wells with 65:35:6 Pozmix cement lead and Type G tail. At the time COEX1 was drilled, the panel 2 longwall was about 1820 ft south of the well site.

Multifinger caliper tools operated by Schlumberger Well Services and processed by Schlumberger-Geoquest were used to measure the casing diameter in the two wells at periodic intervals during longwall mining of panels 2 and 3. Two different multifinger-caliper tools were used in the logging program. One is a 36-arm device. The centralizers for this tool are 102-in. apart and the caliper is 84-in. below the upper centralizer. The sensitivity of this tool is such that it was possible to detect casing offset or diameter changes of less than 0.1 inches. The other multifinger caliper used in the program is an 80-arm tool operated by Prairie Wireline Service. In addition to multifinger caliper logs, the casing shape was measured using a Schlumberger Ultra-Sonic Imagery logging tool (or "Acoustic Caliper") and the casing in the vicinity of bent/damaged areas was inspected several times using a downhole camera supplied by Halliburton Energy Services.

Panel 1 was completed in October 1994. Panel 2 was started in November 1994. The first multifinger caliper log of COEX1 was performed on August 14, 1995, when the longwall face was about

608 ft from the well, and the last one was run on September 18, 1995, when the longwall was only about 138 ft away. In all, the Schlumberger multifinger caliper was used 4 times in COEX1 and the Prairie multifinger caliper was used once. The first multifinger caliper run in COEX2 was on 8/25/95 when the northwest corner of the panel 2 longwall was about 600 ft from the well. The Schlumberger multifinger caliper was used 9 times in COEX2, and the Prairie multifinger caliper was used once. While the results of the Prairie caliper are similar to those of the Schlumberger caliper, the geometry of the tools is very different and it is difficult to directly correlate their data. Because of this, comparisons between successive logs showing bedding plane deformations are based on the Schlumberger tool.

Caliper logs of COEX1 show small horizontal offsets at several depths in the well which tend to become larger with the approach of the longwall. In COEX2, significant-sized "kinks" in the casing were created when panel 2 approached within 500 ft east of the well late in 1995. Unfortunately, these deformations were not measured during the time period when panel 2 was passing east of COEX2. Multifinger caliper measurements of COEX2 during the mining of longwall panel 3 showed that new movements added to those that had previously occurred.

Table 5.1 lists the depths below ground surface where significant bedding plane-type horizontal offsets were detected in the observation wells. Some of the bedding planes were first detected as small deformations in the earliest caliper logs and they enlarged in the succeeding measurements. Others were not detected until late in the program when the longwall was very close to the observation well.

Displacements in COEX1 are shown on Plate 5-3 for seven of the bedding planes listed above. Note that displacements of 0.1-0.2 in. had occurred on four of the bedding planes before the first downhole log when the longwall was more than 600 ft from COEX1. The maximum displacement shown on this graph is 0.55 in. when the longwall was 137 ft away from the well.

The Panel 2 longwall was completed in November, 1995, and the Panel 3 longwall started in December, 1995, more than 6000 ft south of COEX2. Displacements vs. time and the distance from COEX2 to the longwall are shown on the lower half of Plate 5-4 for six of the bedding planes. At the beginning of panel 3 longwall mining, casing displacements of as much as 0.4 in. had already been created by adjacent Panel 2 mining. These casing deformations continued to accumulate on some of the bedding planes as a result of secondary subsidence when the longwall was many thousands of feet distant, and unlikely to have affected the region around COEX2. However, deformations increased significantly on some of the bedding planes when the longwall came within 1700 to 1200 ft from the well (between 204 and 240 days on Plate 5-4). It is apparent therefore, that longwall mining at the FMC mine can cause bedding plane movements more than 1200 ft and less than 1700 ft from the face of the longwall.

5.4 Vertical Deformations in COEX1 and COEX2

Gamma logs in COEX1 and 2 show the presence of clearly-distinguishable naturally-radioactive markers. By comparing the position of these layers in successive logs, Schlumberger can estimate the compaction of shale layers located between the marker layers. Analysis of the gamma log subsidence data is ongoing at this time and the results will be included in the report of the Technical Committee.

5.5 Engineering Properties of Rock Layers

5.5.1 Downhole Sonic Measurements

One phase of the program consisted of downhole measurements using logging tools such as gamma ray, litho-density, photoelectric effect, compensated neutron, resistivity, shear wave, compressional wave and acoustic impedance to determine rock properties. Sonic logging and waveform analysis provided a means for obtaining continuous measurements of compression and shear wave velocities. These data, in conjunction with the bulk density measurements, permitted calculation of engineering properties such as low-strain elastic moduli.

Log-derived profiles of Young's Modulus and Poisson's Ratio are shown on Plates 5-5 and 5-6, respectively. Results of logging runs on March 25, 1995, and June 12, 1995, are similar, although there appears to be somewhat less variability within the shales between the ground surface and ~880 ft in the June 12, 1995 log.

The locations of bedding plane sliding in COEX2 (plus one location in COEX1) are also shown on Plate 5-6. In general, the slide planes found in the uppermost shales occur at locations of low modulus and at the upper and lower surfaces of strong, high modulus sandstones. However, bedding plane displacements were not found at the locations of some of these low-to-high modulus transitions so the presence of a low modulus zone does not guarantee that a displacement plane will develop during trona mining.

5.5.2 Rock Descriptions and Laboratory Tests

Six core barrel intervals were sampled in COEX2 as follows;

(1)484-510 ft.	(3)1022-1028 ft	(5)1583-1608 ft
(2)870-894 ft	(4)1256-1283 ft	(6)1608-1631 ft

Depth measurements are referenced to the kelly bushing (KB). Recovery was 97.7 % of the total of the cored intervals. The samples were described by the Project Manager, W. G. Fischer, and were sent to TerraTek Inc. for testing of physical properties.

Core run #1 is summarized as hard siltstone containing high angle, short (1 ft or less) fractures from 484 ft to 504 ft where a 2-ft thick claystone is encountered. Weak, friable marlstone was found from 505.15 ft to the bottom of the run.

Core run #2 is summarized as thin (0.2- to 2-ft thick) layers of hard shales, limestones, dolomites, sandstones and marlstones from 870 ft to 888.7 ft where a layer of zeolite or very hard anhydrite was encountered. Hard, highly calcareous sandstone occurs below the zeolite/anhydrite from 889.1 to 894 ft.

Core run # 3 is summarized as poorly cemented to well cemented layers of sandstone with occasional thin (~0.2-0.3-ft thick) layers of organic oil shale, coal and dolomite.

Core run #4 is summarized as weak, friable clay-shale with thin layers of trona ~0.2 to 0.6-ft thick.

Core run #5 is summarized as layers of trona, soft claystone, oil shale and very weak, friable dolomitic marl. The base of trona bed #17 was identified at 1596.28 ft making a total thickness of 9.21 ft.

Core run #6 is summarized as weak and friable claystone, mudstone and soft dolomitic marlstone.

The analysis program performed by TerraTek consisted of triaxial compression tests, direct shear tests, creep tests, and tensile tests. In addition acoustic velocities (P and S waves) were measured on the triaxial test specimens. The results of the testing program are given in the report by TerraTek (1996).

Laboratory measurements of Young's Modulus and Poisson's Ratio are shown on Plates 5-7 and 5-8, respectively. Static test values of Young's Modulus shown on Plate 5-7 tend to be much smaller than dynamic test values. These differences are expected, because small strains are inherent with sonic velocity logging devices. Thus, the elastic modulus values are zero-stress tangent elastic moduli and form an upper bound. Mining-induced strains are likely to be larger than dynamic (logging) values and (because of non-linearity effects) the moduli will decrease at larger strains. According to work performed by Chenevert (1964), the ratio of dynamic to static elastic modulus can range from 1.21 to 1.35 for Green River Shale. The US Bureau of Reclamation (1953) proposes ratios that vary from 1.06 to 1.85 for clean limestone (for example). More uncertainty exists concerning Poisson's Ratio, as the static values may be higher or lower than the dynamic values (Lama and Vutukuri, 1978).

6. METHODS FOR NUMERICAL ANALYSIS OF MINING-INDUCED SUBSIDENCE

6.1 General Comments on Numerical Modeling

Finite element models have been used for many years to explain and predict deformations within large masses of layered earth and rock materials. In general, it has been found that the success of any particular study is directly related to the quality of information that is available for the model. If there is adequate knowledge of (a) the engineering properties of the various materials and (b) their geologic character and distribution beneath the ground surface, then good results can often be expected. The advent of relatively powerful computers for general use has been a significant factor in this success since it is now possible to create more accurate representations of stratigraphy. Also, there are better numerical representations of stress-strain-failure characteristics for a wider variety of soil and rock materials than had been available in the past (e.g., Desai et al, 1985).

Predicting the mining-induced deformations of sediments in the Green River Basin is a problem of rock layers with contrasting hardness, which are bounded top and bottom by weak bedding planes. The finite element method has been used to investigate problems such as these in the past. For example, Chang and Nair (1974) used a plane strain representation of layered rocks above salt solution mines in Ohio to demonstrate how bedding planes between strong layers can affect the pattern of surface subsidence. They looked at the effects of up to 11 frictional bedding planes within a 1000-ft thick section of marl and shales. Rock materials were modeled using Drucker-Prager plasticity criteria. The Project Manager for this present investigation, W.G. Fischer, once used an axially symmetric finite element model to study bedding plane deformations over trona mines (personal communication). The results indicated that small but significant horizontal displacements could occur between rock layers more than 1000 ft from the face of the mine and he showed that large relative displacements theoretically occurred on bedding planes more than 100 ft from the face.

Recent studies of horizontal slip in layered sediments using finite element methods include investigations of well damage due to reservoir subsidence in the Belridge oil and gas field near Bakersfield, California by Dale et al (1996) and by Hilbert et al (1996). The latter authors reported that they used Drucker-Prager criteria to model the yield of rocks. In a study of well damage in layered rocks over the Wilmington Field, Hamilton, et al (1992) modeled the interfaces between layers of sand and clay with friction angles ranging between 6° and 15° and found that a value of 10° gave the best agreement between predicted and observed subsidence.

The methods used in this present investigation generally follow the techniques used in the studies described above. Of course, the size and shape of our numerical models and the physical properties of the rock layers mimicked conditions at the FMC study site.

6.2 Rock Parameters Used in Numerical Models

Based on the logging data and laboratory tests, we created 13-step linearized profiles for the numerical models used in Phases 1, 2 and 3. The profiles comprise 10 different shale layers, 2 sandstone layers, and a 10-ft thick trona layer.

Layer thickness and engineering properties for the Phase 1 models are listed in Table 6.1. The layers used in Phases 2 and 3 are generally similar in thickness to those used in Phase 1; but as shown on Plates 5-6 and 5-7, both Young's Modulus and Poisson's Ratio are considerably lower than we had used in the earlier study. Engineering parameters for Phase 2 and Phase 3 are listed in Table 6.2 and Table 6.3, respectively.

Another important question for the model is the location of bedding planes and joints or fractures that are potential surfaces for sliding. Unfortunately, no well logging tool responds primarily to fractures (Schlumberger, 1989). When looking for fractured zones on logs, the search is usually focused on areas where they are suspected for different reasons, such as poor core recovery, fractured cores, bit behavior (i.e., deviations) during drilling, or the presence of chipped areas in the walls of the borehole (detected by caliper logs). In Phase 1, we selected bedding planes for the model on the basis of changes in stratigraphy that indicated a geologic unconformity and using dipmeter logs based on interpretations by the Project Manager, W.G. Fischer. Last, and most important to the finite element modeling, were early indications of horizontal deformations found in bore hole COEX 1 described in Section 5.3. Locations of bedding planes used in the Phase 1 model are given in Table 6.1. We used Mohr-Coulomb values of $\phi = 15°$ for the basic case studies and 30° in a parameter study.

In Phases 2 and 3 we selected bedding plane locations based on indications in COEX1 and COEX2 as downhole deformations developed at different times in the study program. Locations of the bedding planes are listed in Tables 6.2 and 6.3.

6.3 Modeling Concepts and Goals

6.3.1 Introduction

The discussion in Section 3 shows that wells can be damaged if they are located in regions of ground subsidence. When the ground moves, loads develop against the casing which can be large enough to crush it. If the well becomes non-productive then the investment is lost. If the production tubing ruptures, then high pressure gas may vent to the surface or may escape through natural fissures to enter a nearby mine.

The following discussion examines the physical relationships between the extraction of trona in the Green River Basin, the resulting regional movements of overburden rock layers, and their effects on well casings. The subject is complex. In part, this is because we are dealing with naturally variable materials, i.e., layered rocks, which are buried beneath hundreds of feet of opaque overburden. It is also complex because there are varieties of ways to conduct trona mining and varieties of ways to design oil & gas wells. All of these factors may affect the magnitude of rock movements around the well and the amount of damage they create. It is apparent, therefore, that each well-siting situation is unique to some degree, and requires consideration of the specific site geology, mining operation and design of the well.

6.3.2 Rock Movement Mechanisms

When the ore is removed, roof layers lose their base support and may fracture and fall to the floor of the mine. In other cases, rock layers may simply bend downward and act as a "beam" carrying the weight of the overlying sediments. At the FMC study site, shale layers found between the roof and the base of sandstones more than 300 ft above the roof tended to fracture and fall. The sandstone layers deflect downward in the form of relatively intact beams or plates. Shale layers above the sandstones follow them down.

An important effect of this bending action is shown on Plate 6-1. In this simplified illustration, rock layers are shown bending into the cavity created by the removal of a tabular ore body. Movements of rock layers close to the roof tend to be confined to the region immediately over the mine. However, the zone of influence widens upwards from the mine and can affect a considerably larger area at the ground surface. The location of the boundary for the zone of influence depends on site geology. In the Green River Basin, for example, an effective angle of 45° from vertical is sometimes be used to estimate the ground surface region that will be affected by mining. However, when the sediments are dissimilar rock layers, stress changes caused by mining are preferentially concentrated in some layers. In this case, there is no simple depth relationship between sediments that are affected by subsidence and those that are not affected.

The lower detail drawing on Plate 6-1 illustrates differential movements that can develop on bedding planes. Studies of these types of movements have shown they have their maximum value in the region of the bending inflection point, where the curvature of the rock layer "beam" changes from concave to convex. Differential movements between the layers are shown to decrease with lateral distance away from the inflection point. Bedding plane sliding was found to be an important control on siting wells in the Green River Basin and it has received most of the analytical attention in this investigation.

Removal of an ore body can also create increased vertical stresses in the rocks surrounding the excavation. If the rock layers are compressible this increase may cause the rock section to shorten and thereby damage a well string. At the FMC study site, the shale layers immediately above and below the trona bed were known to be relatively compressible materials and compaction was the subject of one phase of the investigation.

One phenomenon that was not studied concerns the potential effects of delayed subsidence on wells installed through the fractured rock overlying a collapsed mine. It is known, for example, that vertical subsidence at the FMC mine continues at a slow rate for many years after completing a longwall panel. These "secondary" movements could create both vertical and horizontal loads on a well. This phenomenon requires additional study if wells are to be installed in regions above collapsed mines.

Also, we did not consider the effects that might be caused by the collapse of support pillars or abutments in the mine. A large body of information has been developed concerning the design of support pillars within the Green River Basin trona mining industry and that knowledge should be considered during oil and gas well siting investigations.

6.4 Description of Finite-Element Code and Material Models

6.4.1 ABAQUS

Abaqus is a general purpose finite-element code developed by Hibbitt, Karlsson & Sorenson, Inc. in Pawtucket, Rhode Island. The program allows analytical modeling of static, quasi-static and dynamic loading conditions. A wide selection of element types is available and its capability for nonlinear stress-strain analyses makes it a useful tool for geotechnical engineering. Our numerical models were developed using ABAQUS/Standard Version 5.4 and they were run on a HP Vectra 6/200 Personal Computer with a Pentium Pro processor and 128 megabytes of RAM. Computer processing time ranged from a few minutes for small problems to 5 to 6 hours for the largest problems.

We used several different types of numerical models to examine both regional-scale movements of rocks and rock-conductor interaction. These models included the following:

- Plane Strain models were used to represent cases where a large body of trona is removed over a laterally extensive region. It simulates cases where the width of the mined area is very large, such as when four or more adjacent longwall panels are removed. We often used plane strain models to investigate parameters effects on rock movements since they tend to run faster on the computer than 3-D models.
- 3-dimensional numerical models were used to study the effects of the size of the mined ore body on rock movements. We studied 1-panel and 3-panel extraction scenarios using 3-D models. We also used 3-D models to investigate some of the relationships between rock movements and the resulting deformations of well casings.

Linear elements with full Gaussian integration, (i.e. four-node elements) were used in our plane-strain analyses. Three dimensional representations of trona mining were generally constructed of 8-node linear "brick" elements. Rock/conductor interactions were modeled using 8-node, doubly curved, reduced integration "thick shell" elements to represent the steel casing. The rock and cement elements were 8-node linear bricks.

6.4.2 Constitutive Behavior of Rock Layers

In order to facilitate the numerical algorithm, Abaqus uses a three-dimensional failure envelope known as a "Drucker-Prager" model to represent rock materials. Under certain conditions, Drucker-Prager parameters can be adjusted so as to reproduce the Mohr-Coulomb envelope in two-dimensional space. Assuming that the material behaves in a linearly-elastic, perfectly-plastic manner (in particular, that no dilation occurs in the post-peak regime), the Drucker-Prager angle of friction, β, is related to the Mohr-Coulomb angle of friction, ϕ, by setting:

$$\tan \beta = \sqrt{3} \sin\phi$$

We used this relationship to estimate the Drucker-Prager values used in our Abaqus models.

Phase 1 values for Young's Modulus, Poisson's Ratio and shear strength were derived from an earlier data set of tests reported by FMC (1995). Phase 2 and Phase 3 parameters were developed primarily from downhole logs and from laboratory tests on rock cores from COEX2 (TerraTek, 1996). Parameter profiles are illustrated on Plate 5-7 and 5-8, and are tabulated in Tables 6.1, 6.1 and 6.3.

6.4.3 Creep

ABAQUS offers several ways to model time dependent deformations such as creep. We used a simple power law representation as follows:

$$\delta\varepsilon / \delta t_{creep} = A\, \sigma_{dev}^{\,n}$$

where: $\delta\varepsilon / \delta t_{creep}$ is the creep strain rate,

σ_{dev} is the deviatoric stress, and

A and n are empirical parameters obtained from creep tests.

For Phase 1 studies, we assumed highly conservative values for "n" from Hedley (1967) in the absence of creep parameters for the site. A value for the parameter "A" was chosen by trial and error to obtain a realistic subsidence rate within past experiences at the FMC mine. In Phase 2, values of "n" were derived from creep tests reported by TerraTek (1996). The TerraTek values were much smaller than those assumed in Phase 1.

6.4.4 Bedding Planes

Most of the apparent bedding planes appear as abrupt changes at geologic discontinuities with dissimilar materials on either side of a sharply defined boundary. Little is known from past investigations of Green River sediments concerning the constitutive behavior of bedding planes, nor was it possible to develop new data during the present investigation. Based on our observations of exposed bedding planes at locations such as in Plate 2-2, we could reasonably assume that while they are relatively flat-lying, they also generally exhibit minor irregularities which might create varying degrees of locking between adjacent layers. Some bedding planes appeared to exhibit cementation between layers while others had little apparent cementation. The limited number of observations of apparent bedding planes seen in core samples from COEX2 tend to support these observations since they also showed minor irregularities such as ripples and varying degrees of cementation.

While methods are available for numerical modeling of irregular rock surfaces (Goodman et al, 1968; Barton, 1973; Kulatilake et al, 1995), they require detailed knowledge of the geometry of the slide planes and their mineralogy, factors which are poorly known at this time. We decided, therefore to use a simplified frictional material model which could bound the site conditions. The surfaces are assumed to be flat and horizontal, and bedding planes were modeled using finite element interface elements between each rock layer. The shear resistance, τ_r, is assumed to be proportional to the normal stress acting on the surface, σ_n, and ϕ is the angle of friction of the surface;

$$\tau_r = \sigma_n \tan \phi$$

We assume there is no cementation on the surface.

In some cases, sliding between Green River shales and sandstones might occur along surfaces which contain small to moderate percentages of clay minerals. On other cases, the opposing surfaces are composed of granular particles in siltstones. Surfaces containing clay minerals could have frictional ϕ values as low as 10°. Granular-based surfaces such as those between siltstones might range up to 35-40° (Lama and Vutukuri, 1978). We chose values of ϕ ranging between 15° and 30° for this investigation. In most of the analyses we used 15° for bedding plane friction. We feel this is a reasonably conservative estimate within the context of other regional parameters used in the study.

6.4.5 In Situ Stresses

Failure in the rock matrix and along bedding planes also depends on the initial state of stress. Abaqus allows the user to choose an arbitrary initial state of stress as long as it is in equilibrium with the boundary conditions and the body forces. The only body force in our problem is gravity. Further, it is assumed that tectonic forces are negligible. Therefore, the vertical stresses are obtained from integration of the rock unit weight versus depth. Finally, the uniaxial strain hypothesis was used to compute horizontal stresses. The rock is assumed to be horizontally isotropic and elastic, and horizontal continuity requires that no lateral displacement can take place. Then, ν being Poisson's Ratio, the relationship between horizontal and vertical stress becomes:

$$\sigma_{horizontal} = \sigma_{vertical} [\nu / (1-\nu)]$$

6.5 Modeling Strategies

Several configurations of 2-dimensional and 3-dimensional finite element models were used during the investigation. A plane strain mesh used in Phase 3 is shown on Plate 6-2. This model represents a rock profile 1700-ft deep and 5000-ft long for some Phase 3 studies and 10,000-ft long for other Phase 3 studies. It is divided into 170 rows and 100 columns. Nine bedding planes are shown in dark green. The trona layer is located between 1570 ft and 1580 ft. The side boundaries of the model are assumed to be frictionless surfaces constrained from moving in the horizontal direction and the bottom of the model is a frictionless surface constrained from moving vertically. The top surface is unconstrained. There are assumed to be 13 distinct rock layers.

The plane strain mesh used in Phase 1 represents a region 1700-ft deep and 6000-ft long. The Phase 1 mesh was composed of 20 rows and 40 columns, which is a coarser grid than used in Phase 3. The Phase 1 plane strain mesh contained 13 rock layers and 7 bedding planes.

Plate 6-3 illustrates the layout for the 3-D models. For both Phase 2 and Phase 3, the region is modeled as 1700-ft deep, 4100-ft long and 2300-ft wide. Since the near face of the model is a plane of symmetry, this represents a "real width" of 4600 ft. For a single panel longwall mining operation, the trona layer that is "mined" in the model is 2850-ft long and 250-ft wide, representing a longwall panel width of 500 ft because of symmetry considerations. Positions for five hypothetical "wells" that are discussed in the report are also shown. The side and bottom boundaries of the model are assumed to be frictionless, and are constrained from moving normal to the boundary. The top surface is unconstrained.

The nine bedding planes shown on Plate 6-3 pertain to the Phase 3 investigation. Seven bedding planes were used in the Phase 2 investigation.

Plate 6-4 is a plan view of the Plate 6-3 isometric drawing. Both 1-Panel and 3-Panel excavation configurations are shown. In Phase 2, a single panel was removed to create movements in the overburden strata. In Phase 3, trona was modeled both in 1-panel and 3-panel configurations to investigate the effect of the panel-width parameter.

The trona layer was removed in increments starting from the origin of the model, and calculations were performed to define movements in the model at the end of each increment. For example, Plate 6-5 illustrates an 8-stage excavation sequence which started with the removal of a 633-ft long section of the panel and then moved forward in increments of 317 ft until the full panel length of 2850 ft was accomplished. Incremental mining was also used in some of the plane strain studies.

We used three different techniques to model trona removal in a longwall panel operation. These "Scenarios", shown on Plate 6-6, are described as follows:

- **Normal Cavity Scenario** allows the roof to sag down elastically when the trona is removed. In general, the sag line takes a smooth curved shape from the abutments into the cave zone. In 1-panel excavation studies, the roof sag might stop short of the floor or barely reach the floor because of the relatively short side spans.
- **Pull-Down Scenario** is modeled by forcing (numerically) the roof line to come into direct contact with the floor. This creates artificially large stresses in the immediate vicinity of the abutments. However, studies showed these stress concentrations had small effect on bedding plane sliding or vertical subsidence within the range of

accuracy required for this investigation when compared to Normal Cavity Scenario results.

- **Enlarged Cavity Scenario** models the effects of fracture and roof fall of shales located between the mine and the base of the sandstones about 300 ft above the top of the trona bed. Observations of roof collapse in longwall trona mines by FMC and measurements in wells COEX1 and COEX2 show that the shales gradually fracture, separate from the base of the sandstone layers, and come to rest on the floor of the mine. We modeled this in ABAQUS by removing a 300-ft high section of elements above the trona and allowing the overlying sandstone to sag elastically. The vertical movement was held numerically to a maximum value of 10 ft (the model thickness of the trona bed) for those instances where it would have exceeded that value.

The shape of the section of elements that is removed in an enlarged cavity study is illustrated on Plate 6-7. In some instances, some of the top and side elements were constructed of trapezoidal shapes to better fit our interpretation of the shape of the roof cave zone.

A 3-D expanded cavity scenario model is shown on Plate 6-8. Note that elements are smallest above the mine and in front of the end of the panel. Larger elements are used for the sides of the model. The position of the longwall panel and the cavity are seen on the lower face. Only one panel is removed in this model. Plate 6-9 shows a 3-panel excavation model which uses the "pull-down" technique. The finite element meshes on Plates 6-8 and 6-9 were used in Phase 3 and have 9 bedding planes. The 3-D finite element models used in Phase 2 look similar to these but have 7 bedding planes.

Well casing deformations were studied using the model shown on Plate 6-10 and 6-11. The model is composed of two rock layers separated by a frictional bedding plane. The model is assumed to have a total thickness of 15 ft and a diameter of 30 ft. A 12-in. dia. hole is assumed in the center of the model with a 2-in. thick layer of cement and a steel casing. This section of rock is assumed to be similar in properties to Layer V shales found between 640 and 880 ft (Table 6.3). The rock material is "elasto-plastic," modeled by an elastic modulus and Drucker-Prager yield criteria. The cement is represented by an ABAQUS cement material model and the steel casing is represented by ABAQUS "thick-shell" elements.

In our analysis, a geostatic stress is first applied equivalent to the depth of the layer times the unit weight of overburden rock. Then, the nodes around the periphery of the mesh are all moved an equal amount in the direction +1 for the upper disk of rock and in the direction -1 for the lower disk of rock. This node movement represents the regional displacements of the rock mass. The analysis then calculates the effects of these movements on the rock around the borehole, and for the cement and steel casing.

7. SUMMARY OF PHASE 1 STUDIES

7.1 Introduction

A relatively simple plane strain model was created in Phase 1 and was used to investigate the effects of major parameters on mining-related ground movements. The Phase 1 model simulates a rock profile 6000 ft long and 1700 ft thick with 7 bedding planes. Trona mining is conducted in two stages (Plate 7-1). In Sequence 1 mining, the ore is mined left to right up to the face of a "pillar" or "abutment" that is 2850 ft from the start of the panel (Plate 7-1). Sequence 2 mining is then started at the far right side of the model and the trona layer is mined to the left for 2850 ft up to the back side of the pillar/abutment. The unmined section is 300 feet wide.

The basic model was composed of 13 rock layers with geologic and engineering characteristics that were estimated from regional borings performed years earlier by FMC and from published geologic studies of Green River Basin sediments. Variations on this basic case included the following:

- Changes in shear strength of rock layers
- Changes in Young's Modulus
- Changes in bedding plane friction
- Changes in the number of bedding planes
- Introduction of creep in weak shale layers

Detail of these studies are in the Phase 1 report. Some of the more important results are summarized in the following sections.

7.2 Movements on Bedding Planes

The color contours on Plate 7-2 show the horizontal displacements of rock layers at the end of the first stage of trona mining. The maximum horizontal displacements occur along the bedding plane 1 contact surface (390 ft below the ground surface in Phase 1). According to this example, the maximum horizontal displacements occur about 500 ft back from the face of the longwall. The bottom rock layer moves a maximum of almost 2 ft to the left (negative direction) and the top rock layer moves a maximum of almost 1 ft to the right (positive direction) for a maximum relative displacement of about 3 ft. Horizontal movements within the 300 ft wide zone of the future pillar are considerably smaller than 3 ft, but are significant.

Plate 7-3 shows how horizontal motion changes on this bedding plane at a position located over the center of the pillar. In this example, Sequence 1 and Sequence 2 mining have been separated into 18 extraction increments of 158.33 ft each. Thus, increment #18 removes the last section of trona up to the face of the pillar moving from left to right. Increment 19, however, is taken from the trona bed at the far right of the model. The curves show that small movements towards the longwall can be expected at the end of increment 8 when the longwall is more than 1500 ft away. However, serious large-scale differential slip does not start until increment 14 when the longwall is about 630 ft away from the center of the pillar.

Maximum relative slip at the center of the pillar is about 1.6 ft at the end of Sequence 1. The approach of the Sequence 2 longwall initially causes increased relative slip to 1.8 ft, but relative slip decreases to about 1 ft when the longwall gets close to the back of the pillar. Relative slip does not return to zero at the end of mining even though the excavation is balanced either side of the center of the pillar. It is apparent, therefore, that there is a strong potential for hysteresis effects in bedding plane movements.

7.2.1 Effect of Number of Bedding Planes and Their Spacing

The uppermost layer in the model was initially assumed to be 390-ft thick in the basic case studies, and the effects of layer thickness on horizontal slip were investigated by adding new bedding planes. Plate 7-4 shows the effect of adding 2 bedding planes as calculated for the end of Sequence 1 mining. One is at 190 ft (200 ft above bedding plane 1) and the other is at 640 ft (250 ft below bedding plane 1).

The addition of these bedding planes to the numerical model causes the maximum relative slip on bedding plane 1 to decrease from 2.2 ft to 1.3 ft. Also, the horizontal distance of significant slip is reduced by having more bedding planes and thinner layers. A relative slip of 0.1 ft can be felt nearly 900 ft from the face of the longwall when there are 7 slip planes with a thick upper layer. The effective distance is reduced to about 600 ft by adding two more slip planes.

7.2.2 Effect of Bedding Plane Friction

The friction on bedding planes was increased from 15° to 30° to study the effect on relative slip. Plate 7-5 shows results calculated at the end of Sequence 1 mining for two example bedding planes. For bedding plane 1 at 390 ft, the maximum slip decreased about 35% from 2.2 ft to 1.4 ft. The effect was even greater for bedding plane 5 at 1265 ft, showing a 65 % decrease in maximum horizontal slip from 1.4 ft to 0.5 ft. There are also significant decreases in the effective distance from the active mine face that relative slip can be felt.

7.3 Vertical Strain in Pillars and Abutments

Vertical strain profiles calculated for the center of the pillar at the end of Sequence 2 mining are shown on Plate 7-6. Maximum values occur in weak shale layers lying between the bottom of sandstone layers (assumed to be at 1265 ft in Phase 1) and the top of the trona bed. Strains in the weak shales increased by a factor of about two when we decreased their shear strength and Young's Modulus by a factor of two. Strains are 1.5 % for both the upper portions of the Stratum 9 shale (1265-1475 ft). This shale layer is 210-ft thick as represented in the mesh, and would experience an average decrease in thickness of 37.8 inches. Most of the increase in vertical strain was related to an increase in plastic strain in the shales caused by the lower strength.

7.4 Creep Parameter Study

Observations at the FMC mine have generally shown that full subsidence does not happen immediately with excavation, but requires many months to fully develop. Several physical mechanisms can contribute to this "secondary subsidence" effect. They include time-dependent creep strains in highly stressed shale layers lying above and below the trona. In Phase 1, we had no satisfactory test data to estimate the creep potential of Green River Basin rocks and assumed highly conservative parameter values that had been given by Hedley (1967) for the creep of salt. We further assumed that any creep effects would be confined to shale layers from 1475 ft to 1700 ft, and used the exponential creep law discussed in Section 6.4.3.

Plate 7-7 illustrates the large increase in vertical strain caused by creep of shales within the 300-ft wide pillar left at the end of the Sequence 2 excavation of trona. The calculations were performed for a time period of 180 days after completing Sequence 2 mining. Creep in the shale layers above and below the trona exhibit strains of 2 to 3.7 %. These values are about 6 times larger than those before the onset of creep. These shale layers plus the trona bed have a combined thickness of 230 ft in our model, and would compress a total of 75 inches by 540 days.

Subsequent studies of creep based on tests of rock samples from COEX2 showed that creep potential for the shales is much less than assumed in our model. Phase 2 studies showed that creep may to be a minor factor in the time-dependent development of subsidence effects at the FMC test site.

7.5 Significant Conclusions of Phase 1 Studies

Based on the relatively simple plane strain model used in Panel 1, we reached the following conclusions;

1. Rock layers may slide over each other on weak bedding planes causing potentially damaging differential displacements at 900 ft or more in front of the advancing mine face.

2. The largest differential displacements and the greatest influence distance from the active mining face occurs for those bedding planes closest to the ground surface. The magnitude of effect is controlled primarily by the number of bedding planes between the ground surface and the trona, and by the distance between these sliding surfaces.
3. Vertical compression strains may be an important design consideration for wells drilled in pillars or in barriers between longwall panels. The most damaging strains will probably be associated with shale layers that exhibit high creep potential. An example calculation using conservative estimates of creep parameters showed potential strains as high as 3.7 % (subsequent studies based on rock sample tests showed creep parameters at the FMC site are much lower than assumed in Phase 1 and creep movements are probably small).
4. The patterns of subsidence-related movements calculated by the Abaqus analytical model appear to be realistic based on the limited field measurements for Green River trona mining conditions. The interactions between mining and ground movements is complex, however, and cannot be fully represented by the relatively simple assumptions inherent in a plane strain model.

8. SUMMARY OF PHASE 2 STUDIES

8.1 Introduction

A disadvantage of the 2-dimensional plane strain method described in Section 7, is that it generally overestimates deformations for problems that are inherently 3-dimensional in character. It is difficult, therefore, to verify the accuracy of a 2-D model by field measurements when the trona mining is limited in aerial extent compared to the depth of excavation. In Phase 2, we created a 3-D model based on preliminary information concerning rock layers and the locations of bedding planes. This model was used to study the general characteristics of 3-D response of a layered rock system to trona mining.

8.2 Outline of Phase 2 Studies

For our analysis, we created a finite element model which analytically represents a 1700-ft thick section of horizontally-lying, laterally-continuous layers of shale and sandstone rock with a 10-ft thick trona bed at 1570 ft below the ground surface. The model is 4100-ft long in the N-S direction and is 2300-ft wide from east to west. Because of symmetry assumptions in the model, this is a "real width" of 4600 ft. The trona is assumed to be removed by a long-wall mining process moving from south to north over a length of 2850 ft. The mined layer is 250-ft wide in the model, which represents a 500-ft wide extraction face due to symmetry along the N-S axis of the mine. Seven potential bedding-plane slide surfaces were placed between rock layers with inter-layer shear strengths modeled by stress-controlled friction. The locations of the bedding planes were chosen from preliminary indications of possible geologic unconformities noted in core samples of COEX2 and downhole logging.

The 3-D model was used to evaluate the most efficient approach to the numerical analysis of rock deformations. Studies were performed to evaluate the importance of plasticity criteria such as shear strength to the performance of the model. Also, a variety of methods for numerically "mining" the trona layer were tried. Phase 2 was intended to build an interim 3-D model which would then be adjusted as needed once the field and laboratory testing programs were completed.

8.3 Results of Phase 2 Studies

Our initial studies with the 3-D model showed that rock layers could be efficiently represented as purely elastic materials. There was no need to consider nonlinear stress-strain characteristics, shear strength, or yield surfaces of rock layers. While the analysis indicated that plastic strains did occur in the rock overburden on removal of the trona layer, the plasticity effects are all confined to the region close to the mine and have little effect on regional stresses or rock movements. In addition, results of creep testing of rock specimens taken in COEX2 showed that creep parameters are generally smaller than we had assumed in our Phase 1 investigation. Our Phase 2 calculations show that creep effects, as represented by the continued deformation of coherent rock masses at constant stress, do not contribute significantly to regional movements. As a result, it was not necessary to consider nonlinear stress-strain characteristics or creep effects in the Phase 2 material model.

The isometric view of the 3-D model on Plate 8-1 shows the horizontal strains which occur in direction "1" along the mine axis when a single longwall panel is removed. Horizontal movements are concentrated on the seven bedding planes. Maximum horizontal movements are in excess of 1 ft on the bottom surface of bedding plane 5. The top surface of bedding plane 5 has moved about 0.1 ft in the direction opposite to that of the lower surface. On Plate 8-2 we have removed some of the layers between bedding planes to better view horizontal displacements in direction "2", perpendicular to the mine axis. Horizontal movements in excess of 1 ft are also seen on the top surface of bedding plane 5 in this direction.

Vertical displacements are shown on Plate 8-3. Movements at the ground surface are only about 2 ft due to arching of the rock layers over the mine cavity. The rock layer at the top of the cave zone appears to have moved down about 5 ft.

The model demonstrated significant boundary effects in the region beyond the face of the longwall panel. These effects can be removed from the model, using the techniques shown on Plate 8-4. This figure shows the vertical subsidence that is calculated at the end of each of eight increments (stages) of trona extraction (see also Plate 6-5). In stage 1, for example, the longwall face is 3467 ft from the far end of the model. While the beginning of the Stage 1 profile is distorted by the short distance from the "south" wall of the model (only 633 ft), the far boundary has no effect on the result. With each succeeding extraction increment (Stages, 2, 3, 4, etc.), the south wall has less and less effect on the beginning of the subsidence profile. When we normalize all of the profiles to the face of the longwall, the resulting curve shows the shape as it would be without boundary interference.

This same technique is used on Plate 8-5 to show the shape of the horizontal sliding on bedding plane 1 (-390 ft) without boundary effects. The normalized curves show a model section that is more than 6000 ft in length even though the finite element mesh is only 4100 ft long. By means of this curve, it can be seen that relative slip of 0.1 ft occurs more than 1000 ft in front of the face of the longwall. Detectable slip (0.01 ft can be detected by multifinger calipers) occurs 1500 ft away from the longwall face.

The extraction process is modeled in Phase 2 by three different techniques (see illustrations on Plate 6-6). In the "basic" model, the trona is incrementally removed at the long wall face and the roof of the mine settles as an intact unit, bending downward from the sidewalls and from the headwall. The rock is assumed to have no fractures or vertical joints. This creates unrealistically-long roof spans into the mined space compared to the observed total collapse of the roof onto the floor of the FMC mine. The roof collapse is somewhat-better represented by the "pull-down" method. In this second technique, the roof is analytically forced into contact with the floor close to the sidewalls and at a short distance behind the long wall. Ground surface subsidence predictions using the pull-down method show significantly better agreement with surveying measurements than those of the basic model. Both the basic and pull-down methods indicate that mining-induced stresses are likely to cause fracture and collapse of the rock immediately above the mined area, which agrees with field observations suggesting that overburden layers may fracture throughout more than 300 ft of rock above the mine. Our third technique, the "cavity model," attempts to represent roof collapse by removing various-sized "elements" immediately above the trona, resulting in downward deflection of the overburden rock layers (Plate 6-7).

The effects of these different "mining" techniques on bedding plane slip are demonstrated on Plates 8-6 and 8-7. We note from these graphs that results of the cavity method and the pull-down method are essentially the same for slip on bedding plane 1. Both show considerably larger slip than derived from the elastic model.

The graphs also illustrate the effects of several variables besides the trona extraction method. For example, when we changed Poisson's Ratio from upper bound to lower bound values (Table 6.2) the slip on bedding plane 1 only changed by about 1 to 2%, and when we changed bedding plane friction from 15° to 30°, bedding plane movements only changed by 5 to 7%.

Based on the results of the Phase 2 studies, we conclude the following;

1. A 3-dimensional model better represents the movements that occur in the field. Predictions of about 2 ft of vertical subsidence are reasonably close to initial measured values for a 1-panel wide longwall mine.
2. The cavity extraction and the pull-down trona extraction methods provide similar predictions of vertical subsidence and horizontal slip on bedding planes. The basic "elastic" extraction models show lesser values of subsidence and bedding plane slip. Results of cavity and pull-down extraction analyses appear to correlate better with the initial field measurements.
3. Parameter variables such as Poisson's Ratio and friction resistance on bedding planes are not as important as the choice of the type of model (3-D vs. plane strain) nor the technique used to numerically "mine" the trona.
4. Nonlinear stress-strain properties of rocks and creep potential of shales are relatively inconsequential factors for the FMC test site conditions.

9. PHASE 3 STUDIES

9.1 Introduction

The Phase 3 investigation was initiated following the completion of panel 3 trona mining in November, 1996. In Phase 3, (a) the regional finite element mesh was adjusted to better fit the location of bedding planes that had been detected in COEX1 and COEX2, and (b) the effects of panel width were analyzed using a 3-panel wide 3-D model and a plane strain model. Also, a new finite element model was created to examine the influence of a steel casing on rock deformations.

9.2 Regional Movements of Rock Layers

9.2.1 Description of Phase 3 Regional 3-D Model for 1-Panel Excavation Model

While the basic configuration of the Phase 2 model was retained in Phase 3, several minor adjustments were made to the thickness of the thirteen rock layers. Also, the locations of slip planes were changed and two new slip planes were added bringing the total number to nine. The locations of Phase 3 bedding planes are shown on Plate 6-3.

Studies of subsidence for 1-panel width excavations were performed using the finite element model shown on Plate 6-8. This is an expanded cavity extraction scenario where up to 300 ft of rock is numerically removed to better replicate the roof fall that occurs during longwall mining. The base of the overlying sandstone layer is restrained in the mesh from moving downward more than 10 ft. The 3-panel width model is shown on Plate 6-9. The arrangement of the mesh is the same as for the 1-panel model, but a 750-ft wide section of trona is removed instead of 250 ft. We used the "pull-down" technique to ensure the roof layer is in contact with the floor of the trona mine.

The rock layers are assumed to be elastic with the physical properties given in Table 6.3. We used the upper bound Poisson's Ratio profile (Table 6.3) for the analysis reported in this section of the report. Bedding planes are assumed to be frictional planar surfaces with $\phi = 15°$.

9.2.2 Horizontal Sliding on Bedding Planes, 1-Panel Excavation Model

Regional horizontal movements following 1-panel longwall mining are shown on Plate 9-1. The colored contours indicate that discernible slip may occur on bedding planes 3, 5, and 8 for considerable distances from the face of the longwall. The patterns of bedding plane slip are detailed on Plates 9-5 through 9-13.

As an example, consider the contour lines for bedding plane 3 shown on Plate 9-7. Relative slip between the upper and lower surfaces amounts to 0.03 ft nearly 100 ft in front of the longwall face. In the direction perpendicular to the mine axis, the 0.03 ft contour is found more than 1500 ft from the axis of the mine (or more than 1250 ft from the sidewall). The blue-colored arrows on Plate 9-5 are vectors which indicate the absolute value of relative slip and the line of its direction. Note that the direction of the vector changes by 90° in the vicinity of the face of the longwall. Considering the progressive advance of the longwall towards and past hypothetical well locations such as Well 4 and Well 5 on Plate 6.4, it is obvious that the bedding plane movements experienced at a well location are not unidirectional during mining.

Similar patterns of horizontal slip are seen on the other bedding planes with some variations in magnitude of movement vs. distance that are believed to be related to the thickness of the layers and their relative stiffness. The exception is the anomalous pattern of contours for bedding plane 9 shown on Plate 9-13.

According to the contours on Plate 9-13, significant relative slip occurs several thousand feet from the boundaries of the mine. Similar results were found in studies of the 3-panel width model and the plane strain model. We found this is caused by the close proximity of the bottom boundary to bedding plane 9 and is an artifact of the modeling. As a result, the bedding plane 9 numerical results should largely be disregarded. The indicated magnitude of relative slip on bedding plane 9 close to the face and sides of the mine (up to 3 ft) is believed to be only slightly exaggerated, but magnitudes of indicated slip located more than 1000 ft from the mine are probably erroneous. However, we believe that bottom boundary interference does not significantly effect relative slip on bedding planes 1 through 8.

The sawtooth-shape profiles of horizontal slip vs. depth shown on Plate 9-14 illustrate the patterns of relative slip that are expected at five hypothetical well locations sited close to the longwall face and sidewall of the mine. The relative slip is nearly 0.3 ft in Well 1 for bedding plane 3, and is almost 0.5 ft in Well 5, bedding plane 3. As previously discussed, the large movements indicated for bedding plane 9 may be somewhat exaggerated. However, the movements of bedding planes 1-8 are believed to be unaffected by the close proximity of the bottom boundary of the model.

9.2.3 Vertical Subsidence and Strain for 1-Panel Excavation Model

Vertical subsidence in the 1-panel model is indicated in the isometric view on Plate 9-2. The contours suggest that the maximum vertical movement is about 5 ft for rock layers that are immediately above the cave zone. Vertical deformations decrease upwards, and are only about 2 ft at the ground surface. Vertical displacement profiles at the five hypothetical well locations are shown on Plate 9-15. Clearly, most of the vertical subsidence experienced at the well locations occurs in the weak shale layers below bedding plane 9.

The patterns of vertical strain for rock layers lying between bedding plane 7 and bedding plane 9 are illustrated in the isometric view on Plate 9-3, and vertical strain in the trona layer is on Plate 9-4. The vertical strain profiles on Plate 9-16 show that strains are concentrated in the weak shales lying between 1270 ft and 1440 ft (Layer IX in Table 6.3) amounting to $3x10^{-3}$ in Well 1 close to the face of the longwall, and $7x10^{-3}$ in Well 5.

9.2.4 Results of 3-Panel Excavation Model and Plane Strain Model

Analyses of 3-D deformations were performed using the 3-panel finite element model shown on Plate 6-9. The purpose of the study was to investigate the relationships between the size of the mined region and the resulting deformations in the overburden rock layers. For larger mining operation, say when more than three adjacent longwall panels are developed, a plane strain model is believed to be most appropriate. The plane strain model shown on Plate 6-3 was used for Phase 3 studies of large-region subsidence.

Horizontal displacement contours for the Phase 3 plane strain model are shown on Plate 9-17. As described earlier, bottom boundary interference affected horizontal movements in rock layers below bedding plane 9 and the contours in that region should be largely disregarded. Results for bedding planes 1-8 on Plate 9-17 are consistent with those found with the 1-panel model, but the magnitude of relative slip is greater and the effects tend to spread further laterally. Vertical subsidence on Plate 9-18 shows a full 10 ft for the plane strain model.

Vertical subsidence and horizontal slip values calculated with the 3-D numerical model were often equal to the values obtained with the plane strain model. The comparison profile on Plate 9-19 shows excellent agreement for vertical subsidence profiles in the direction of the mine axis. Plane strain and 3-panel model relative slip values for bedding planes 1, 2, 3 and 6 are compared on Plates 9-20 and 9-21. The 3-panel and plane strain models give similar results out to about 1000 ft from the face of the longwall. The 1-panel values for the same bedding planes, also shown here, are much smaller in magnitude, demonstrating the influence of the size of the mine on the scale of rock deformations outside the immediate mine area.

Horizontal slip on bedding plane 3 for the plane strain model on Plate 9-21 shows a zero motion position or "null point" about 900 ft from the face of the longwall. This is a location where the relative motion between the upper and lower layer boundaries reverses. As indicated on the profile drawing, relative slip in excess of 0.1 ft extends out to about 2000 ft from the face of the longwall on bedding plane 3.

9.2.5 Room and Pillar Mine Simulation

We used the Phase 3 plane strain model to simulate 50% area extraction for a "room and pillar mine". With reference to the illustration of the model on Plate 6-2, we simulated this effect by reducing Young's Modulus of the trona layer 50% over a distance of 2500 ft starting at the beginning. Results showed minor downward deflections of the top of the trona layer (generally less than 0.1 ft). The numerical calculations also indicated there is no significant relative slip on bedding planes for a 50% extraction case.

An alternative 50% extraction model could be created by removing every other element of trona over a length of 2500 ft. While this technique would create localized stresses in the roof layer, it would give near-identical results for higher rock layers.

9.3 Numerical Analysis of Well Casing Deformations

The movements in the rock immediately adjacent to a well casing were studied using the 3-D sliding plates model illustrated on Plates 6-10 and 6-11. The rock is assumed to be equivalent to Layer V with the properties given in Table 6.3 and the steel casing is that used in wells COEX1 and COEX2. The cement filling the void between the wall of the borehole and the casing is assumed to be equivalent to 3000 psi material.

When the upper and lower slabs of rock move sideways, stresses develop in the rock around the borehole due to the localized restraint created by the cement and steel casing. The horizontal and vertical stresses that develop in the rock and cement due to a relative bedding plane slip of about 0.75 in. are shown on Plates 9-22 and 9-23. The patterns of horizontal and vertical stresses seen on these plates are consistent with the development of bending stresses in the region of cement and casing close to the bedding plane.

A relationship between the regional relative movement of the bedding plane and the movement of the casing centerline is shown on Plate 9-24. The curve indicates that the initial bedding plane movements are taken up in localized crushing and compression within the rock and cement surrounding the casing. However, once bedding plane slip exceeds about 0.12 ft (1.4 in.) the increment of casing offset equals the increment of bedding plane slip.

One observation of this initial-motion offset relationship is that movements in COEX1 and COEX2 cannot be detected by multifinger calipers until the bedding planes have slipped by about 0.1 ft. Also, we note that the magnitude of the initial motion offset value depends on the physical characteristics of the opposing rock layers and the cement at the FMC test site; so, there is a potential for variations more or less than 0.1 ft.

9.4 Comparisons Between Field Measurements and Numerical Predictions

Plate 9-25 shows the vertical subsidence measurements of the ground surface derived from the April 18, 1997 survey (Plate 4-2). Predictions of vertical movements for 1-panel and 3-panel models are also shown. The field measurements appear to follow the general pattern of numerical subsidence but the values lie between the 1-panel and 3-panel relationships. At the time of the field survey, the underground workings probably more closely resembled the 3-panel configuration because panel 3 had been completed.

The differences between the measured and predicted values are believed to be due to two primary factors:

1. The model should have been designed to have a maximum surface subsidence of about 8.5 ft in order to account for the actual extraction ratios that occur in the FMC mining operation, and
2. Secondary effects will add to the vertical subsidence during the next 6 years.

When these factors are qualitatively accounted for, the ultimate subsidence is considerably more like predicted values. Similarly, the measurements of vertical subsidence along the line perpendicular to the mine axis shown on Plate 9-26 are in basic agreement with the numerical models.

Horizontal movements of the ground surface are compared to model predictions on Plate 9-27. Again, there is a basic agreement between the measured values and the predicted relationships.

10. CONCLUSIONS AND RECOMMENDATIONS

The finite element models that were developed in Phase 3 of this investigation provide reasonably accurate representations of the relationships between longwall trona mining and movements within the surrounding rock. The numerical models account for the major factors which, at the FMC test site, can influence the magnitude of bedding plane sliding and the distance it can extend away from the mine. The numerical predictions are verified by field measurements of ground surface motion and downhole bedding plane sliding.

It appears likely that small bedding plane movements can occur two and possibly three thousand feet away from the active mine operation. Large movements (more than 0.5 ft) are likely within 700 ft from an active longwall mine. These movements are capable of damaging oil and gas wells that are located near active longwall trona mines. A suggested relationship between bedding plane movements and the distance from a longwall operation is shown on Plate 9-28.

The design relationship on Plate 9-28 is estimated from 3-panel and plane strain model analyses which assumed 100% trona extraction. In general, this is a conservative assumption because trona extraction ratios historically only range 75% to 90% for longwall and pillar-extraction mines (report section 4). While we did not study the relationship between bedding plane sliding and trona extraction ratios in this investigation, we believe that ratios of 75%, such as expected regionally for the FMC test site, would create slightly smaller movements than predicted by Plate 9-28. We also note that bedding plane movements were detected in COEX2 when the longwall was 1200 to 1700 ft away from the well (section 5.3). If we assume that regional bedding plane movements must be 0.092 ft before they can be detected by the most sensitive multifinger caliper, as shown on Plate 9-24, then the design relationship curve on Plate 9-28 agrees very well with the measured values. The curve is somewhat conservative compared to the field data, but not excessively so.

The numerical models can be adjusted and modified to represent the full range of geologic stratigraphy and rock engineering properties expected within the Green River Basin KSLA. Also, we believe it is flexible enough to mimic room and pillar mining and solution mining operations. A test analysis showed that bedding plane deformations are likely to be too small to be noticeable for some room and pillar operations that do not cause the collapse of the mine roof.

Each trona mining operation has a unique geologic environment and there are significant differences in the trona extraction techniques used by the various mines in the Green River Basin KSLA. The present study indicates that good agreement can be achieved between numerical predictions and field performance if these factors are accounted for. The design of an oil and gas well should consider the potential effects of differences in rock stratigraphy, rock engineering properties and mining operations.

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