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Design and Stability of Salt Caverns for Compressed Air Energy Storage (CAES)

Shosei Serata[1] and Bhupen Mehta[2]

[1]*Serata Geomechanics, Inc., Richmond, CA, USA*
[2]*Electric Power Research Institute, Palo Alto, CA, USA*

ABSTRACT

An economical method of compressed air energy storage (CAES) has been developed for commercial application using underground salt caverns. The first CAES plant was constructed by Nortwestdeutsche Kraftwerke AG (NWK) (now merged with Preussen Elektra) in Huntorf, Germany in the mid-1970s. The success of this plant led to the development and construction of the first commercial CAES plant in the U.S. by the Alabama Electric Cooperative, Inc. and the Electric Power Research Institute.

Based on the FEM computer simulation method developed for design of the German CAES cavern, the U.S. CAES caverns were designed for the McIntosh salt dome. This required increased sophistication due to the much smaller size of the salt dome and its crowding with existing solution mining operations. The stability of the McIntosh CAES caverns was analyzed using the computer program GEO by modeling the behavior of the entire salt dome, containing fourteen caverns, over 70 years, including 40 years of continuous CAES operation. To monitor the computer-predicted surface behavior, a microlevel surface subsidence measurement network was installed.

INTRODUCTION

Compressed air energy storage (CAES) is a new load management technology for storing energy in the form of compressed air. Relatively inexpensive off-peak energy is used to drive a motor to compress the air which is stored in solution-mined salt cavities, hard rock caverns, or porous media formations. When peaking or intermediate power is needed, the compressed air is withdrawn from the underground storage, heated, and expanded through turbine generators. The first 110 MW U.S CAES plant built by the Alabama Electric Cooperative, Inc. in McIntosh, Alabama uses a 0.538×10^6 m^3 (19 million ft^3) solution-mined salt cavern for storing compressed air to generate 100 MW power continuously for 26 hours, i.e., 2600 MWh of energy storage capacity. This plant began operating commercially on June 1, 1991. The brine produced from this first CAES plant cavern was used by Olin Chemicals Company, which had solution-mined nine cavities in the same salt dome prior to CAES plant cavern construction.

The consequences of excavating caverns within a salt dome are delayed due to the viscosity of the salt. The resulting deformations are likely to continue for a protracted period, causing reduction of storage volume as well as surface subsidence. Excessive ground movement is of concern as it can damage the well casings at the salt/caprock interface. A site-specific FEM computer model for McIntosh salt dome and the CAES cavern was developed to establish deformation patterns, stress profiles, subsidence rate, and cavern closure over an extended period. A microlevel measurement system for continuous monitoring of surface movement was installed to validate the model predictions. The geomechanical safety of the CAES operation has been evaluated with regard to the underlying assumptions required for design analysis.

BACKGROUND

Alabama Electric Cooperative (AEC) is a generation and transmission cooperative formed in 1941 to supply power to its rural cooperative members in central and south Alabama and the panhandle of Florida. The AEC-owned generation (685 MW) is almost totally coal-fired steam units with small hydro and combustion turbines. The load growth projections indicated a need for approximately 600

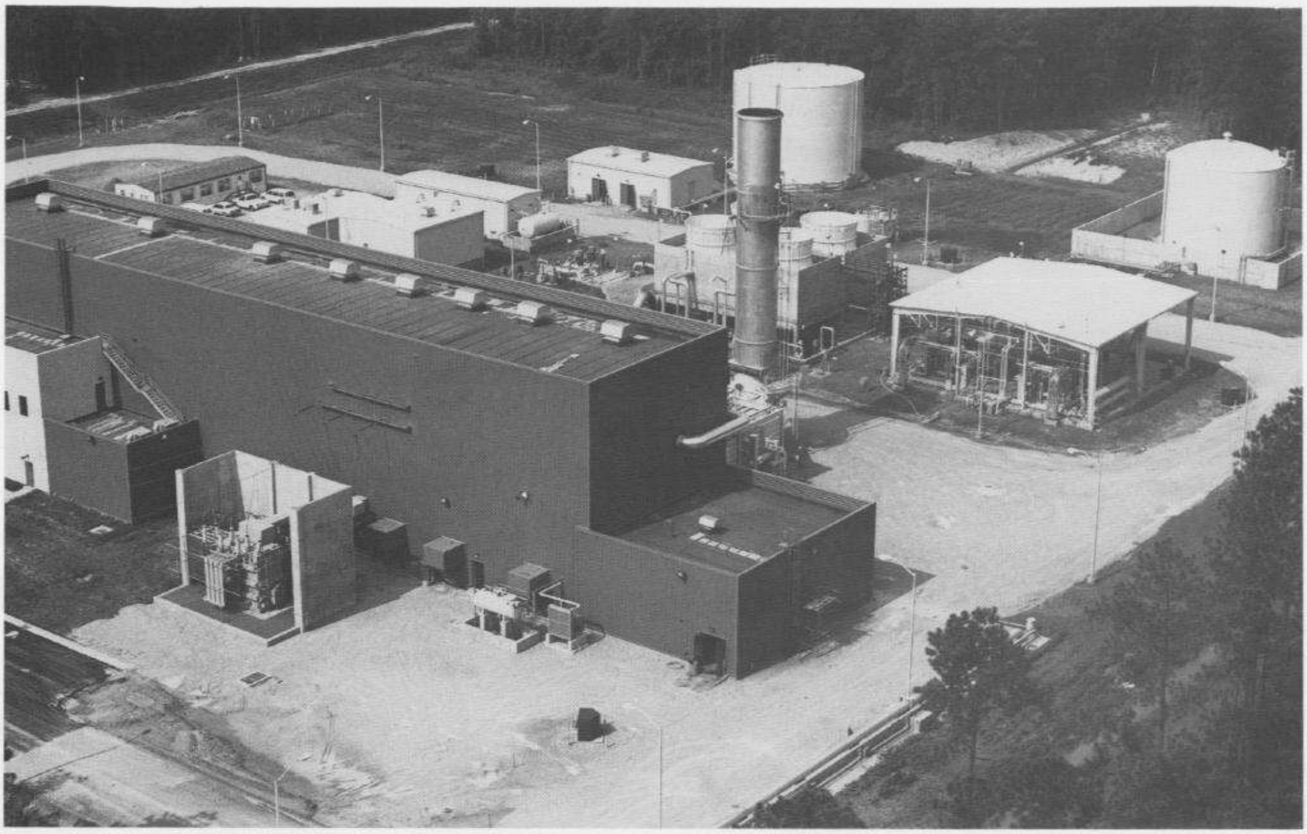

Fig. 1. First U.S. compressed air energy storage (CAES) plant, built by Alabama Electric Cooperative utilizing solution cavern in McIntosh salt dome, Alabama.

MW of new peaking and intermediate capacity by the year 2000. The extensive economic analysis of various options preferred CAES technology for the next generating unit.

The McIntosh site was selected because of its major advantages such as proximity to the base-load coal plant and transmission system, seismically stable salt dome location, and environmentally acceptable disposal of brine to the nearby Olin Chemical plant for chlor-alkali production. All major environmental permits and approvals to construct were obtained in less than six months. The overall project took about five and a half years from the start of planning to the start of operation, including three years of design and preparatory work and two years of construction. Figure 1 is a photograph of the completed plant.

The cavern location was selected on the basis of two test well drilling and coring analyses to determine the edge of the southwest flank of the dome, chemical and structural properties of the salt, and the characteristics of the caprock material. The presence of highly soluble carnallite salt in the first test well samples suggested that the cavern should be constructed near the center of the dome where such salt impurities were absent. A number of geophysical logs and laboratory analyses of core samples from the second test well confirmed the salt quality and structural strength. These geotechnical and exploratory tests reduced the risks associated with drilling the CAES well, its successful completion, and nitrogen testing.

The solution mining process was the most critical construction activity for this project and AEC had allowed for significant contingency funds for unforeseen problems. However, the CAES well construction and solution mining of the cavern progressed as scheduled with few interruptions due to Olin Chemical plant shutdowns. The innovative scheme of simultaneous dewatering and air pressurization of the cavern saved about four months of construction time.

Serata (1959) developed the basic design principles for storage of nuclear waste in underground salt caverns. A series of research programs aimed at establishing a rational basis for describing the complex behavior of rock salt and surrounding formations was begun in the 1960s by Serata and his colleagues (Sakurai, 1966; Adachi, 1970). A constitutive model incorporated the time-dependent and

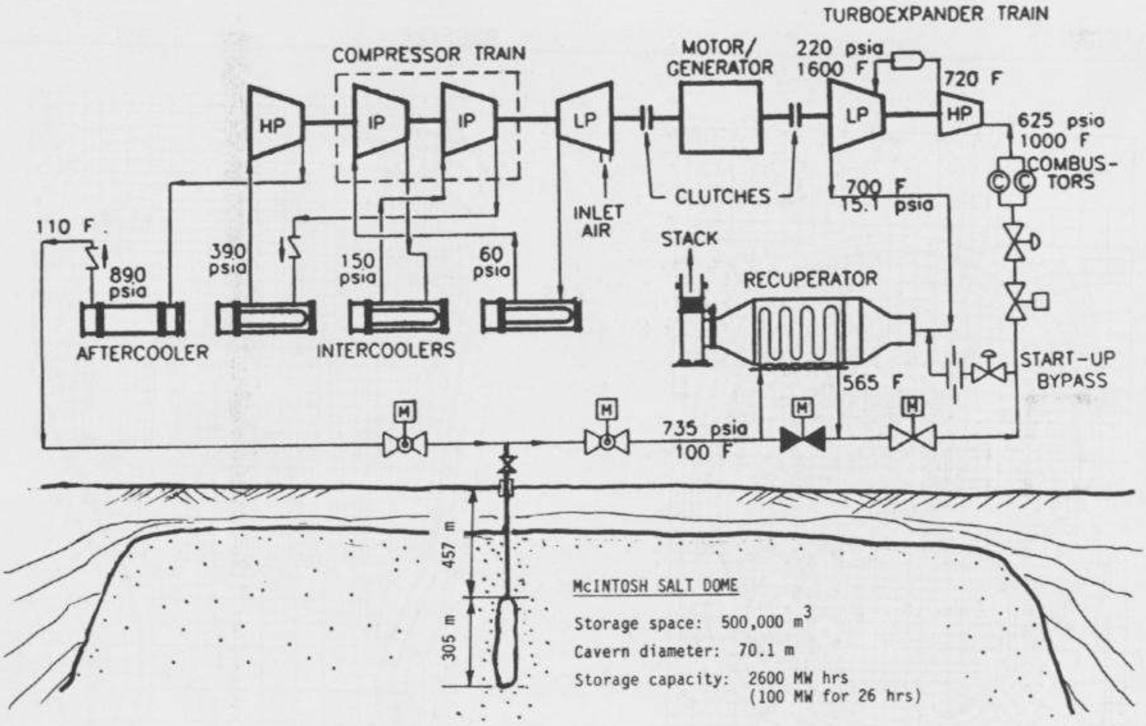

Fig. 2. Schematic diagram of CAES plant and cavern developed for Alabama Electric Cooperative.

property-deteriorating aspects of brittle–ductile salt behavior including viscoelasticity, viscoplasticity, dilatancy, brittle–ductile failure, and strength deterioration has now been successfully formulated.

Design principles for underground openings were proposed and verified through extensive laboratory and field testing in a dry salt mine (Dickie et al., 1993). The actual behaviors of the earth material are numerically incorporated in program GEO (Serata and Fuenkajorn, 1993), which is an outgrowth of the REM code originally developed to design the CAES caverns in Huntorf, Germany (1973–1975).

CAES PLANT DESCRIPTION

The CAES plant is designed to fulfil the AEC power system requirements on a weekly basis. The plant machinery shown schematically in Fig. 2 will generate power during on-peak hours of five weekdays and compress air during off-peak hours of weeknights and weekends. The plant specifications are given in Table 1.

Each kWh (net) of energy generated requires 0.8 kWh of off-peak electric energy for compression and 4100 Btu (high heating value) of fuel to raise the temperature of the cavern air. The recuperator is a first-of-a-kind heat exchanger, not installed in the Huntorf plant, to recover heat from the turbine exhaust by preheating cavern air. The recuperator reduces fuel consumption by 25% as compared to the Huntorf plant.

A solution mining data acquisition computer and a mathematical simulation were used to monitor development of the cavern. The secondary effects of compression and expansion within the cavern were analyzed (Nakhamkin et al., 1989; Swensen et al.,

TABLE 1

CAES plant specifications

Plant rating	110 MW maximum (net)
Compressors	48.9 MW
Cavern space	0.538×10^6 m^3 (19×10^6 ft^3) (26 h at 100 MW)
Cavern diameter	70 m (230 ft)
Cavern length	305 m (1000 ft)
Cavern pressure	7.93 MPa (1150 psig) max design 5.17 MPa (750 psig) min operating
Expanders	HP/LP
pressure-inlet (psig)	630/213
temperature-inlet (°F)	1000/1600
air flow at 110 MW (lb/s)	340.4
Dual fuel	natural gas/no. 2 fuel oil
Compression rate	1.7 h compression per h generation

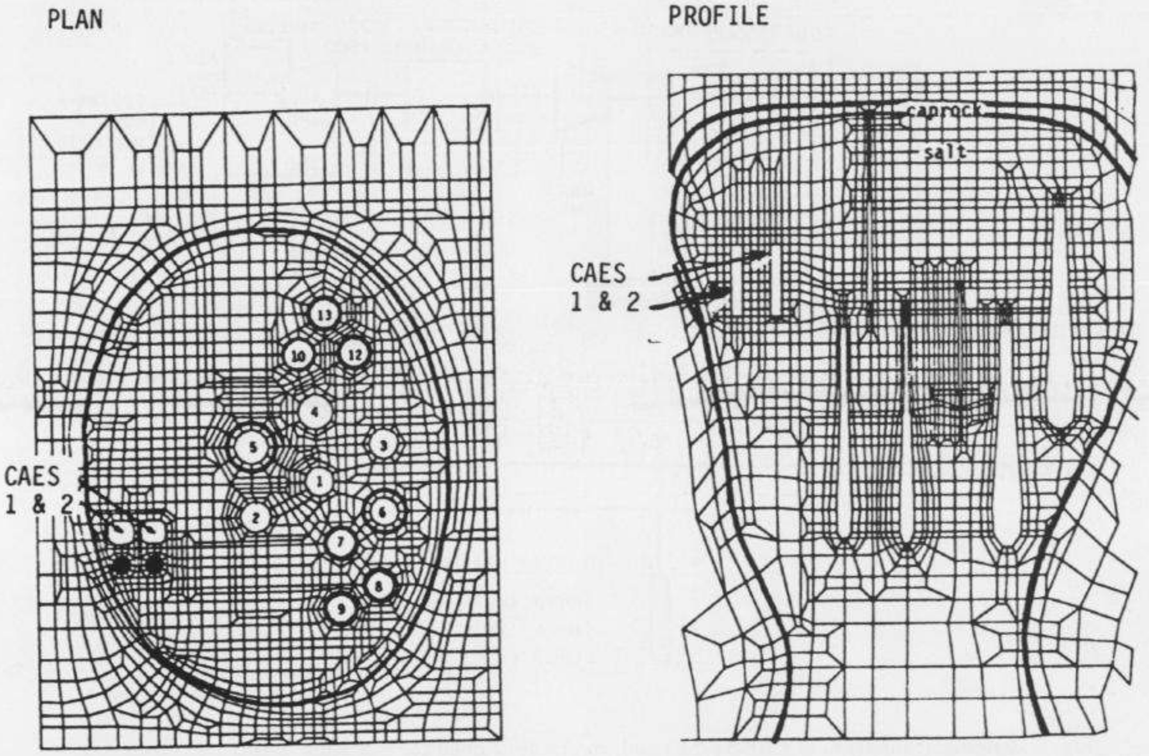

Fig. 3. Finite element meshes for horizontal and vertical cross-sections of McIntosh salt dome, including CAES caverns and solution mining caverns.

1990) in terms of temperature transients. These temperature effects required 30% larger cavern volume for 2600 MWh storage capacity than the isothermal assumption. The various advances and lessons learned during the design and construction of the plant have been published in numerous journals (Mehta, 1991).

SALT DOME AND INITIAL STRESS STATE

The CAES operation is located in the southwest portion of the dome. Although only one cavern is planned for construction at this time, the analysis allowed for two such caverns. Finite element meshes for horizontal and vertical cross-sections of the McIntosh salt dome are given in Fig. 3, showing the CAES caverns and Olin Chemical's solution mining caverns.

The state of underground stress is a matter of special interest and considerable debate. Typically, the stress is assumed to be geostatic with the vertical stress being equal to the overburden weight. However, recent studies have shown that the lateral stresses in the salt dome are in excess of the overburden weight. For the current study, both geostatic and excess lateral stress states (20% of the maximum allowable lateral stress) are considered.

LABORATORY TESTING OF CORE SAMPLES

The property parameters used in GEO constitutive modeling can be derived systematically in the laboratory. Since no core specimens were available at the beginning of the study, the parameters were obtained from Serata Geomechanics' historical data base, and were found to be adequate to determine the feasibility of the proposed cavern design because of the generally consistent salt properties. Once the feasibility of the CAES operation was established by the computer model analysis, salt core specimens were obtained from two different test wells penetrating to 915 m (3000 ft). These salt samples were subjected to long-term four to six weeks) tests, and time-dependent creep properties were evaluated. The material properties obtained from core samples (octahedral shear strength $K_o = 5.8 - 6.2$ MPa) were in good general agreement with those employed in the initial feasibility analysis ($K_o = 5.0 - 5.6$ MPa).

FINITE ELEMENT ANALYSIS

Stability analysis of an underground cavern field is essentially a three-dimensional problem, but a sliced cross-section can be modeled as a two-dimensional projection under plane strain idealization by

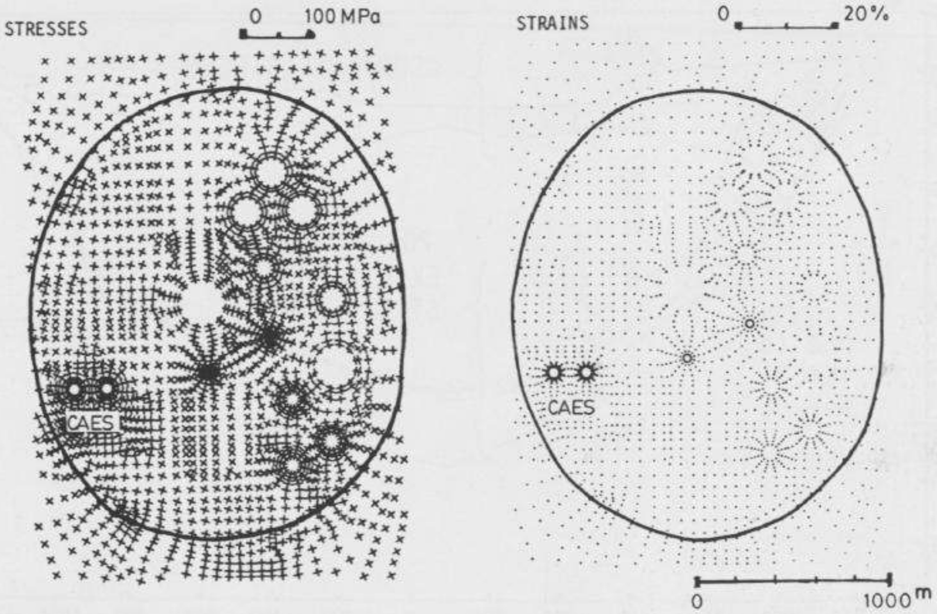

Fig. 4. Distribution of principal stresses and strains in horizontal cross-section of McIntosh salt dome after 40 years of CAES operation under geostatic stress state.

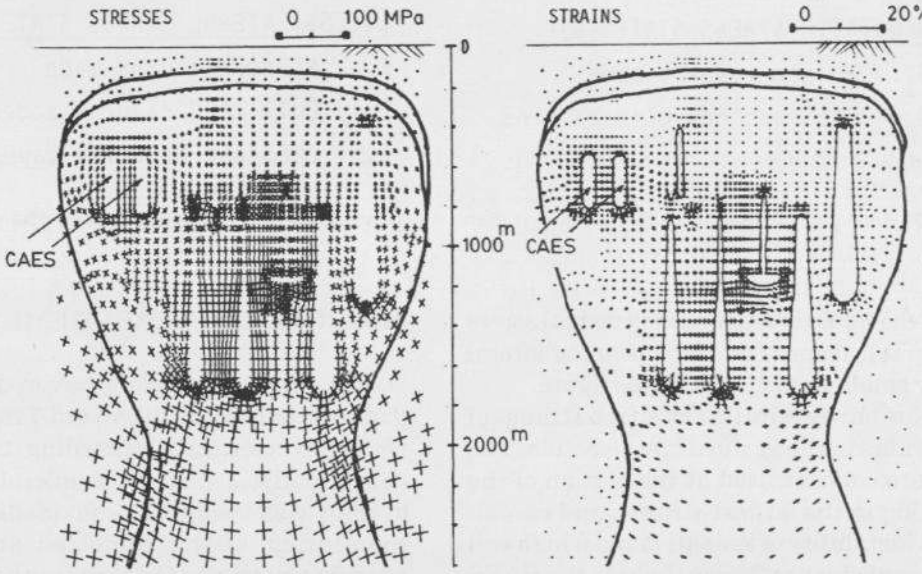

Fig. 5. Distribution of principal stress and strains in vertical profile of McIntosh salt dome after 40 years of CAES operation under geostatic stress state.

combined use of horizontal and vertical cross-sections of the salt dome (Fig. 3). The finite element method (FEM) analysis in the vertical cross-section employed 2586 four-noded quadrilateral elements. A refined mesh was used in the vicinity of the caverns. The strata surrounding the salt were classified as six material types: silty sand, silty clay, sandy shale, soft shale, sandstone, and hard shale. The horizontal cross-section, located at a depth of 608 m (2000 ft), was discretized into 2928 elements.

The model analysis covered 70 years, including 30 years past and 40 years future ground behaviors. The distribution of principal stresses and strains after 40 years of the storage operation are given in Figs. 4 and 5 for the horizontal and vertical cross-sections, respectively. The horizontal stress distribution (Fig. 4) discloses the horizontal stability of the entire salt dome achieved at 600 m depth by the rigidity of the surrounding hard sedimentary rock formation. This mechanism is revealed by the

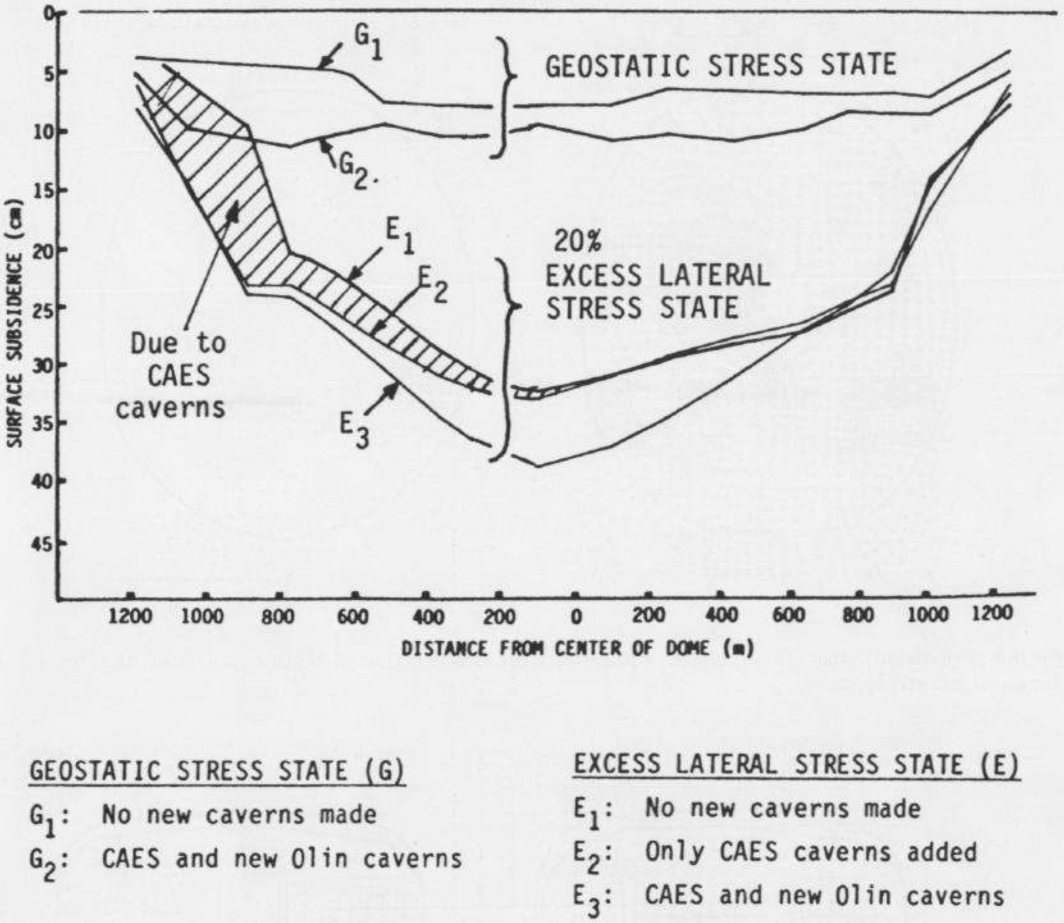

Fig. 6. Projected surface subsidences over McIntosh salt dome with various future excavation plans under geostatic and excess lateral stresses.

development of the circle of maximum principal stress surrounding the salt dome. The corresponding lateral strains are very small, as also seen in the figure.

Figure 5 compares similar distributions of stresses and strains in the vertical cross-section. The large stresses are concentrated at the bottom of the caverns, resulting in the largest strains, and revealing the vertical instability of the salt dome which will produce surface subsidence. Nevertheless, the CAES caverns are found to be basically stable.

Figure 6 shows the surface subsidence expected in the next 40 years of CAES operation under various lateral stress states. Under the geostatic stress state, the surface subsidence over 40 years is very limited, less than 10 cm even with expansion of solution mining for CAES and Olin Chemicals. The subsidence is increased several times with the presence of 20% excess lateral stress. The large subsidence is due to removal of the lateral stress by creep closure of the caverns, resulting in an increase of shear stress throughout the salt dome; this phenomenon is known as the "honeycomb effect."

MICROLEVEL MEASUREMENT SYSTEM

The surface subsidence over the CAES cavern is expected to be up to 40 cm (15.7 in.) over the 40 years of future operation, according to the dome subsidence analysis (Fig. 6). A microlevel measurement system was designed and installed for long-term monitoring of the projected subsidence for two specific objectives: to examine and improve the GEO model of the CAES cavern by comparing these measured values with the model predictions, and to monitor any abnormal of catastrophic ground behavior including air leak due to fatigue deterioration of the salt.

The system, comprising five stations, uses a liquid level to monitor the microscopic movement of the surface at five locations. The system layout is shown in Fig. 7. The system's water table is read and monitored hourly, and the data are processed automatically on site. Station 4 was placed on the well casing, and the others directly on the ground. All stations are equipped with electronic sensors, which are

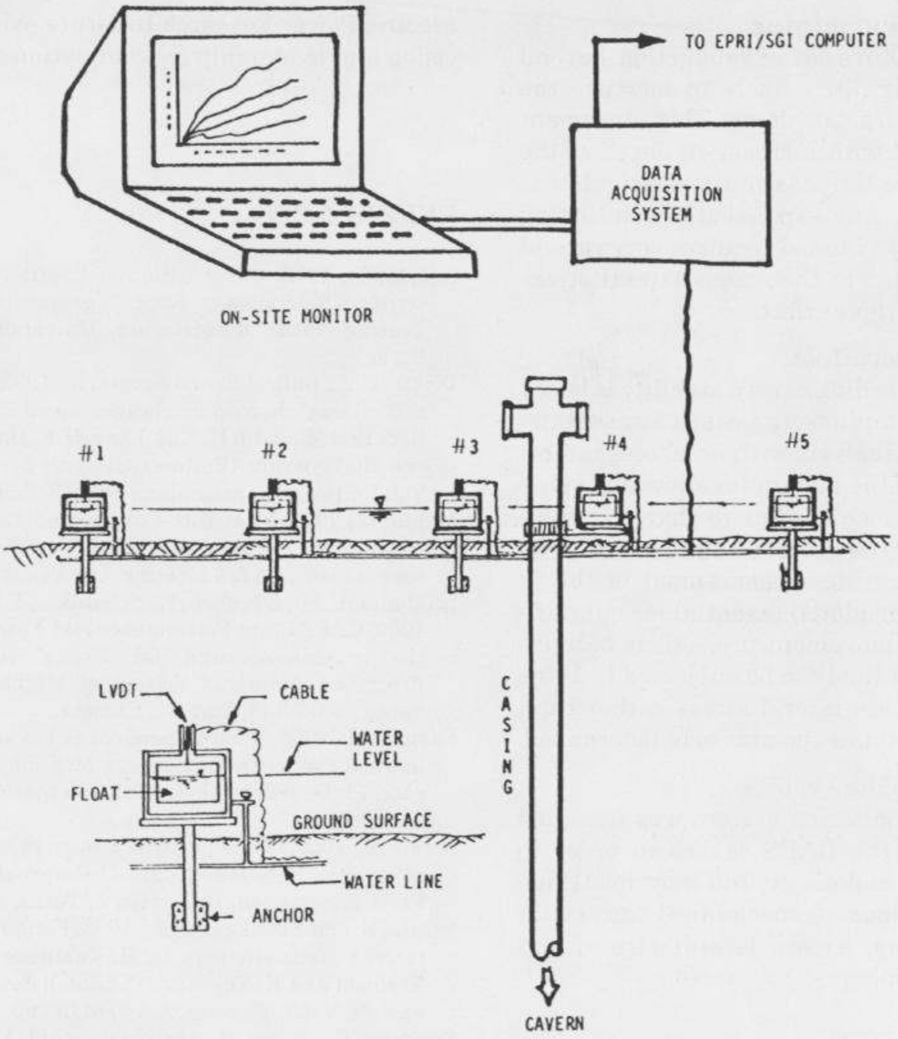

Fig. 7. Schematic diagram of microlevel meter over cavern area for long-term monitorng of CAES cavern safety.

packaged in a cooler box. One on-site computer for the entire system is placed in the monitoring house near the wellhead.

A number of problems were encountered in operating and maintaining the system, including lightning damage, accidental cutting of the water line, and biological growth in the water system. These problems have been overcome, and the basic stability of the system is shown by the continuous cyclic motion of the water.

DISCUSSION AND CONCLUSIONS

Cavern stability

The CAES cavern and its surroundings are found to be quite stable from the geomechanical point of view for a period of 40 years, with strains of less than 1% and cavern closure of about 3% by volume under idealized conditions of (1) limited expansion of future solution mining, (2) excess lateral stress not exceeding 20% of the maximum allowable value, and (3) no fatigue damage to permeability of the salt boundary.

Material fatigue effect

The material property parameters derived from the laboratory test results showed generally good agreement with the material properties employed in the initial and revised model analyses. Although the laboratory-tested strength of the core specimens is considerably (20%) higher than the assumed value, the stability of the CAES cavern calculated with the assumed property values should be considered quite realistic because the salt dome contains certain weaknesses which cannot be fully quantified. For future stability, close attention should be paid to the possible increase of salt permeability due to fatigue deterioration of the salt, including microstructural studies.

Expansion of solution mining

Any increase in Olin's brine production beyond the present plan (Fig. 3) is likely to increase the movement of the entire salt dome. This movement would be accelerated with increase in depth of the cavern bottom, where the maximum plastic flow is taking place (Fig. 5). Any expansion of solutioning beyond that presently planned requires very careful evaluation with regard to the excess lateral stress state and material fatigue effect.

Excess lateral stress effect

The conclusion regarding cavern stability is based primarily on the assumption of geostatic stress state. However, the model analysis with an excess lateral stress state of 20% of the maximum allowable value resulted in surface subsidence more than 2.5 times greater than that for the geostatic stress state (Fig. 6). In retrospect, accurate measurement of the in situ stress state is considered essential for quantification of the ground movement projections because the salt dome is most likely to be subjected to 100% of the maximum excess lateral stress rather than 20%. The actual stress state remains to be determined.

Microlevel monitoring system

The microlevel monitoring system was installed on the surface over the CAES cavern in order to monitor possible anomalous ground movement due to the effects of various geomechanical uncertainties: material fatigue, excess lateral stress, and excess cavern solutioning.

ACKNOWLEDGMENTS

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