Investigation of Residual Stresses in Salt

H. Reginald Hardy, Jr. and Arnis Mangolds

Geomechanics Section, Department of Mineral Engineering, The Pennsylvania State University, University Park, Pennsylvania, and Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

ABSTRACT

Unexplainable, excessive closure in a recently developed natural gas storage facility in southern United States suggests that residual stresses may be important in the design and performance of salt cavities used for storage, particularly those located in salt domes. An experimental study has, therefore, been undertaken by the writers to investigate the ability of salt (NaCl) to retain stresses imposed by previous geological deformations. This paper contains a brief review of the concept of residual stress and describes experimental studies using stress relief and x-ray techniques presently underway by the writers.

INTRODUCTION

Extensive and premature closure of storage facilities constructed in salt has accented the lack of understanding of environmental and material properties of this material. Since 1975 the Rock Mechanics Laboratory at The Pennsylvania State University has been involved in a research program aimed at developing a better understanding of the basic mechanical behavior of salt, particularly as it relates to the design and stability of cavities for storage of natural gas (Hardy, 1976; Hardy and Roberts, 1977).

Halite for all its simple structure provides a challenging subject with respect to definition of its material properties and response behavior to various stress conditions. In particular, the existence of residual stresses within Halite has often, if not categorically, been overlooked, since the apparently low yield stress and propensity of salt to creep was thought to preclude the existence of recoverable strain. Late in 1976 the writers initiated a laboratory study to investigate the possibility of residual stress retention in Halite. This paper, which forms part of a M.S. thesis by one of the writers (Mangolds) will briefly outline the concept of residual stress, discuss experimental techniques developed for laboratory study of residual stress in Halite, and present some of the preliminary results obtained to date. More detailed discussions on a number of aspects of the study are available elsewhere (Mangolds, 1978).

It should be pointed out that a number of questions must be resolved in order to have a complete understanding of residual stresses and their relation to underground design in salt, namely: 1) Can Halite retain residual stresses? 2) How can residual stresses be measured, and how can they be quantitatively expressed? 3) How is residual stress stored in Halite and on what scale? Is it stored on an atomic scale (hyperfine effects), molecular (lattice distortion), grain contact, or on mesoscopic scales? 4) How can the stored energy be released and how effective would various stress relief techniques be, especially if the energy is stored simultaneously at various scales? 5) How much stress can be stored and for how long? 6) What effects does stored strain energy really have on the material properties of salt, and can measurements be made to determine stress history?

The preceding questions are many and involved, and it should be appreciated that the current research project did not have the expectation of solving all of them, but rather to be an initial phase investigation. Indeed, the most immediate concern was to establish if Halite could in fact even retain residual stresses.

RESIDUAL STRESSES IN GEOLOGIC STRUCTURES

Introduction. The determination of the complete in-situ stress field prior to the initiation of engineering projects has become more critical as such projects become increasingly costly and approach the state of art in design. Numerous references cite examples of unexpectedly high stresses (up to 6000 psi) which could not be accounted for by gravity loading or active tectonism (Coates, 1964; Friedman, 1972, Swolfs et al., 1974; Russel et al., 1973; White et al., 1973).

The possibility of residual stresses causing anomalous conditions has been recognized in the metallurgical industry for some time (Cullity, 1967), though its acceptance in the field of geology has only come relatively recently (Denkhaus, 1967; Voight, 1967; Fairhurst, 1967; Varnes, 1970; Friedman, 1972). Phenomena such as rock bursts, closure of excavations, buckling of quarry floors, shearing of drill holes, spalling, exfoliation, and the existence of minifaults in theoretically stable areas have now been related to residual stresses.

The most likely source of practical concern of residual stress in Halite is with regard to construction of storage cavities in salt diapirs. The very nature of diapir emplacement infers anomalous stress conditions during upward mobilization. Aside from the overburden and possible tectonic forces, stresses may be stored within the displaced country rock, or within the diapir material itself. Residual stresses may have been imparted mechanically or thermally by the turbulent upward flow, or transmitted from the surrounding compressed rock.

General concepts. Residual stresses as defined by Voight (1967) are, "self-equilibrating stress components that remain in a structure if all external forces and moments are removed." The classic model of residual stresses is represented by a three spring and yoke analogy. When two springs of the same length are fastened to a yoke with a third spring of different length, an equilibrium will exist where one set of springs will be in tension, and the other in compression as shown in Figure 1. Energy used in the elastic deformation of such a system is effectively stored, yet is returnable. Failure of any component in this system, defined as an equilibrium domain, will initiate the elastic response. Most geologic materials are not perfectly elastic, however, and contain plastic and viscous components. The spring-yoke model may also be modified to include these components as shown in Figure 2.

Fairhurst (1967) describes a mechanism of retaining residual stress in a two component system. The grains which must support the effective stress may be of high strength material, while the matrix would be of a soft viscous nature.

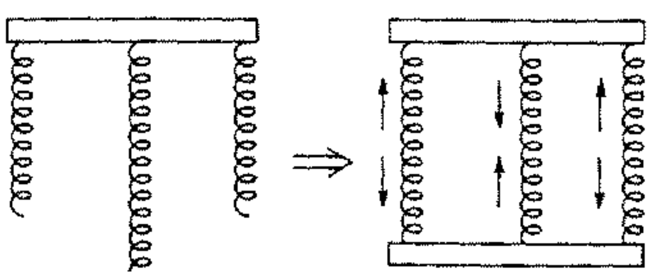

Figure 1.

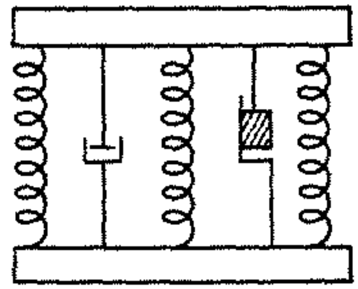

Figure 2.

Assuming uniaxial compression, the stresses will be absorbed instantaneously by the elastic grains (effective stress), and cause axial contraction due to Poisson's ratio. If an arbitrary cross section is taken parallel to the end-piece (perpendicular to the axis of applied load), the total stress across the plane must equal the applied load. A viscous matrix will flow from the areas of high pressure to low stress regions, redistributing the load and relieving stress differences within the specimen. The total load will still equal the applied load.

The retarding action of the viscous flow of the matrix will cause a time delay in total readjustment. If after equilibrium is reached, the applied load is removed, the elastic grains will try to return to their unstressed state by shape readjustment, impeded again by the matrix flow. As the grains return to their original state, pressure differences decrease, and matrix flow slows down at an exponentially decreasing rate. If the matrix had become in the mean time less viscous (i.e., by chemical alteration), or the yield point has been locally exceeded, the matrix or some grains in the exoskeleton may have attained the properties of an encasing cement. Such a restriction would disallow strain relaxation and would effectively seal-in the stresses. Localized variations in mechanical properties are quite common due to the heterogeneity of rocks on a composite scale, and dependence of crystallographic orientation on a grain scale.

Another method of creating locked in stresses may be via flexural flow folding (Donath and Parker, 1964), as shown in Figure 3, where during bending, the outer regions of a beam may flow plastically in tension and compression, while the core remains in the elastic state. After the load is released the elastic core is held in place by the plastically deformed skin. This model may roughly describe the elastic domain structures found in crystal lattices.

Domains may be simple in a directional sense, as in the spring-yoke analogy or three-dimensionally complex. The opposing stress field also does not necessarily occupy equal areas or volumes, or need it be similar in restraining mechanism. Several domains may be stacked on one another, forming unit boundaries. Using the spring-yoke analogy, it may be seen, as shown in Figure 4, that the domains may act as boundary units themselves.

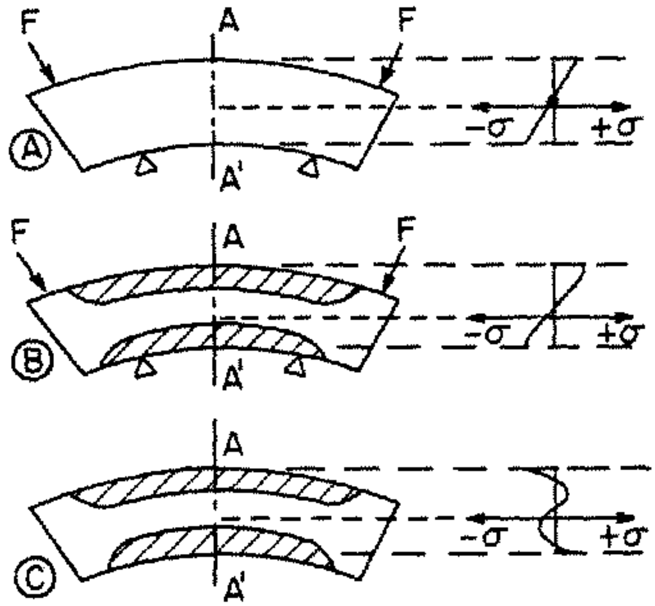

Figure 3.

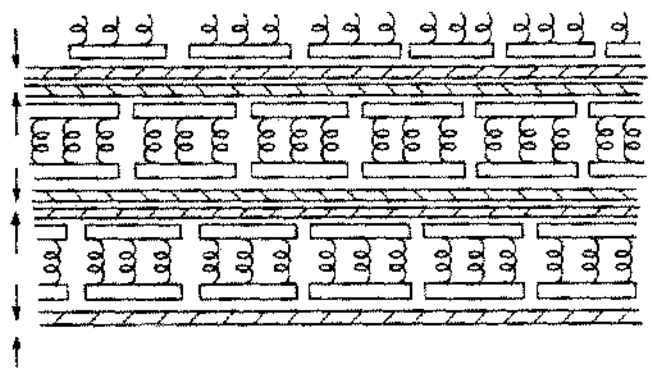

Figure 4.

The scale of the equilibrium systems may vary several magnitudes within one host body; from atomic (nuclear hyperfine effects), molecular (lattice distortions), intracrystalline (elastic and mechanical constraints), up to mesoscopic and macroscopic ranges, as evidenced by some jointing, exfoliation domes, and pop-up features.

Even though an applied stress field will be transmitted through the body, complete communication between individual domains does not necessarily exist. Just as the equilibrium domains can span several scales within a single host, so also may the effects of relaxation. Creation of a freeface with corresponding breaks in the equilibrium, do not necessarily relieve all the locked in stresses. It is apparent, therefore, that the values of recoverable strain observed may only reflect those strains covered by the measuring technique used.

Effects of stress mobilization. Assuming that active stresses are somehow stored in a salt body, the question arises as to the significance of it, and how it will effect design structures. Referring back to the spring-yoke analogy, it may be seen that if the original constraints are altered (i.e., if a spring or a yoke was broken), thereby upsetting the equilibrium, the residual stresses will mobilize in the form of strain in an attempt to reach a minimum energy level. If the unbalance was caused by physical alteration of the host body (e.g., cavity development), mobilization of the stresses will occur at the free-free. Those volume and shape changes will occur which will result in a reorientation and reduction of the surrounding forces.

The most realistic effect of residual stresses on material behavior becomes apparent when the stored stress is thought of in terms of stored strain energy. Assuming the material behaves in a manner represented by Figure 5, it may be seen that as the energy level applied increases, the distance to the yield point [or to various stages of inelastic behavior such as creep] decreases. If this energy is stored internal to the material, for example, at a level corresponding to the point E_a, only a slight amount of additional energy (ΔE) is required to put the material into the plastic region. The additional energy necessary may be the result of stress concentrations or due to the thermal loading from cavity fill (i.e., fluids or nuclear wastes). The deleterious end result then is not so much the expected strain relief which occurs with cavity creation, but the unrealized decrease in effective material strength resulting in subsequent deformation from other stress sources.

Methods of determining residual stress. In general two categories of residual stress measurement are practical today. These include x-ray diffraction (XRD) and the various strain release methods. The XRD technique is based on the measuring the lattice spacing of in-situ (in the test

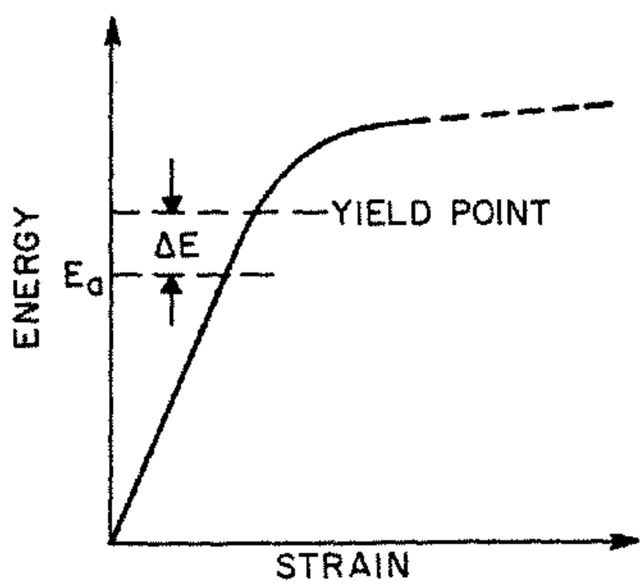

Figure 5.

specimen) crystals. Changes in the lattice spacings occur proportional to the applied stress. Plastic deformation may also be determined in a semi-quantitative manner using this technique. The lattice planes measured cover a small area thereby providing data essentially at a point. This is convenient for determining stress gradients and boundary effects on single crystals. Plastic deformation, microcracking, grain separation, and other nonelastic phenomena do not effect the results so that only elastic strains are measured. Due to the nature of the measurement, the complete stress ellipsoid can be relatively easily determined in a nondestructive manner. Disadvantages of the technique include its relative insensitivity, and the restriction to certain lattice planes satisfying various diffraction equations. Furthermore, only surface stress fields can be measured without resorting to surface removal by etching. To date one of the writers (Mangolds) has devoted a considerable amount of time to making the XRD method operational for use on salt. A report summarizing the theory, correction factors, and experimental techniques is presently in preparation. Due to time limitations, this technique has not as yet been implemented in the current study, and further details will, therefore, not be included in this paper.

In contrast to the XRD method, the strain release method, which was used in the current study, is based on the assumption that a strain measuring device can be mounted on a specimen (or a rock mass in the field) while it is still in a stressed equilibrium state. The specimen (or rock mass) is then cut or drilled in various configurations to allow strain release, and the amount of subsequent strain is monitored and related to the residual stress. In such studies foil-type strain gages are the most common method of strain measurement. The principle advantages are that they are relatively cheap, reliable, relatively sensitive, and provide average data for the area covered by the strain gage (anomalous stress distributions tend to be masked out by the averaging process). Disadvantages include the necessity of destructive testing in the creation of a free face, and the assumption that all the stresses are relieved under the gage area. Furthermore, relief cut configuration and orientation may also effect the amount of strain recovered; and inelastic deformation including plastic flow, microcrack deformation, etc. will also be detected by the attached strain gages.

RECENT STRESS RELIEF STUDIES

Outline of the experimental study. Studies of residual stresses in geologic materials have to date been concerned with naturally occurring rocks, often of complex composition, containing residual stresses induced sometime in their geologic past. To thoroughly understand a phenomenon or process, however, it should be observed from the beginning, under controlled conditions. When dealing with such materials the normal experimental and analytical problems are, therefore, complicated by a lack of positive information on the initial loading conditions. In contrast the present study involved a relatively simple mono-mineralic substance, Halite, loaded to a known initial stress state. The specimen was first stressed under controlled loading conditions, then unloaded, noting the so-called permanent set (unload strain) and the amount if any, of the recoverable strain still contained within the material.

Specimen preparation and strain gaging. Specimen preparation was difficult in a number of cases due to the high degree of brittleness of many of the salt samples. Tensile cracks along cleavage planes, and shear or tensile failure along grain contacts were the most common form of damage encountered. Accurate measurement of residual stresses requires the creation of a single, intact freeface. If crack propagation occurs into the specimen, away from the intended freeface, stresses may be relieved in an uncontrolled manner.

In all, 22 right circular cylinders were prepared from a number of blocks of commercially available recompacted salt (denoted here as artificial salt) obtained from a local retailer (originally produced by Morton Salt). Four double-crystal (intergrowth) specimens, seven single crystal specimens, and five polycrystalline natural salt specimens were prepared in prismatic form, from salt blocks obtained from the evaporite strataform of the Salina formation, Detroit, Michigan. Six right circular cylinders were prepared from field core (site and depth unknown) obtained from the National Cooperative Refinery (NCR), Kansas, and three field core samples obtained from Jefferson Island, Louisiana, cored at the 1500 foot level of the Diamond Crystal Salt mine located in domal salt.

Specimen strains were monitored by foil-type SR-4 resistance strain gages cemented directly to the surface of the prepared test specimens. A variety of different gage sizes and configurations were investigated. Gages were installed using MM 610 heat-cure epoxy.

Further details on specimen preparation techniques, dimensions of the completed specimens, and a detailed description of the strain gage installation techniques developed for this study are presented elsewhere (Mangolds, 1978).

Instrumentation. Figure 6 illustrates the experimental set-up used in the current study. The specimens were loaded in uniaxial compression using a Baldwin testing machine with an attached strain gage load cell. Each of the specimen monitoring strain gages were wired into separate bridge completion units. Both the load cell and the various strain gage bridge circuits were powered by constant voltage power supplies and continuous recording of load and strains was accomplished using a series of dual channel strip chart recorders. To provide a check on thermal strain effects, an extra monitoring channel was used to constantly record

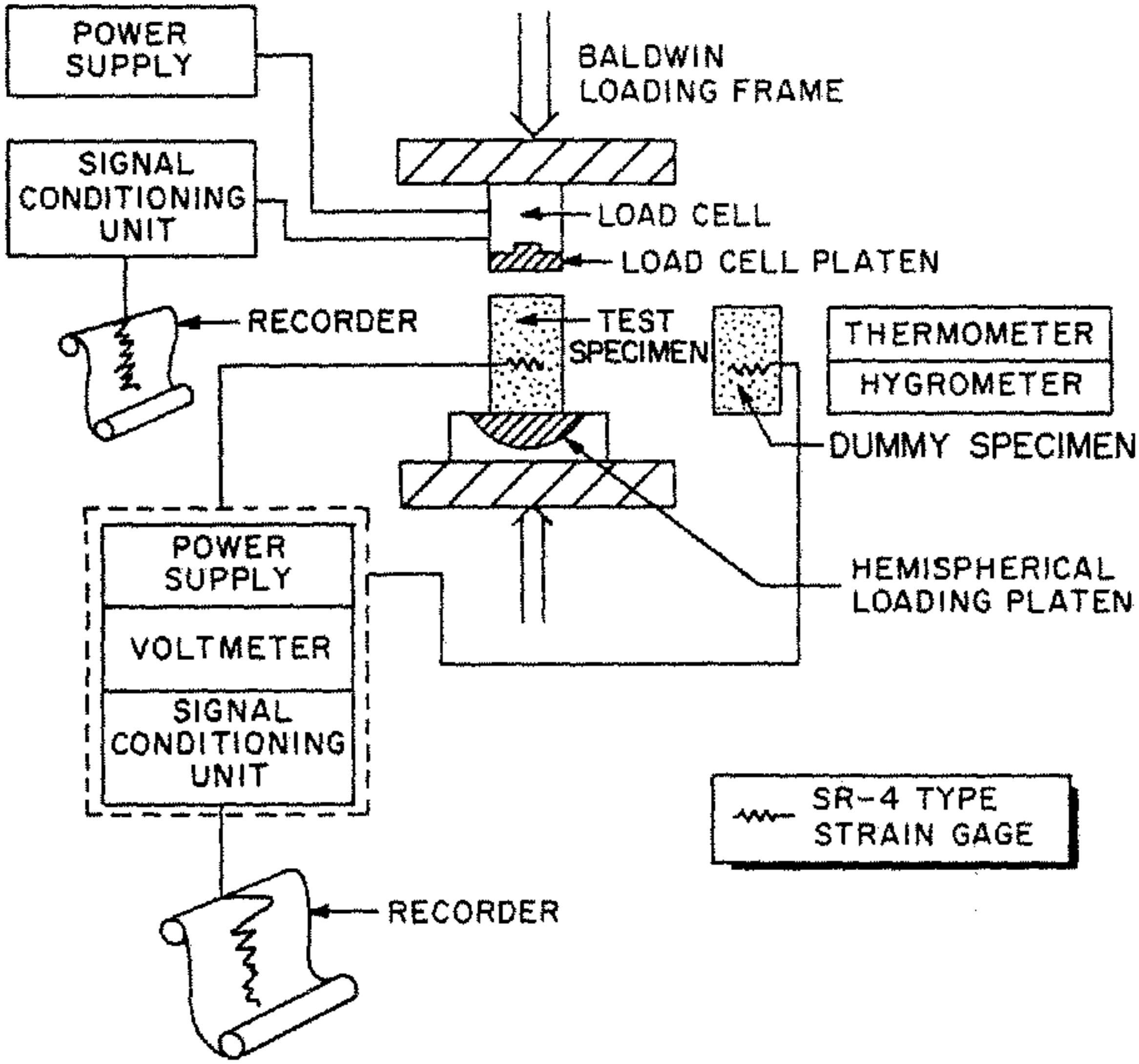

Figure 6.

strain in a dummy salt specimen placed close to the testing area. In addition a thermometer and hygrometer were also located in the immediate vicinity of the test area in order to monitor ambient test conditions.

Testing procedure. All of the various shaped specimens were tested in a somewhat similar manner, however, the description included here will be limited to tests on cylindrical test specimens. The specimen and the temperature monitoring strain gages were first wired into the associated strain gage circuits and the strip chart recorders, power supplies and bridge circuitry were warmed up for at least ½ hour prior to testing. A specific load increment was then applied to the test specimen, held constant for a period of ten minutes, and then released. Loading rates averaged 50 psi per second and with a few exceptions constant load was obtainable within ±50 psi. The unloading rate was comparable to that of loading. The specimen strains were continuously monitored after unloading to determine the equilibrium unload strain level. An average time of one hour was required in most cases. The specimen was then removed from the testing machine, however, the strain gages remained connected to the monitoring system.

Stress relaxation cuts were subsequently made using a hack saw, roughly a ½ inch deep. The first was made at a point above the strain gages, followed by a cut below, to the right side, and to the left side. Figure 7 shows the sequence of stress relaxation cuts. Strain stabilization was noted after each cut before preceding to the next one. The gaged block, once isolated at the surface from the surrounding specimen, was then separated from the parent specimen by carefully prying it loose with a screwdriver. The block was then cut and finally sanded to a thickness of approximately 0.1 inch,

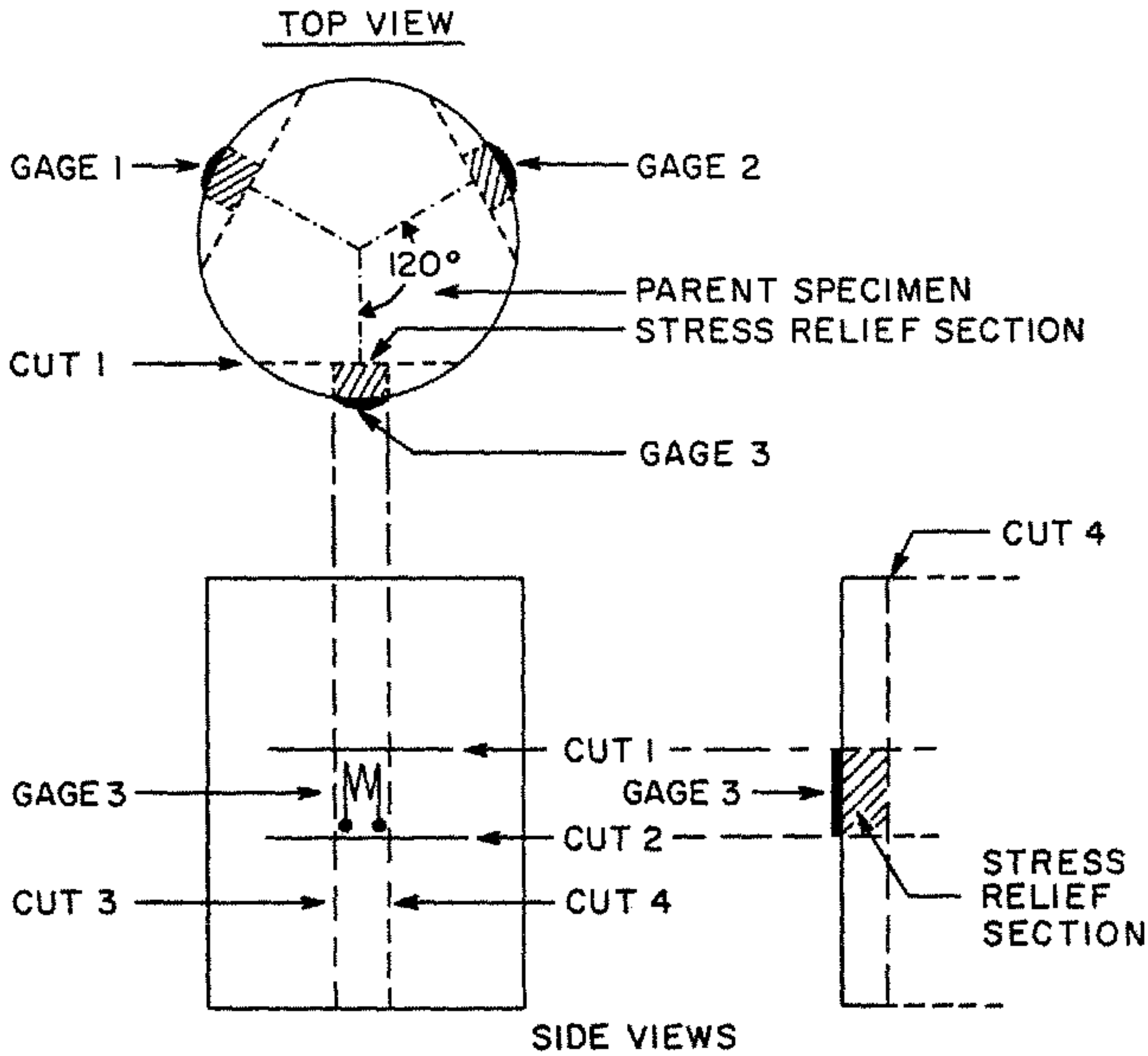

Figure 7.

again waiting for strain stabilization between each step. The test was then terminated.

Strain gaged specimens that had not undergone the loading cycle were randomly picked and cut to determine whether stresses existed in them prior to testing. These specimens were subjected to the same thermal loading due to strain gage heating and ambient conditions. This also provided a check on test repeatability. Average strain variations of ±3.5 μin./in. were found for tests on "artificial" salt specimens.

Typical test data. Typical test data are illustrated diagramatically in Figure 8 where the applied stress and observed strain are shown as a function of time. During the constant stress region (A–A′) varying degrees of creep (region a–a′) were observed. At (A′) the applied load was reduced to zero, reaching that level at the point (A″). The specimen strain during unloading varied over the path (a′–a″) and even after the load was fully removed the strain continued to slowly decrease to an eventual equilibrium value at the point (b). At this point the strain gaged regions were freed from the parent specimen in a number of steps following the procedures described earlier, and subsequent strain relief was obtained as indicated by sections of the strain-time curve (b) and through (f).

The majority of the specimens tested were instrumented with two or more strain gages. Strain relief data, similar to that presented in Figure 8, were obtained for each individual gage, therefore, the results for each gage are treated as separate data points. Such treatment of the data provided more realistic allowances for such factors as uneven load

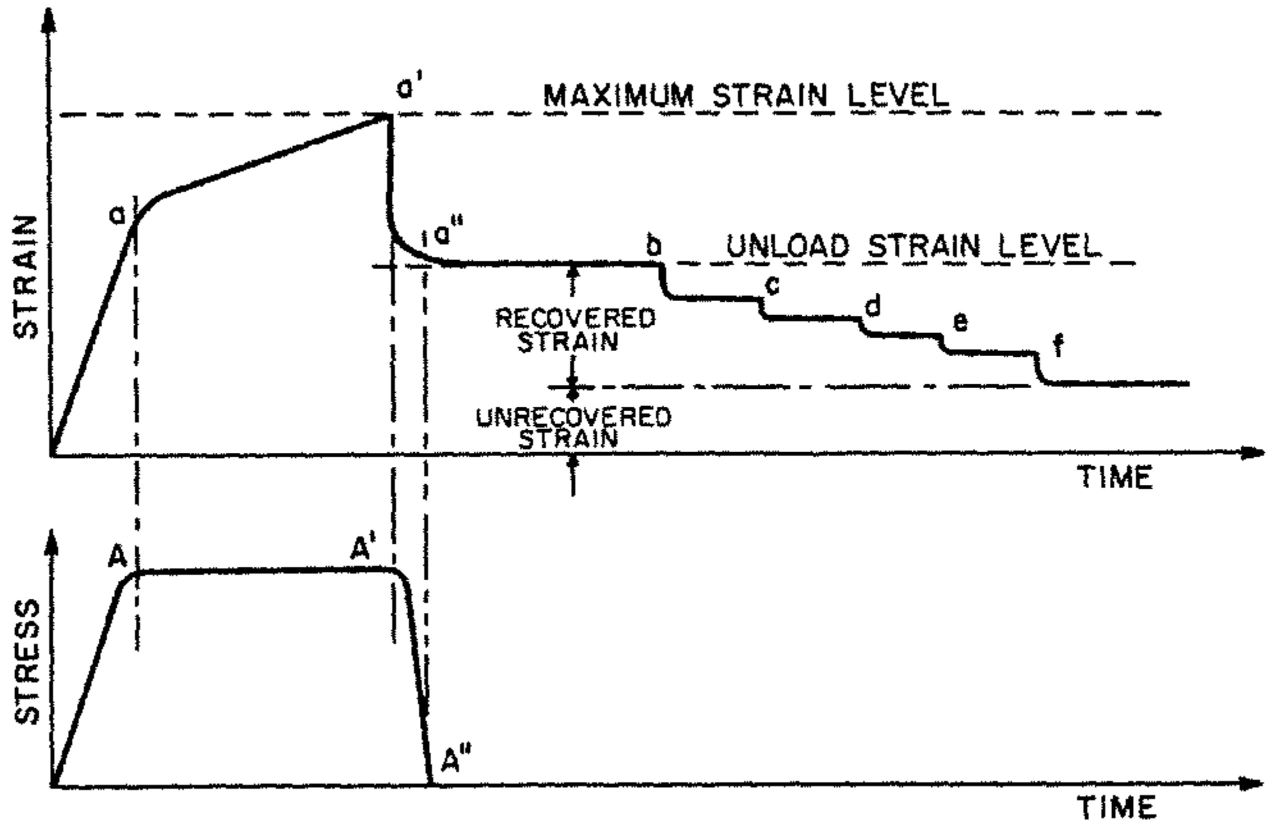

Figure 8.

distribution and insured that results would not be invalidated if a single gage was accidentally cut or pulled loose during the various strain relief operations.

RESULTS AND DISCUSSIONS

As has been noted earlier the purpose of this paper was to outline the concept of residual stress, to describe experimental techniques developed for the detection of possible residual stress in salt, and to comment briefly on typical results. During the current study some 50 tests have been run on a total of 45 specimens (several were cycled), prepared from a variety of different types of salt. Only a limited amount of data reduction has been completed to date. As an example of experimental results obtained, Table 1 lists selected preliminary data.

In general, based on all of the data obtained during the current testing program, the following tentative conclusions appear valid:

1. In those cases where tests were conducted on relatively fine-grained uniform material, there is good agreement in the recovered strains obtained from different gaged sections of the same parent specimen. For example, in Table 1 "artificial" salt specimen 6SL-4 gave values of 41.7, 44.9, 38.4, and 57.7 μin./in. (a spread of less than 35%) for four different gaged sections. Similar results were obtained for many other specimens of this material. Such data must be considered excellent in light of the inherent difficulties in the overall experimental technique. A larger scatter in the results were obtained for other salt types but this appeared to be due mainly to the coarse-grained nature of the material.
2. The magnitude of the recovered strains in the originally loaded specimens (ranging generally from 10–400 μin./in.) are well above those in the unloaded specimens (ranging from 2.2–15 μin./in.). This data strongly suggests that deformed salt is in fact capable of storing residual strain which may be released, at least partially, by suitable stress relief techniques.
3. Although there is considerable scatter in the results, the data suggests that in the case of the polycrystalline material the "artificial" and domal salt appear to be capable of the maximum degree of stress relief. This may well be due to their fine grain structure. Single crystals also appear capable of high residual stress retention.
4. A rough estimate of the residual stresses released from deformed "artificial" salt specimens, which had a Young's modulus in compression of the order of 3.5×10^6 psi, varied from 100–1400 psi depending on

TABLE I

Selected Preliminary Data from Stress Relief Experiments Carried Out on a Variety of Types of Salt

Test Number	Specimen Details	Applied Stress psi	Gaged Section	Maximum Strain μin./in.	Unload Strain μin./in.	Recovered Strain μin./in.	Percent Recovered Strain
19SX-2	Single Crystal (1)	1,001	1	394.8	367.0	34.3	9.3
			2	778.8	753.2	86.6	11.5
			3(5)	—	—	—	—
20SX-3	Single Crystal (1)	1,019	1	91.3	80.1	42.9	53.5
			2	172.7	154.5	32.7	21.2
			3(5)	—	—	—	—
36T-2	Intergrowth Crystal (1)	1,630	1(5)	—	—	—	—
			2	284.2	247.4	21.4	8.6
			3	346.3	314.3	4.3	1.4
6SL-4	Artificial Polycrystalline (2)	1,854	1	1073.7	801.3	41.7	5.3
			2	618.6	314.1	44.9	14.3
			3	666.6	282.0	38.4	13.6
			4	1105.7	814.1	57.7	7.1
7SL-5	Artificial Polycrystalline (2)	2,256	1	903.8	679.5	400.7	59.0
			2	1038.4	826.9	307.7	37.2
			3	1044.8	810.9	378.2	46.6
15SL-11	Artificial Polycrystalline (2)	unstressed	1	—	—	3.5	—
			2	—	—	5.8	—
			3	—	—	2.6	—
25NCR-1	Polycrystalline Bedded (3)	unstressed	1	—	—	2.2	—
			2	—	—	7.0	—
			3	—	—	10.9	—
39NCR-2	Polycrystalline Bedded (3)	2,050	1	526.9	448.8	10.9	2.4
			2	857.2	787.4	9.6	1.2
			3	697.8	627.4	6.4	1.0
44NCR-4	Polycrystalline Bedded (3)	2,017	1	332.9	272.7	54.4	19.9
			2	617.8	568.2	8.0	1.4
			3	448.1	382.5	5.4	1.4
27PC-2	Polycrystalline Bedded (1)	unstressed	1	—	—	−4.5	—
			2	—	—	−3.8	—
30PC-3	Polycrystalline Bedded (1)	2,041	1	248.1	195.1	−8.0	—
			2	240.1	196.1	9.6	4.9
			3	341.3	275.6	26.3	9.5
43J-1	Polycrystalline Domal (4)	1,515	1	737.8	609.8	40.0	6.5
			2	640.2	530.7	95.4	18.0
			3	934.7	853.1	91.3	10.7
41J-2	Polycrystalline Domal (4)	unstressed	1	—	—	3.8	—
			2	—	—	14.7	—
			3(5)	—	—	—	—

(1) Salinas Formation, Michigan; (2) Morton Salt; (3) National Cooperative Refinery, Kansas; (4) Jefferson Island, Louisiana; (5) Strain gage failed.

the original applied stress level. The associated data exhibited considerable scatter but the average value appears to be in the range of 300–400 psi.

In conclusion the writers feel that the current studies have definitely shown that deformed salt may retain considerable residual stress. Analysis is continuing and final conclusions based on the results of the current study will be withheld until all data has been thoroughly evaluated. It is expected that this should be completed late in 1978. It should be noted, however, that the current study must be considered only a preliminary one and considerable additional research on this topic is required to firmly validate the importance of residual stress retention in salt cavity design.

ACKNOWLEDGEMENTS

The financial support for the studies described in this paper has been provided from general departmental funds and the Pipeline Research Committee of the American Gas Association (Project

PR-12-71). Assistance by E. Kimble, research aide, during the laboratory stage of the study, is gratefully acknowledged.

REFERENCES

Coates, D.F. 1964. Some Cases of Residual Stresses in Engineering Work, *Conference on State of Stress in the Earths Crust*, Elsevier, 679.

Cullity, B. 1967. *Elements of X-Ray Diffraction*, Addison Wesley, 514.

Denkhaus, H. 1966. The Nature of Stress and Comments, *Proceedings 1st ISRM Congress*, (Lisbon, 1966), 312–319.

Donath, F. and Parker, B. 1964. Folds and Folding, Bull. Geol. Soc. of Amer., 75: 45–62.

Fairhurst, C. 1967. Methods of Determining In-Situ Rock Stresses at Great Depths, *U.S. Army Corp. of Engineers Report DA-25-066-ENG-14*.

Friedman, M. 1972. Residual Elastic Strain in Rocks, Tectonophysics. 15: 297.

——— and J. Logan. 1970. Influence of Residual Elastic Strain on the Orientation of Experimental Fractures in Three Quartzose Sandstones, J. Geophysical Res. 75: (2).

Hardy, H.R., Jr. 1976. Salt Cavity Design and Performance, *Proceedings AGA Transmission Conference* (Las Vegas, 1976), AGA Cat. X50176, T350–T353.

——— and D. Roberts. 1977. Evaluating the Physical Properties of Salt Associated with Design of Salt Cavities for Natural Gas Storage, *Proceedings AGA Transmission Conference* (St. Louis, 1977), AGA Cat. No. X50477, T266–T272.

Mangolds, A. 1978. Review of Stress Retention Studies on Salt, Internal Report RML-IR/78-2, Geomechanics Section, Department of Mineral Engineering, The Pennsylvania State University.

Russel, J. and E. Hoskins. 1973. Residual Stresses in Rock, Proceedings 14th Symposium on Rock Mechanics, ASCE, 1–24.

Swolfs, H., J. Handin, and H. Pratt. 1974. Field Measurements of Residual Strain in Granite Rock Masses. *Proceedings 3rd ISRM Congress*, (Denver, 1974), 563–568.

Varnes, L. 1972. Hypothesis of Mobilization of Residual Stresses in Rock, Bull. Geol. Soc. Amer. 83: 2863–2866.

Voight, B. 1967. Interpretation of In-Situ Stress Measurements, *Proceedings 1st ISRM Congress*, (Lisbon, 1967), 332–348.

White, O., P. Karrow, and J. McDonald. 1973. Residual Stress Relief Phenomena in Southern Ontario, *Proceedings 9th Canadian Symposium on Rock Mechanics*, 323–348.