

Evaluation of *In-Situ* Stresses in Salt Using Acoustic Emission Techniques

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ABSTRACT

During the study of the mechanical behavior of metals, J. Kaiser at the University of Munich in 1950, discovered that the acoustic emission (AE) response of metals showed a pronounced 'memory' of the maximum previously applied stress. This memory is commonly referred to as the Kaiser effect. Over the last 40 years, continued research on the Kaiser effect in metals, ceramics, composites, concrete and geologic materials has enabled the development of a number of practical applications. The current paper will provide a brief review of the various mechanical property studies on salt carried out in the Penn State Rock Mechanics Laboratory, in particular those where AE measurements were included. This will be followed by a brief outline of the Kaiser effect studies carried out on geologic materials in general. Such studies have indicated that the Kaiser effect may provide an inexpensive and convenient means of determining *in-situ* stresses in geologic structures. The paper will include a discussion of the results of a limited number of Kaiser effect studies carried out on salt and potash.

INTRODUCTION

Research on the mechanical behavior of salt has been particularly active since the late 1970s. This has been due to accelerated use of solution-mined underground caverns for the storage of liquids and gases, and the interest in salt as a storage medium for radioactive wastes. Although numerous papers have been published throughout the literature, prime sources of technical information on the mechanical behavior of salt, as well as other evaporites, are the proceedings of past six Salt Symposia, particularly the fifth and sixth (Coogan and Hauber, 1980; Schreiber and Harner, 1985) and the proceedings of the two conferences on the Mechanical Behavior of Salt (Hardy and Langer, 1984; 1988) sponsored by the Penn State Rock Mechanics Laboratory. Research by this laboratory has included a variety of studies associated with the design of solution-mined caverns for the storage of natural gas. A monograph on these studies, including a detailed bibliography on salt and salt related research, is available (Hardy, 1982).

The rational design of underground structures, such as fluid storage caverns, mining operations and radioactive waste repositories, requires detailed data on the state of stress in the area of the proposed structure. Unfortunately a review of the 'salt litera-

ture' indicates that very little information on the *in-situ* state of stress in either bedded or domal salt is available. This paper will include a brief outline of available literature on the concept of *in-situ* stress, conventional methods for evaluating *in-situ* stress, acoustic emission (AE) concepts, and the use of AE as an indirect means for evaluating *in-situ* stress.

IN-SITU STRESS

General

The mechanical stability of an underground structure depends on a number of factors including the virgin underground stress field, the geometry and size of the structure, the mechanical properties of the material, and the characteristic of any associated artificial support. Past experience has clearly indicated that the magnitude and direction of the virgin *in-situ* stress field must be known in order to achieve a safe and optimum structural design. Furthermore, the *in-situ* stresses associated with critical areas of the structure should be monitored during and after construction.

The recent Symposium on Rock Stress (Stephanson, 1986) includes a number of excellent papers and associated bibliographic material on the state of stress in the earth's crust, and methods for determining

both the virgin *in-situ* stress field and the stresses associated with underground development. The opening paper at the symposium (Fairhurst, 1986) provides a reasonably recent overview of the subject and includes a discussion on the variation of vertical and horizontal virgin *in-situ* stresses with depth for various locations throughout the world. A second symposium paper (Eriksson and Michalski, 1986) considers the virgin state of stress in salt domes in southwestern USA.

Generally it is noted that the vertical *in-situ* stress, S_V , varies nearly linearly with depth below surface, namely: $S_V = 0.027 Z$, where Z is the depth below surface in meters. In contrast the horizontal stress, S_H , is given by: $S_H = k S_V$, where the limits of k are $[(100/Z) + 0.3] < k < [(1500/Z) + 0.5]$ depending on the location. For example at a depth of 500 m the above limits reduce to $0.5 < k < 3.5$. In contrast, the recent paper by Eriksson and Michalski (1986) indicates that for salt domes a near-hydrostatic condition ($k = 1.0$) exists.

Studies by Hardy and Mangolds (1980) have indicated that deformed salt may retain a considerable level of residual stress. The residual stresses released from a number of experimentally deformed salt specimens were found to vary from -0.52 to $+10.99$ MPa. A polycrystalline artificial salt, type-SL, exhibited the maximum value (10.99 MPa), followed by the type-SX single crystal salt, (3.69 MPa) and the type-J polycrystalline natural (domal) salt (1.30 MPa).

Based on the preceding, it is clear that meaningful *in-situ* stress data for a specific site can only be obtained by stress measurements associated with that site.

In-Situ Stress Measurement

During the last 40 years a variety of experimental techniques have been developed for the measurement of *in-situ* stresses. The basic concepts associated with each of these are described in Obert and Duvall (1967). Recent papers describe the use of overcoring (Heusermann, 1988) and hydraulic fracturing techniques (Nelson and Kocherhans, 1984) for the measurement of *in-situ* stress in salt. The application of these stress measurement techniques to inelastic materials such as salt introduces a number of additional complications. For example, in many salt projects (e.g. storage cavern development), stress data are often required at depths of 1500 m or more. Besides the technical difficulties and limitations, the cost of even near-surface stress measurements in elastic materials is expensive, often involving thousands of dollars to determine the *in-situ* stress at a single location.

A possible solution to the problems associated with conventional *in-situ* stress measurement techniques may be provided by the use of techniques utilizing the so-called Kaiser effect. Here, laboratory loading tests are carried out on specimens of salt obtained from underground areas of interest using borehole coring techniques. During loading, micro-level seismic activity (acoustic emission) occurring within the material is recorded. Suitable analysis of this data provides information on the *in-situ* state of stress at the point in the structure where the test specimen was originally located. In potash, a material similar in many ways to salt, studies by Vance (1983) and Mottahead and Vance (1988) have validated the suitability of the Kaiser effect technique. Furthermore, in the past, a variety of informal tests by the author and others has suggested that the Kaiser effect should also provide a realistic technique for the measurement of *in-situ* stress in salt.

ACOUSTIC EMISSION

General

The basis of the Kaiser effect method for *in-situ* stress evaluation is the so-called acoustic emission technique (Hardy, 1972, 1981). It is generally accepted today that most solids emit low-level seismic events when they are stressed or deformed. This phenomenon will be referred to here as acoustic emission (AE). In essence, the measurement of AE activity in a laboratory specimen or field structure is relatively simple. A suitable transducer is attached to the specimen or structure, the output of the transducer is connected to an associated monitoring system, and the AE events occurring in the structure, due to internal or external stress or deformation, are suitably acquired, pre-processed and recorded. In a fully automated system, a variety of computer-based techniques may be applied for on-line processing of AE data.

The Penn State Rock Mechanics Laboratory has been involved in both field and laboratory AE research since 1964, including a variety of laboratory scale AE studies carried out on salt. A number of AE field and laboratory studies have also been carried out on potash by Vance (1983) and Mottahead and Vance (1988).

AE studies on salt

The fact that salt generates AE activity when loaded and/or deformed has been verified by a number of Penn State studies. AE has been noted during a variety of simple loading experiments (Hardy, 1982; Mrugala, 1985). A number of more detailed studies, relative to creep, yield stress determination

and dissolution, include a wide range of AE related investigations.

A three-phase laboratory study to evaluate the creep behavior of salt was carried out at Penn State during the period 1975–1985 (Hardy, 1982; Mrugala, 1985). During Phase I of these studies (Roberts, 1980), AE activity was also monitored. In these studies, AE activity was found to occur during both creep and recovery following specimen unloading. The AE rate during creep was found to be nearly an order of magnitude greater than that during recovery.

At Penn State, laboratory investigations were undertaken into several phenomena associated with the plastic behavior of salt and methods for objective determination of the yield stress (yield point) (Richardson, 1980; Hardy, 1982). Studies were carried out on both single and polycrystal specimens of salt. For single crystal specimens, the AE rate was found to exhibit a well-defined peak at the yield point, presumably due to dislocation multiplication. For polycrystalline material, the AE investigations were inconclusive and it is felt that further, more detailed evaluation of the AE technique should be undertaken.

A recent paper by Hardy (1988) reviews a number of laboratory studies undertaken to evaluate the usefulness of AE techniques for monitoring the stability of salt under conditions where dissolution would be expected to occur. A brief outline of the results of these studies indicate that during dissolution, unstressed salt exhibits detectable AE activity. For unstressed specimens the observed AE rate decreases with increased brine concentration and for a saturated brine solution, unstressed specimens exhibit no AE activity. The studies indicated that a salt specimen stressed in a saturated brine solution exhibits a transient AE behavior during periods of rapid loading and a very low or zero level of AE

activity when the applied stress is held constant. In contrast, surprising results were obtained when both a stressed and an unstressed specimen were located in a saturated brine solution. Here it appears that a pressure solution phenomenon is active, and mass transfer occurs between the stressed and unstressed specimens. This mass transfer is clearly detectable by monitoring the AE activity of both the stressed and unstressed specimens. The pressure solution and mass transfer aspects noted may well have an important bearing on the mechanical stability of salt structures such as those developed as nuclear waste repositories. Further, more refined dissolution studies are planned in the future.

Kaiser effect studies

An important application of the AE technique is its use in the determination of *in-situ* stresses in rock. The AE phenomenon which makes such stress determination possible is the so-called 'Kaiser effect' or 'stress memory'. Kaiser (1953) was the first researcher to observe the phenomenon which now bears his name. The discovery was made during a study of the AE response of metals which Kaiser conducted in the early 1950s. Over the last 40 years, continued research on the Kaiser effect in metals and other manufactured materials has enabled the development of a number of practical applications. Research to date on the applicability of the Kaiser effect to *in-situ* stress determination in rock appears favorable, and continued research should, in the future, provide the geotechnical engineer with a powerful new tool.

The Kaiser effect can be described by considering a simple experiment in which the phenomenon is evident. Consider, for example, the simplified laboratory set-up, shown in Fig. 1a, in which a rock specimen is subjected to two cycles of loading. As illustrated in Fig. 1b, in the first load cycle, stress is applied to the specimen at a constant rate up to a value of s_{max} and then returned to zero. In the second cycle, stress is increased in a similar fashion, however, the previous maximum stress (s_{max}) is exceeded. During each cycle, AE activity is monitored and accumulated AE counts (or events) recorded as a function of applied stress. Figure 1b shows data which is typical of such an experiment. Here the cumulative number of AE counts generated within the specimen during each of the two load cycles is illustrated. It can be seen that AE activity is generated at all stress levels during the first cycle. However, during the second load cycle little or no activity is generated until the maximum stress level (s_{max}) attained in the first load cycle is exceeded. Thus, the Kaiser effect can be defined as the absence

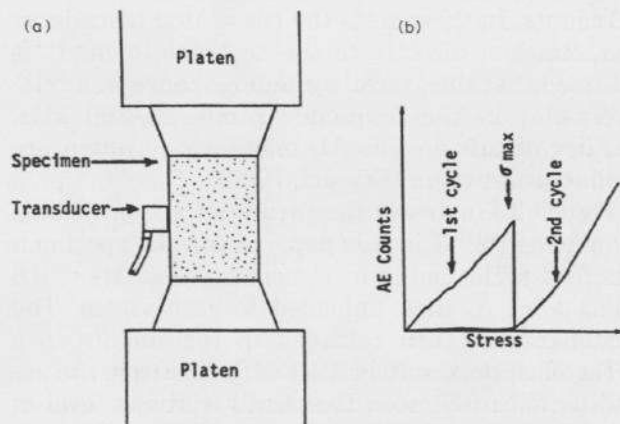


Fig. 1. A simple laboratory arrangement and typical data associated with Kaiser effect tests (after Hardy et al., 1989). (a) Testing arrangement; (b) typical test data.

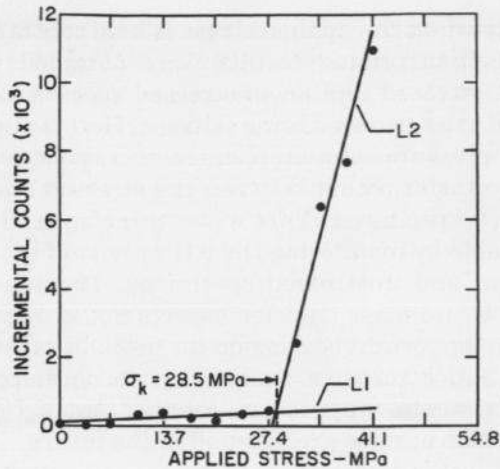


Fig. 2. AE/MS incremental counts versus stress for Indiana Limestone (Specimen 3) preloaded under uniaxial stress (after Hardy et al., 1989). Uniaxial preload $\sigma_p = 27.77$ MPa; Kaiser stress $\sigma_k = 28.5$ MPa.

of AE activity at stress levels below a previously applied maximum stress.

In geotechnical applications, rock cores would first be obtained from a field structure where *in-situ* stress data was required. These cores would then be prepared into test specimens and loaded in the laboratory over a suitable stress range, while the associated AE data was recorded. Analysis of the resulting AE data would provide the Kaiser stress (σ_k) values, which are assumed to represent the *in-situ* stresses at those points in the field structure where the rock cores were obtained.

Detailed Kaiser effect studies have been under way in the Penn State Rock Mechanics Laboratory over the last ten years. To date, studies have been carried out on a variety of sandstones, limestones, granite, marble, and more recently salt. Tests have been undertaken on specimens originally loaded under both uniaxial and triaxial conditions. Figure 2 shows data for a uniaxial test on Indiana Limestone originally preloaded to stress of 27.77 MPa. Here incremental counts, namely the number of counts for each approximately 3.43 MPa increase in the reload stress, are shown plotted against the applied stress level. Linear regression techniques were then applied to the data and two lines (L1 and L2) fitted to the data below and above the apparent Kaiser stress level. The intersection of lines L1 and L2 was then projected to the stress axis to define the Kaiser stress (σ_k). Data from tests on 9 specimens, preloaded to approximately 27.4 MPa were evaluated using this procedure. Estimation of the preload stress level from the associated AE data resulted in errors ranging from 2.4% to 12.0%, with a mean error of 6.5%.

A detailed historical review of research carried

out by workers in Canada, Japan and the USA is presented in a paper by Hardy et al. (1989). A more recent paper by Montoto and Hardy (1991) extends the earlier review and includes research material relative to on-going studies of the thermally-induced Kaiser effect.

A major problem relative to the use of the Kaiser effect as a routine method for *in-situ* stress evaluation, is the need for an objective method for estimation of the Kaiser stress from the AE versus stress data. A recent paper (Shen and Hardy, 1993) describes on-going studies on this problem.

KAISER EFFECT STUDIES IN EVAPORITES

A rapid survey of the literature suggests that the application of AE techniques to evaporites, under laboratory and field conditions, has been relatively limited. Furthermore, only a very few Kaiser effect studies have been carried out on such materials. In this section the author will briefly review the Kaiser effect studies carried out on potash and domal salt.

Potash studies

For a number of years the Potash Corporation of Saskatchewan has been actively involved in a comprehensive rock mechanics program at a number of its underground mining operations. Papers by Vance (1983) and Mottahead and Vance (1988) describe this research, including limited data on the investigation of the Kaiser effect as a means of *in-situ* stress evaluation.

Vance (1983) describes a number of experiments carried out on specimens of potash ore. Here the test material was prepared into 10.2 cm cubes and loaded using a conventional open-loop testing machine. During loading, AE activity was monitored using a McPhar type RM-1 Rock Monitor, set to provide total AE counts. In these tests the associated transducer was attached directly to the test specimen. It is assumed that the overall system response was relatively flat in the frequency range 30–200 kHz. Further details on this AE monitoring system are available elsewhere (Ersvac, 1989).

Figure 3 illustrates the results of a typical test, denoted as PSC-1 in this paper. Here the specimen was first preloaded in increments to a stress of 8.6 MPa, point A, then unloaded to zero stress. The specimen was then reloaded in increments to a stress of approximately 12.9 MPa. During the re-loading it can be seen that until a stress level of approximately 8.6 MPa is reached, point B, relatively few AE events are recorded, namely 855 total events. This is considerably less than the 7603 total events observed during preloading, and shows that

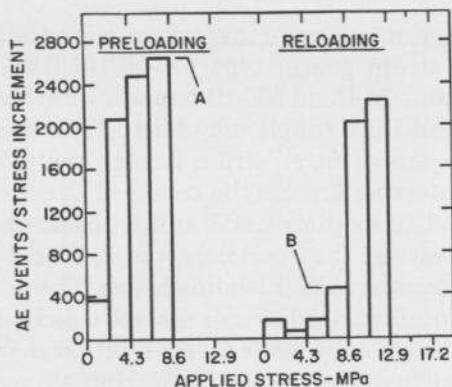


Fig. 3. Kaiser effect data obtained from test PCS-1 on potash ore (after Vance, 1983). Stress increment — 2.15 MPa.

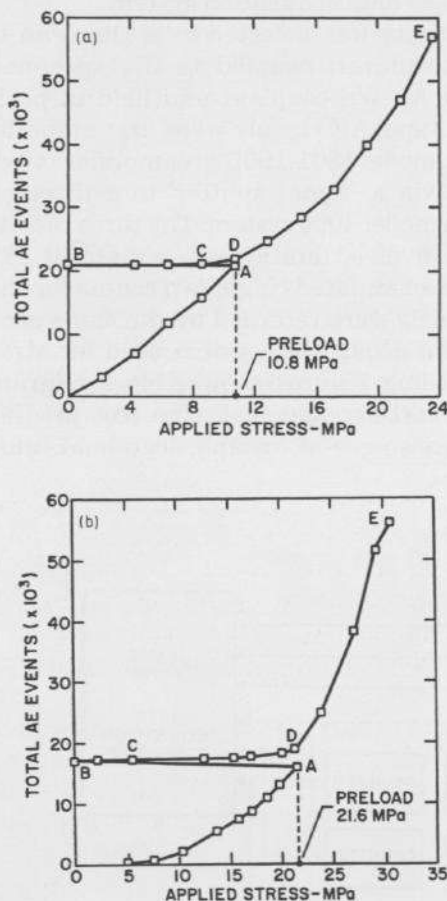


Fig. 4. Kaiser effect data obtained from tests on potash ore (after Mottahead and Vance, 1989). (A, top) Test PCS-2, preload 10.6 MPa; (B, bottom) Test PCS-3, preload 21.6 MPa.

potash ore clearly exhibits the Kaiser effect.

The later paper by Mottahead and Vance (1988) describes additional Kaiser effect tests on potash ore. Data from two of these tests, denoted in this paper as PCS-2 and PCS-3, are shown in Fig. 4. It

appears that the same experimental procedure was used in these tests as for PCS-1 (Fig. 3). However the AE event data in Fig. 4 is shown as total AE events, namely the total number of AE events monitored from zero stress to a specific stress level. In both of these tests, the applied stress during preloading was raised from zero to a point A, then decreased to zero. During reloading the applied stress was raised again to a higher stress level, point E. In both tests, it is observed that during reloading relatively few additional AE events were recorded until the stress exceeded the original maximum stress (point A). The results of the tests are additional evidence that potash ore exhibits the Kaiser effect.

It is also interesting to note that the Felicity effect is observed for all potash tests, namely the computed Felicity ratio is seen to decrease with the maximum preload stress (Anon., 1990, p. 503). The 'Felicity Ratio' (FR) is defined as the ratio of the stress at which AE activity occurs during reloading to the previously applied maximum stress. For example in Fig. 4, $FR = (BC/BA)$, and the associated data are presented in Table 1. A value of $FR = 1.0$ indicates that the Kaiser effect is fully valid, whereas, values of $FR \neq 1.0$ suggest that the Kaiser effect, at least in some regions of the test specimen, is not fully operational. Generally values of $FR < 1.0$ indicate that the specimen has suffered some form of permanent damage. In the case of the potash ore specimens, it is assumed that the preload stress levels, particularly that for specimen PCS-3 (21.6 MPa), are well above the yield point of the material. The observed value of $FR = 0.26$ for PCS-3 suggests that during loading this specimen was stressed well into the dilatant region, resulting in permanent damage to the material.

Unfortunately the papers by Vance (1983) and Mottahead and Vance (1988) do not provide detailed experimental data. However, sufficient data is presented to substantiate the fact that potash ore clearly exhibits the Kaiser effect.

TABLE 1

Approximate preload stress and felicity ratio for tests on potash ore

Test number	Maximum preload stress (MPa)	Felicity ratio
PCS-1	8.6	$>0.88^1$
PCS-2	10.8	0.79
PCS-3	21.6	0.26

¹Value may be greater but insufficient data is available for a more accurate calculation.

Salt studies

Although casual comments relative to the Kaiser effect in salt are evident in the literature, no detailed study of the Kaiser effect has as yet been undertaken for this material. In order to bring the Kaiser effect, and its use in evaluating *in-situ* stress, to the attention of those at the 7th Symposium on Salt, a series of laboratory studies on domal salt were initiated in early 1991. Some preliminary results of these studies are included in this paper.

Sample material

Experiments were carried out on specimens of type S5 salt, cored from a large block (45 kg) during earlier Penn State studies. This material was obtained from a Texas salt dome. It was massive, white and fine grained, and no obvious macroscopic grain orientation or major discontinuities were evident. Grains were transparent and nearly colorless, and grain size varied from 2.5 to 12.7 mm with an average grain size of approximately 5.1 mm. The results of limited earlier laboratory tests indicated that the material had a uniaxial compressive strength of 14.8 MPa, a bulk specific gravity of 2.13, and a porosity of 1.3%. Further information on this material is presented elsewhere (Hardy, 1982).

Experimental details

Test specimens were nominally 5.4 cm in diameter and 13.2 cm in length, and were prepared following procedures described earlier by Hardy

(1982). Specimens were instrumented with SR-4 resistance strain gages, type EA-06-10CBE-120, attached using M-Bond AE-10 cement. Both the gages and cement were supplied by Micro-Measurements, Inc. Two sets of three strain gages, located at 120 degree intervals around the center of the specimen, were used to monitor axial and transverse strain. During testing, the specimen was located between special stress equalizer loading heads. These loading heads contained hard rubber inserts which also provided a degree of acoustic noise isolation to increase the signal-to-noise ratio (SNR) during AE measurements. The specimen was loaded uniaxially using an MTS programmable testing facility, and the applied load was monitored using an integral load cell. Strains and applied load were recorded using a computer-based data acquisition system.

AE activity was detected by a Dunegan type D-140B transducer, coupled to the specimen with Dunegan AC-WS couplant and held in place with masking tape. AE signals were first amplified by a Dunegan model 1801-190B preamplifier (40 dB) and then fed via a 'signal splitter' to a three channel Dunegan model 3000 system. The three resulting AE channels involved total system gains of 83, 88 and 93 dB. The accumulated ring-down counts for the three AE channels were recorded by the same computer-based data acquisition system used for strain and load recording. Figure 5 shows a block diagram of the experimental arrangement. The test program employed ten stages of loading, load-hold, unloading

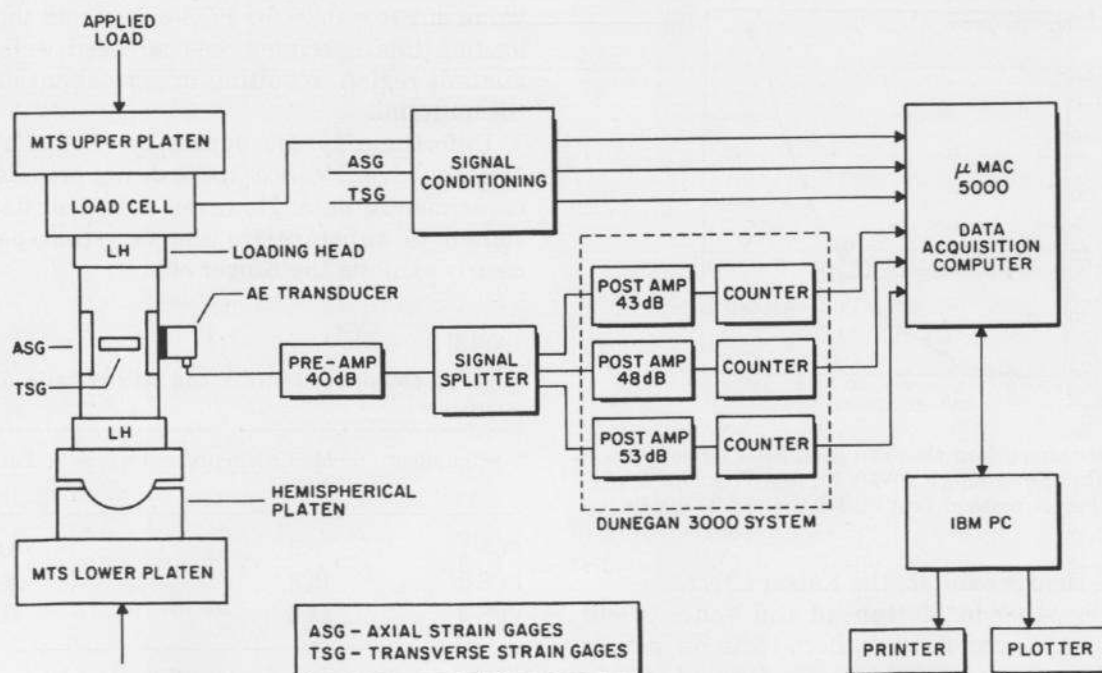


Fig. 5. Block diagram of experimental arrangement used for Kaiser effect studies on salt.

and zero load rest. The loading and unloading rates were 0.034 MPa/s, and both the load-hold and zero load rest periods were 900 s in duration. Each sub-

sequent load-hold level was increased 0.68 MPa over the proceeding one, resulting in load-hold stresses of 0.68, 1.36, 2.04, ..., 6.12, 6.85 MPa. As a result, during each loading stage the current load-hold stress level was 0.68 MPa greater than the previous maximum stress level.

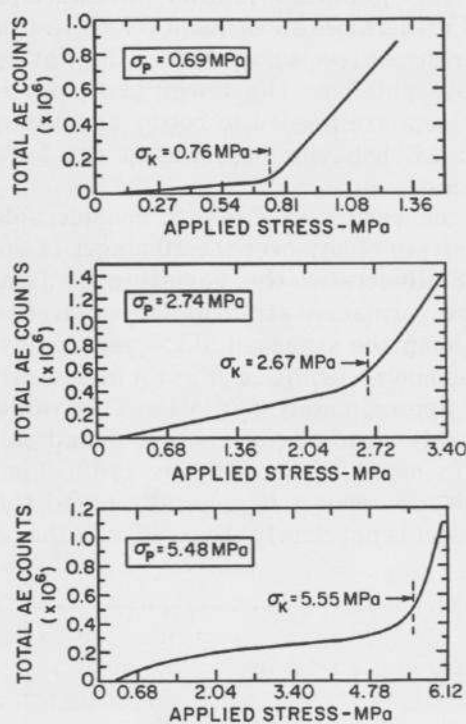


Fig. 6. Examples of AE versus applied stress data for specimen S5-WS/1 with AE monitored at a 93 dB system gain.

Typical results

This paper does not allow a detailed discussion of the results of the current experiments. However, a brief review of some typical results for specimen S5-WS/1 will be included here. Figure 6 shows examples of AE data monitored at an overall gain of 95 dB versus applied stress, for three different preload levels, 0.69, 2.74 and 5.48 MPa. The general character of the curves are similar to those observed for a wide range of rock types. Using a simplified form of the tangent-intercept method for evaluation of the Kaiser stress level (see Fig. 2 presented earlier), values of the Kaiser stress (s_k) and the Felicity ratio (FR) were computed for tests at all prestress levels and for AE data monitored at 83, 88 and 93 dB total system gains. These data are presented in Table 2 along with the associated axial (e_a) and transverse (e_t) permanent strains, and the values of the calculated volumetric (e_v) permanent strain. It should be noted that although limited elastic strains were noted, these were small compared to the permanent strains.

For AE system gains of 88 and 93 dB, it was noted that values of the Felicity ratio (FR) vary over the

TABLE 2

Data from Kaiser stress tests on salt specimen S5-WS/1

Test stage	Permanent strains due to previous load cycle				AE monitoring channel gain						
	σ_p^1 MPa	e_a μs	e_t μs	e_v^2 μs	83 dB		88 dB		93 dB		
					σ_k MPa	FR	σ_k MPa	FR	σ_k MPa	FR	
1	0.00	0	0	0							
2	0.68	-17	0	-17	ND ³	ND	0.75	1.10	0.76	1.11	
3	1.36	-50	+2	-46	1.32	0.97	1.47	1.08	1.40	1.03	
4	2.04	-140	+15	-110	1.97	0.96	2.20	1.08	1.98	0.97	
5	2.72	-390	+60	-270	ND	ND	2.53	0.93	2.67	0.98	
6	3.40	-1250	+300	-650	ND	ND	3.23	0.95	3.33	0.98	
7	4.08	-2900	+800	-1300	3.67	0.90	3.92	0.96	3.88	0.95	
8	4.76	-4300	+1400	-1500	4.28	0.90	4.71	0.99	4.47	0.94	
9	5.44	-5400	+1900	-1600	4.79	0.88	5.49	1.01	5.49	1.01	
10	6.12	-6250	+2450	-1350	5.63	0.92	6.30	1.03	6.24	1.02	
Average values of felicity ratio						0.92		1.01		1.00	

¹Parameters are defined in the text.

² $e_v = e_a + 2e_t$.

³No available data.

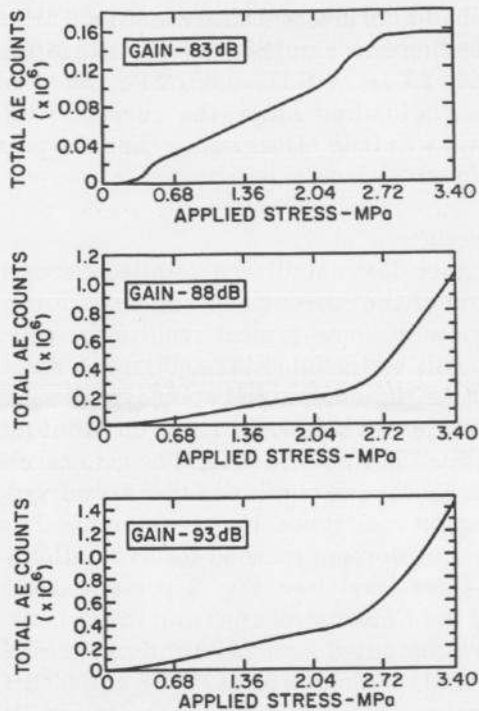


Fig. 7. AE versus applied stress data for specimen S5-WS/1, at a prestress of 2.72 MPa for three different AE system gains.

range 1.11–0.93, with average values of 1.01 and 1.00, respectively. This indicates that for the uniaxial preload conditions used in these tests the Kaiser effect was able to very accurately predict the prestress levels, provided a sufficiently high AE system gain was employed. The effect of AE system gain is illustrated in Fig. 7 where test data for a prestress of 2.72 MPa and AE system gains of 83, 88 and 93 dB are presented. Here, it is clearly seen that although the results for gains of 88 and 93 dB are similar, results for a gain of 83 dB are very different, both in magnitude and curve shape. For example, in general 8–10 times more events are counted at the higher gains. Furthermore, for higher gains as the applied stress approaches the prestress level the AE count accelerates, whereas at the 83 dB level the data decelerates and becomes 'flat' near the prestress level.

The overall system gain determines the size of AE events that will be counted, and subsequently recorded. For example, at a gain of 83 dB, only the larger AE events will be counted. The flat region of the 83 dB AE count versus applied stress data in Fig. 7 indicates that few large AE events occur once the applied stress reaches and exceeds the preload stress. In contrast the data in Fig. 7, for gains of 88 and 93 dB, indicates that many small events occur at applied stresses greater than the preload stress.

The observed effect of AE system gain suggests

that during the loading of polycrystalline salt, events with a wide range of amplitudes occur during loading up to the preload stress level. However, above the prestress level the associated deformation/failure mechanisms generate mainly small amplitude events. Furthermore subsequent 83 dB test data at higher prestress levels do not show the 'flat' regions previously noted at the lower prestress levels. Further tests are needed to better understand the observed AE behavior observed at the lower AE system gains

As noted earlier in Table 2, considerable permanent strain occurs over the 10 stages of the test. Figure 8 illustrates the variation of axial and volumetric permanent strain as a function of preload stress. Using the standard '0.2% permanent axial strain yield point definition', Fig. 8A indicates a yield stress of approximately 3.74 MPa. This value compares closely with that of another domal salt (S4) studied in detail earlier (Hardy, 1982). For more brittle elastic rocks it is generally noted that the Kaiser effect is not clearly observed once the preload

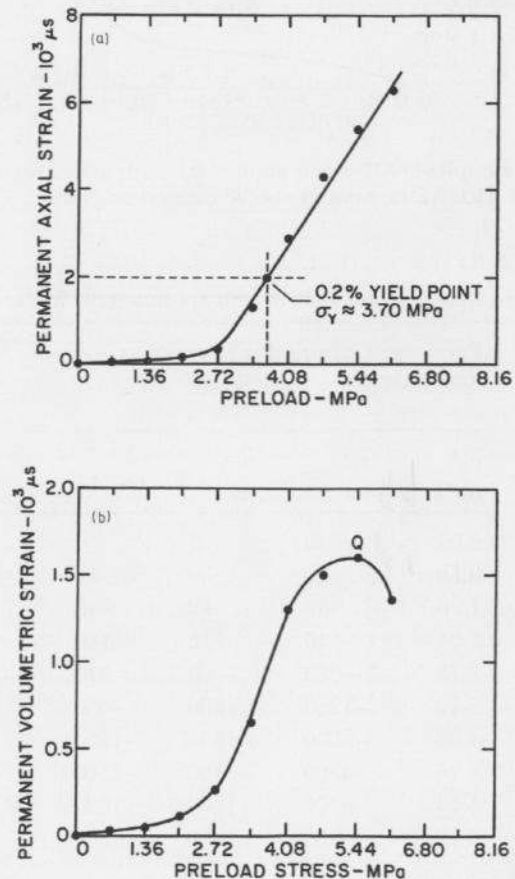


Fig. 8. Axial and volumetric permanent strains versus preload stress for specimen S5-WS/1. Strains shown are compressive. (A, top) Permanent axial strain. (B, bottom) Permanent volumetric strain.

exceeds the stress necessary to cause dilatancy (positive volume strains). It was assumed that a similar problem would arise for inelastic materials like the evaporites, once the preload stress exceeded the yield point. In the case of the salt investigated in the current study, this is clearly not the case since at an AE system gain of 93 dB, the average Felicity ratio for preloads above the 3.74 MPa yield point was 0.98. To investigate this situation in more detail, the volume changes associated with the permanent strains were investigated and Fig. 8B shows the variation of volumetric strain with preload stress for specimen S5-WS/1. It is clear that, even at the 6.12 MPa preload level, the specimen volume change is still negative (compressive) and dilatancy has not occurred. It is interesting to note that the compressive volume strain curve peaks at a preload stress of approximately 5.48 MPa (point Q). For the 6.12 MPa preload, the curve shows a downward trend and it is assumed that for sufficiently high preloads, dilatancy and associated breakdown of the Kaiser effect will occur.

Conclusions regarding the Kaiser effect in evaporites

A review of the limited data on potash ore available from the literature and preliminary analysis of data from ongoing in-house studies on domal salt indicates the following:

(1) Evaporites, such as potash and salt, exhibit the Kaiser effect. Unfortunately the data available for potash was insufficient for a detailed analysis.

(2) Tests on domal salt indicates a well defined Kaiser effect. Using suitable AE monitoring system gains, Felicity ratios in the range 0.94–1.11 (average 1.00) were obtained for prestress levels from 0.68 to 6.12 MPa.

(3) The shape of the AE total count versus applied stress curve depends on the overall AE system gain. Anomalous results were obtained using an 83 dB system gain.

(4) Accurate Kaiser stress data can be obtained from salt even at stresses well above the yield point.

(5) Further experiments are required to develop a more detailed data bank relative to the relationship between the mechanical behavior of salt and the associated acoustic emission.

SUMMARY

This paper has discussed the problems of evaluating *in-situ* stresses and the potential use of acoustic emission (AE) techniques for investigating the mechanical behavior of salt. Continuing research on the mechanical behavior of salt under way in the Penn

State Rock Mechanics Laboratory has been described. At Penn State, AE studies associated with the evaluation of the Kaiser effect as a indirect means for the evaluation of *in-situ* stresses in salt structures is presently under way. Preliminary experiments have been encouraging; however, additional research is required in order to resolve a number of unknowns.

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REFERENCES

- Anon., 1990. Standard Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP) ASTM 1990 Annual Book of Standards, Vol. 03.03, pp. 503–514.
- Coogan, A.H. and Hauber L. (Editors), 1980. Fifth Symposium on Salt, Vol. 1 & 2, The Northern Ohio Geological Society, Inc., c/o Department of Geology, Case Western Reserve University, Cleveland, Ohio, 1032 pp.
- Eriksson, L.G. and Michalski A., 1986. Hydrostatic conditions in salt domes — a reality or a modeling simplification. Proceedings International Symposium on Rock Stress and Rock Stress Measurement, Stockholm (September 1986), Centek Publishers, Lulea, Sweden, pp. 121–132.
- Ersavci, M.N., 1989. Recent studies relative to the application of the McPhar Rock Stress Monitor. Proceedings Fourth Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, Pennsylvania State University (October 1985), Trans Tech Publications, Clausthal, Germany, pp. 145–158.
- Fairhurst, C., 1986. *In-situ* stress determination — an appraisal of its significance in rock mechanics. Proceedings International Symposium on Rock Stress and Rock Stress Measurement, Stockholm (September 1986), Centek Publishers, Lulea, Sweden, pp. 3–15.
- Hardy, H.R., Jr., 1972. Applications of acoustic emission techniques to rock mechanics research. Proceedings ASTM Symposium on Acoustic Emission, Bal Harbor (December 1971), ASTM STP-505, Acoustic Emission, pp. 41–83.
- Hardy, H.R., Jr., 1981. Applications of acoustic emission techniques to rock and rock structures: a state-of-the-art review. ASTM Symposium on Acoustic Emission in Geotechnical Engineering, Detroit (June 1981), ASTM STP 750, pp. 4–92.
- Hardy, H.R., Jr., 1982. Theoretical and Laboratory Studies Relative to the Design of Salt Caverns for the Storage of Natural Gas, AGA Monograph Cat. No. L51411, American Gas Association, Arlington, Virginia, 709 pp.
- Hardy, H.R., Jr., 1988. Acoustic emission during dissolution of salt. Proceedings Second Conference on the Mechanical Behavior of Salt, BGR Hannover (September 1984), Trans Tech Publications, Clausthal, Germany, pp. 159–177.
- Hardy, H.R., Jr. and Langer M. (Editors), 1984. Proceedings

- First Conference on the Mechanical Behavior of Salt, Penn State University (November 1981), Trans Tech Publications, Clausthal, Germany, 901 pp.
- Hardy, H.R., Jr. and Langer M. (Editors), 1988. Proceedings Second Conference on the Mechanical Behavior of Salt, BGR Hannover (September 1984), Trans Tech Publications, Clausthal, Germany, 781 pp.
- Hardy, H.R., Jr. and Mangolds, A., 1980. Investigation of residual stresses in salt. In: A.H. Coogan and L. Hauber (Editors), Fifth Symposium on Salt, Vol. 1, Northern Ohio Geological Society, Inc. Cleveland, Ohio, pp. 55-63.
- Hardy, H.R. Jr., Zhang, D. and Zelanko J.C., 1989. Recent studies of the Kaiser effect in geologic materials. Proceedings Fourth Conference on Acoustic Emission/Microseismic Activity in Geological Structures and Materials, Pennsylvania State University (October 1985), Trans Tech Publications, Clausthal, Germany, pp. 27-55.
- Heusermann, S., 1988. Aspects of overcoring stress measurements in rock salt. Proceedings Second Conference on the Mechanical Behavior of Salt, BGR Hannover (September 1984), Trans Tech Publications, Clausthal, Germany, pp. 273-289.
- Kaiser, J., 1953. Erkenntnisse and Folgerungen aus der Messung von Gerauschen bei Zugbeanspruchung von Metallischen Werkstoffen. Archiv für das Eisenhüttenwesen, Vol. 24, pp. 43-45.
- Montoto, M. and Hardy, Jr., H.R., 1991. Kaiser effect in intact rock: current status as a means of evaluating thermal and mechanical loading. Proceedings Seventh International Congress on Rock Mechanics (Aachen 1991), A.A. Balkema, Rotterdam. pp. 569-572.
- Mottahead, P. and Vance, J.B., 1988. A/E determination of salt behavior under stress, Proceedings Second Conference on the Mechanical Behavior of Salt, BGR Hannover (September 1984), Trans Tech Publications, Clausthal, Germany, pp. 465-474.
- Mrugala, M., 1985. A Laboratory Study of the Time-Dependent Behavior of Salt. Ph.D. Thesis, Department of Mineral Engineering, The Pennsylvania State University, August 1985, 473 pp.
- Nelson, R.A. and Kocherhans, J.G., 1984. *In-Situ* Testing of Salt in a Deep Borehole in Utah. Proceedings First Conference on the Mechanical Behavior of Salt, Penn State University (November 1981), Trans Tech Publication, Clausthal, Germany, pp. 493-510.
- Obert, L. and Duvall, W.I., 1967. Rock Mechanics and the Design of Structures in Rock, John Wiley & Sons, Inc., New York, 650 pp.
- Richardson, A.M., 1980. Using AE techniques in laboratory investigation of salt behavior. Proceedings Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, Pennsylvania State University (November 1978), Trans Tech Publications, Clausthal, Germany, pp. 63-78.
- Roberts, D.A. 1980. Measuring acoustic emission from salt during creep. Proceedings Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, Pennsylvania State University (November 1978), Trans Tech Publications, Clausthal, Germany, pp. 79-86.
- Schreiber, B.C. and Harner, H.L. (Editors), 1985. Sixth Symposium on Salt, Vol. 1 & 2, The Salt Institute, Alexandria, Virginia, 1341 pp.
- Shen, W. and Hardy, Jr., H.R., 1993. Objective Kaiser stress evaluation in rock. Proceedings Fifth Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, Pennsylvania State University (June 1991), Trans Tech Publications, Clausthal, Germany (In Press).
- Stephansson, O. (Editor), 1986, Proceedings International symposium on Rock Stress and Rock Stress Measurement, Stockholm (September 1986), Centek Publishers, Lulea, Sweden, 694 pp.
- Vance, J.B., 1983. Application of microseismic techniques in potash mines. In: R.M. McKercher (Editor), Potash Technology, Pergamon Press, Toronto, pp. 179-184.