# An Investigation into Underground Gas Storage in Brine Well Cavities

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**ABSTRACT**

The ongoing program of research at the Department of Mining Engineering of the University of Newcastle upon Tyne involves certain aspects of the structural response and stability of gas storage cavities in salt. The investigation may be separated into two main areas of interest, first, the "strength" problem associated with storage cavities at shallow and intermediate depths and, second, the "flow" problem at great depth.

Under particular operating conditions it is possible that the tangential stress in the wall-rock of a cavity at shallow depth may become tensile. In order to determine whether a localized or gross tensile failure might ensue, a major program of in situ tests were conducted in an instrument cavity 140 m below ground at Meadow Bank Rock Salt Mine in Cheshire. The results show that, during the rapid withdrawal of gas from a cavity, the thermal stresses induced in the walls by the resulting change of temperature can be of a magnitude sufficient to fracture the salt. Whilst the experimental cavity showed no serious structural deterioration and continued to accept load and hold pressure, the experience so gained suggests that consideration should be given to the possible consequences of high gas withdrawal rates on the integrity of the wall-rocks of an operational cavity.

A major problem in determining a suitable operating pressure range for a deep storage cavity is the capacity of the salt to flow or "creep" under high deviatoric stresses which, if unchecked, may result in a progressive closure of the cavity and an unacceptable loss of storage volume. Closure may be minimized by determining a lower limit for the gas pressure and by operating the cavity accordingly. A possible approach to quantifying the base pressure is to develop a mathematical model which adequately describes the elastic and creep response of the rock and to apply this model in a numerical simulation of the long-term performance of the storage cavity under various operational conditions. The model may be based on the results of laboratory tests on core from the access wells supplemented by whatever field data is available. The qualitative use of creep test results places very special demands on apparatus. A creep testing facility for salt rocks has been developed at Newcastle University to meet these requirements.

## INTRODUCTION

In the era before much of Britain was converted to natural gas from the North Sea, the traditional gas holder was a familiar sight in every town and city. The manufacture of gas by the carbonization of coal was inherently a slow and inflexible process, ill-suited to meeting the variable demands upon the supply by the customer and his daily and weekly routines. Storage enabled these fluctuations to be reconciled with a more or less steady output from the gas producing plant.

Since the introduction of natural gas, the need for storage has not diminished, on the contrary, the scale of the problem has increased. The Oil Industry, anxious to obtain maximum return on its investment, stipulate that gas should flow inshore at load factors which are generally much higher than those of the average domestic customer. The cost of transmitting gas nationwide is such that it makes sound economic sense to ensure that the flow through pipelines is maintained at a high and steady rate.

Short-term fluctuations in demand may be met by varying the pressure in the supply system (line packing), by the provision of high pressure storage in steel pressure vessels or by use of the existing low pressure holders. The more significant seasonal variations cannot be dealt with by any of the above means. At the present time there are only two ways of economically meeting the winter peak demand, other than by the planned interruption of supplies, firstly by the use of supplementary gases such as L.P.G. or manufactured gas and secondly by the bulk storage of natural gas in its liquid phase or underground in a gaseous state[1].

Worldwide, gas is stored underground in a variety of different ways. Depleted oil and gas fields offer an obvious opportunity for the bulk storage of natural gas, as do aquifers, and all have been used extensively for the purpose particularly on the American continent. Cavities in rock salt, have been demonstrated to be highly suitable for storage. Recently the possibility of employing caverns in hard rock has been examined. Abandoned mine workings, although used for low pressure storage, have been treated with some caution because of the problem of ensuring the gas tightness of the surrounding rock. Lined pressure tunnels have found some limited application. Several other methods have been proposed for underground gas storage, notably, in shafts and large diameter boreholes and in covered surface pits[2].

Other than the frozen ground L.N.G. store at Canvey Island, the only operational underground fuel gas storage in Britain at the present time is in brine well cavities in salt. Several other schemes have reached an advanced stage of planning but have been abandoned for a variety of reasons. Cavity 53 at Seal Sands, east of Billingham, on Teesside was brought into operation in 1959 by the Northern Gas Board. The cavity was formed in a rock salt stratum 35 m thick at a depth of 358 m. With a free volume of 9600 $m^3$ and a storage pressure of 3 MPa, the cavity holds 283,000 s.m.$^3$ of gas. Originally used for town gas, the cavity now stores natural gas[3]. Recently two more cavities were planned for the Seal Sands site and scheduled to provide an additional 363,000 s.$m^3$ of storage[4]. To the best of our knowledge these additional cavities are now in operation. The Northern Gas cavities are unusual because of their diurnal operation. In order to provide storage for peak shaving and seasonal load balancing, British Gas Corporation is currently engaged in the development of solution cavities near Hornsea on the Yorkshire coast. The cavities, each to provide a net storage capacity of 30 million s.$m^3$, are in Permian Zechstein salt at a depth of nearly 1800 m[5].

There are considerable uncertainties in the prediction of the structural response of a cavity, particularly for long periods of time. Thus the mechanical response of the rock to loading is complex, and knowledge of weaknesses and inhomogeneities in the rock formation is limited. In addition the primitive stress field around the projected structure is rarely known with any degree of certainty and must be assumed in most cases. As a result the prediction of performance of a cavity can not be made with the confidence or precision normal for structures in man-made materials.

Whilst we must acknowledge these uncertainties, our predictive capability can be improved in the following ways. Firstly, we can enumerate the problems we might expect to encounter in a given structure. Secondly, we can accurately define and quantify the response to stress of the materials of that structure. Thirdly, we can develop analytical and numerical methods with which to model the performance of the structure and investigate the role of material properties, geometry and the stress field in determining its probable response.

Gas storage cavities in salt present a particular and somewhat demanding rock mechanics problem. They are unlined so the uncertainties cannot be allowed for by conservatively designed artificial support. The "design as you go" philosophy of many mining operations cannot be applied to the problem. Salt is a weak rock and its capacity to flow is almost unparalleled in rock engineering. Its behavior is, as yet, imperfectly understood and the techniques by which we apply our knowledge are still being developed and improved. Finally the storage cavity problem cannot be treated simply as a static problem in terms of the geometry of the opening, the imposed stress field and the material properties, since the dynamics of the cavity operation have an important bearing on its structural performance.

Our main concern in this paper is with the techniques by which we can obtain a better understanding of the response of the materials which enclose a storage cavity. In the first part of the paper we advocate an in situ approach to the problem. In the second part of the paper we show a different problem, the solution for which must be based on a groundwork of laboratory experimentation.

## THE STRUCTURAL PERFORMANCE OF CAVITIES AT SHALLOW AND INTERMEDIATE DEPTH

We distinguish somewhat arbitrarily in this paper between cavities at shallow and intermediate depths and those at great depth. The single most important factor governing the likely response of a storage cavern is the "differential pressure", this being the difference between the geostatic stress and the pressure of the stored product. The pressure of gas in a dry storage cavern fluctuates as the gas is withdrawn and replaced. The extremes of these fluctuations and the rate at which they occur are of the greatest concern. Hence our distinction is based solely on the typical manner in which cavities at shallow and at great depths are operated.

In shallow cavities the primitive stress field is comparatively low. Internal pressure of stored gas will reduce the stress concentrations around a cavity. If the cavity walls are cooled relative to the surrounding rock mass, as could happen during gas withdrawal, additional tensile stresses are induced in the tangential directions. These could be sufficient to lead to resultant tensile stresses and the possibility of tensile failure exists.

The effect of these tensile stresses on the cavity surface, and in particular the thermal components, needs investigating and qualifying. To this end an experimental program was devised.

**Objectives of the experimental program.** The results of an earlier theoretical study[6] indicated that, under certain conditions of low threshold pressure and reduced temperature produced during gas withdrawal, there was a possibility of inducing tensile resultant stresses at the surface of a cavity. Tensile thermal stresses could be critical in developing this condition. In view of the low tensile strength of halite and the extreme variability of its laboratory behavior, there was clearly a need to define the material's response to these loading conditions more accurately in order to allow a more precise appreciation of the likelihood of structural failure and hence to define the operational limits for a cavity. The specific issues that had to be resolved were as follows:

1. Could the generally non-linear time-dependent behavior of rock salt be reasonably approximated at low compressive stresses and in tension by a linear elastic or linear viscoelastic model?
2. If so, what are the values of the elastic parameters or the viscoelastic parameters?
3. Could tensile failure of rock salt occur in a confined rock mass by the action of temperature variations, and if so under what conditions would it occur?

**The design of an in-situ experiment.** In designing an experiment to investigate the uncertainties indicated in the previous section, the first and foremost consideration was whether the response of the material to thermally induced stresses could be adequately reproduced under laboratory conditions. The following issues prompted the decision to conduct the experimental program in situ.

The inhomogeneity of the rock salt in question suggested that large test specimens would be required for the test to be representative of the rock mass. Alternatively, a large number of tests on smaller specimens would be needed to provide statistically valid data. In designing tests it would clearly be advantageous to simulate, as nearly as possible, the likely stress configuration of an operational cavity, that is, a laterally constrained free surface with a small or zero normal compressive stress and a high compressive to tensile component parallel to the surface. This would most satisfactorily be achieved by annular specimens. In order to obtain measurable effects, in terms of diametral deformation such annular specimens would have to be large and necessarily expensive. Finally the effects of thermal variation in situ occur as a distributed loading, varying in space and time, which cannot be satisfactorily simulated by mechanical loading.

In a specially prepared in situ cavern of sufficient size only one "specimen" would be required since the volume of ground effectively under test could be large enough to make small-scale variations in the material insignificant. In addition, pressure and temperature loading capabilities could be provided without undue difficulty, the geostatic loading would already be present and the response of a moderate sized cavity would be large enough to be easily measurable (Fig. 1).

The experiment was envisaged as a materials test with "stress modelling" rather than a complete model test. To facilitate the analysis of results it was necessary to use a cavity with simple symmetrical form. A spherical shape, whilst advantageous on theoretical grounds, was rejected as being difficult to construct. A cylindrical shape was eventually chosen as a compromise. The nature of the available site dictated that this should be horizontal, this direction being preferred for practical reasons.

In determining the optimum diameter for this cavity, the necessity for this to be large enough to allow easy access together with the desire to influence as large a mass of ground as possible were weighed against the practical difficulties of producing a cavity of very large diameter. After consultations with various drilling specialists it was decided

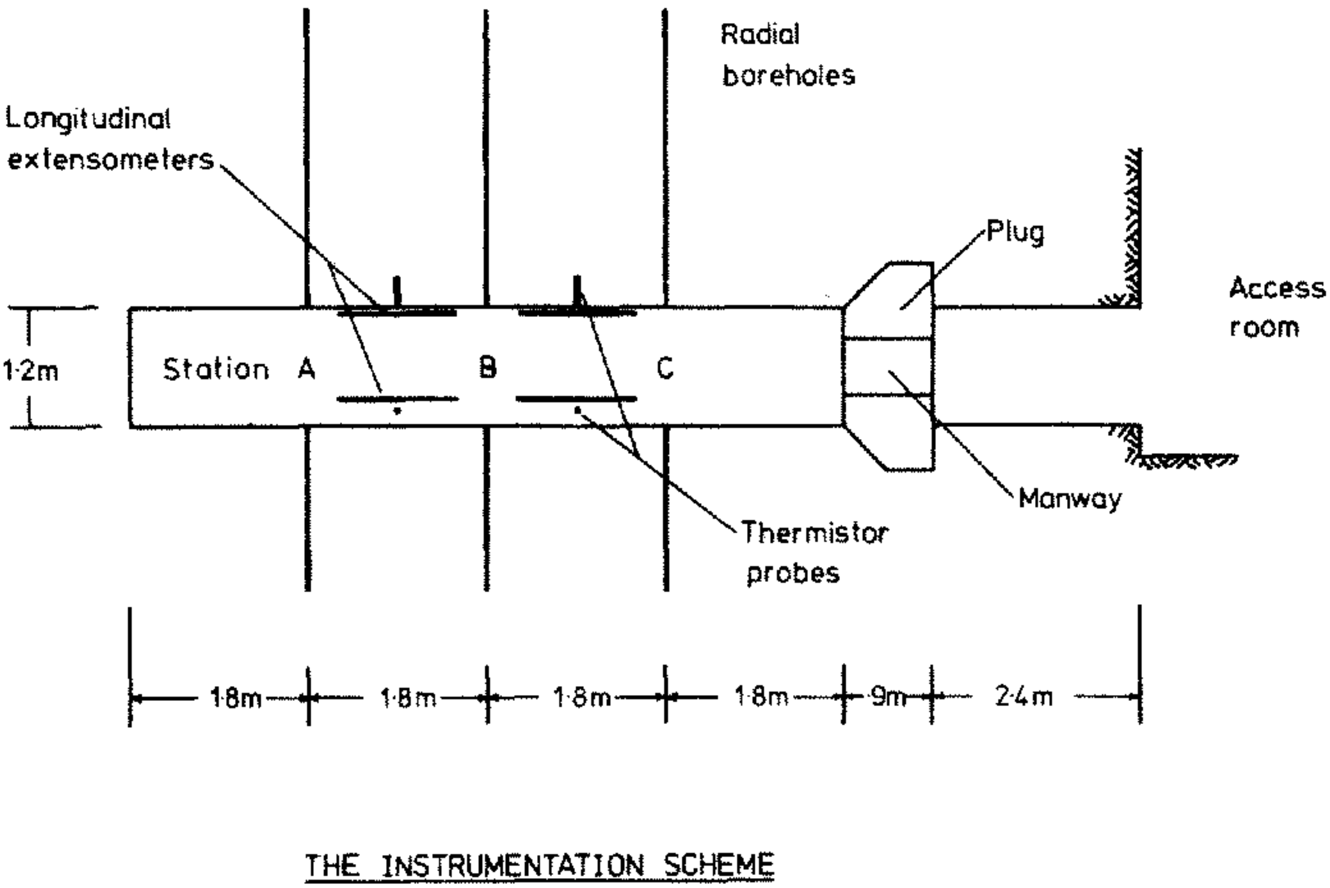


**Figure 1.** Schematic of the experimental cavity.

that a diameter of 1.22 meters was the maximum consistent with the practicalities of production. The working length of the cavity was chosen to eliminate the effects of the ends on the cylindrical stress distribution.

**Design of the loading system.** In determining the loading capability required for the cavity it was necessary to consider the desired effects in terms of the induced stresses. The following points were borne in mind[7].

1. The overall attainable stress range should be as nearly equivalent as was practical to that predicted for an operational cavity.
2. The possible temperature changes in the experiment should be of the same order as those expected in practice.
3. The capability should exist to impose more severe tensile conditions than those implied by the former two criteria.
4. The necessary external constraints and gravitational loading were already present.
5. The value of the primitive stress field was unknown and allowance should be made for an erroneous estimate of its value.
6. The most important zone to be considered was the surface of the cavity, the most important stress being the surface tangential component.

Initially a range of values were assigned to the material properties to predict the probable performance of the cavity. These calculations indicated that, with a temperature variation of ± 15°C on the surface of the cavity, a range of stresses from high tensile to high compressive would be attainable and since this temperature variation is similar to that expected in a shallow operational cavity and could be obtained without too much difficulty, it was retained as the experimental limit[7]. The maximum pressure to be used was dictated by safety, practical limitations and considerations of the required resultant stress field.

**Design of the instrumentation.** In the initial design of this experiment it was assumed that the cylindrical test cavity would react in the same way as an idealized infinitely long cylinder and that an assumption of plane strain would be valid. Although suitable as a design simplification, it seemed probable that neither a plane strain nor a plane stress assumption is strictly applicable in view of the constraint operating. Because of this uncertainty it was decided that deformation in the axial direction should be measured.

In order to determine the depths into the rock mass at which deformation should be measured, it was necessary to evaluate their likely radial distribution. Whilst the deformation due to internal pressure can be readily ascertained, in order to predict the thermally induced displacements an indication of the temperature distribution was required. An analytical relationship derived by Carslaw and Jaeger from numerical results was used in the preliminary study[8].

This study indicated that the most significant part of the deformation field would lie within 1.8 meters while the stress distributions showed that at a radius of 3.7 meters the stress effect of the combined loading would be small. These considerations plus the extreme difficulty of drilling excessively long boreholes from a confined working space and the desirability of not distorting the stress field around the cavity by inordinately large diameter boreholes were instrumental in determining the final layout of the deformation measuring system[7].

The deformation relative to the surface even under the maximum internal pressure of 1.38 MPa were expected to be as small as $2.5 \times 10^{-2}$ mm. It was clearly necessary to select sensitive yet robust measuring instruments. Linear Variable Differential Transformers (L.V.D.T.'s) of the D.C. type with a range of ± 12.7 mm and a voltage sensitivity of approximately 0.16 Volts/mm were chosen for the purpose.

## DESCRIPTION OF THE IN-SITU EXPERIMENT

**The experimental site.** A site was made available for this experimental cavity by Imperial Chemical Industries Ltd., Mond Division, at their Meadow Bank Rock Salt Mine at Winsford in Cheshire. The selected location was at the end of a blind roadway driven in the Hundred Foot Salt of the lower Keuper Saliferous Beds, 140 meters below the surface. A T-shaped access room was opened out at a level of 4.5 meters above the floor of the mine, approached by a 1 in 17 ramp.

Two experimental cavities were produced, one for testing, the other as a standby in case of premature failure of the first. The 1.22 meter diameter holes were drilled by an auger boring machine following a 150 mm pilot hole. The cavity which was subsequently used was bored with a variation of 16 mm of the diameter and a maximum eccentricity of 13 mm. The cavity was a total length of 10.6 meters, 7.3 meters of this length being required for the test chamber and 0.9 meters for a pressure retaining plug situated 2.4 meters from the mouth[9] (Fig. 2).

**The loading system.** Pressures of up to 1.38 MPa were used in the experiment, these being contained by an 0.9 meter thick concrete plug keyed into the cavity walls. The plug was a concrete annulus embedded into the salt to a depth of 0.46 meters with a 45° taper to effect a seal against the salt face. A steel-lined manhole of 0.6 meters diameter provided access to the cavity and was sealed during pressure tests by a 25 mm thick door.

Air pressure was provided by a reciprocating compressor capable of delivering 1.4 MPa at a delivery rate of 3.54 standard m³/minute (Fig. 3). Air from the compressor was cooled by an after cooler to 8°C above ambient and dried to a dew point of −40°C in a dessicant drier, before being stored in an 0.3 m³ air receiver. Control of cavity pressure was achieved by a reducing valve in the 75 mm air main between the receiver and the cavity. Depressurization was regulated by a blow-off valve in the air main. Cavity pressure was monitored by a pair of strain-gauged pressure transducers.

**The temperature system.** Surface rock temperatures were varied by circulating hot or cold ethylene glycol solution through a 75 mm diameter copper pipe heat exchanger coil set close to the cavity surface. Convection effects within the cavity were reduced by two axial flow fans set at

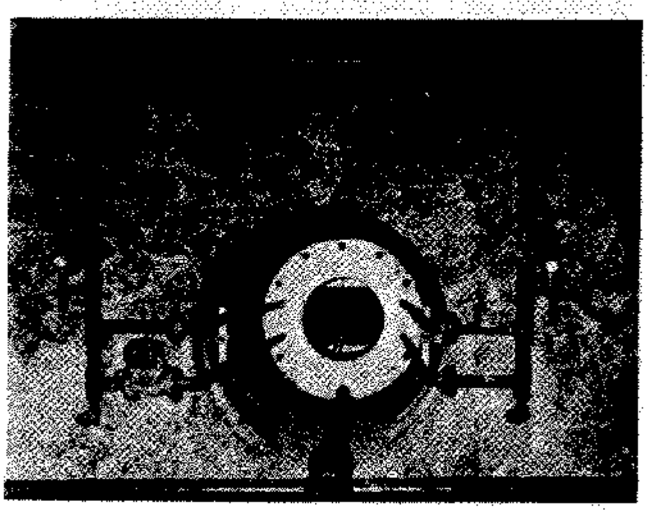

**Figure 2.** External view of the experimental cavity showing the pressure-retaining plug, manhole and pipework.

**Figure 3.** Air compressor (right) and glycol solution heater/chiller unit (left).

either end. The glycol solution was heated by a 3 kW immersion heater and cooled by a chiller unit.

Temperature control was achieved by a motorized mixing valve between the hot and cold glycol supplies. The control temperature was based on the average output of 9 Platinum Resistance Thermometers cemented to different areas of the cavity surface.

## THE INSTRUMENTATION

**The measurement of deformations.** The deformation of the cavity surface and that within the surrounding rock was measured at three measuring stations along the length of the cavity, one central (B) and one at either side. The end stations were situated at a distance of three times the cavity radius from the plug (C) and from the blind end (A). At each station measurements were made in three radial directions, vertical (V), 120° clockwise (R) and 120° anticlockwise (L).

The deformation profile in the walls of the cavity was determined using instrumented boreholes 3.05 meters in length. Four anchors were set in each borehole at radial distances of 0.84, 1.22, 1.83 and 3.66 meters from the cavity centerline. The anchors which were designed for the experiment comprised a 3.175 mm thick split ring tightened against the borehole walls by a stainless steel cone bolted into a housing as shown in Figure 4. Their small area of contact with the rock enabled the points of measurement to be accurately determined. At the borehole mouths, a cluster of four L.V.D.T's were mounted in a stainless steel cage incorporating adjustment screws. The cage was secured by a curved cover plate cemented to the cavity surface. In order to avoid pressurization of the boreholes, the cover plates were of a sufficient size to ensure a reasonable seal. The transducer cores were connected by spring-tensioned 6.4 mm diameter Invar rods to the anchors, the rods for the more distant anchors passing through the nearer ones.

Diametral deformation of the cavity was determined using nine extensometers arranged along the same line as the boreholes as shown in Figure 5. These extensometers comprised 9.5 mm diameter Invar rods supported by P.T.F.E. bushes in an aluminum alloy tubular casing. The spring-loaded instrument was held by force between the appropriate borehole cover plate and a stainless steel mounting pad on the rock surface. The rod movement was sensed by an L.V.D.T. mounted inside the tubular casing of the extensometer.

Instruments of the same design were used to monitor axial strain in the cavity wall rock. These measurements were made in two 1.22 meter bays between the radial stations. The six axial extensometers were mounted between stainless steel pegs cemented into the cavity surface.

**The measurement of rock temperature.** The temperature field in the salt surrounding the cavity was monitored

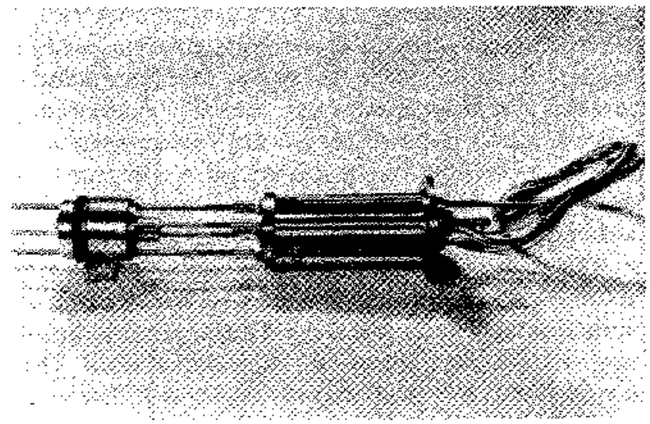

**Figure 4.** Borehole deformation measuring system showing a single anchor and a cluster of transducers.

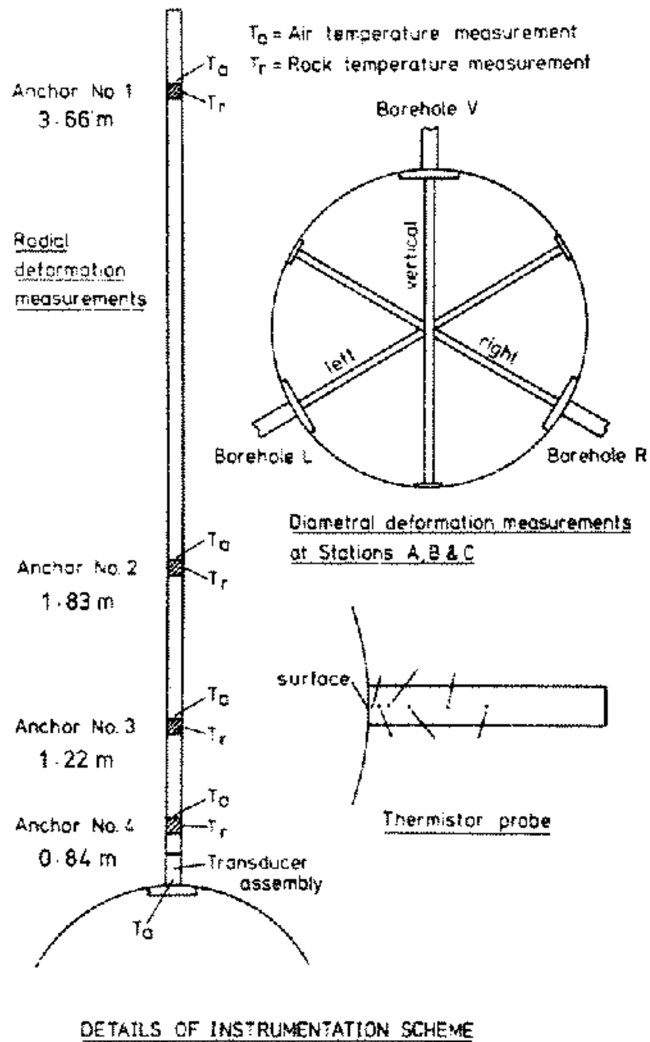


**Figure 5.** The cavity instrumentation showing the positioning of the borehole anchors and the extensometers and the rock temperature measuring arrangements.

using miniature precision thermistors. A total of 45 sensors were employed in the deformation measurement boreholes, one held against the rock surface at each of the anchors and one mounted on each of the borehole cover plates. An additional 42 sensors were employed to provide detailed information on the temperature gradient near the cavity surface. These were incorporated in prepared salt cores of 305 mm length which were cemented into short 51 mm diameter boreholes using a mixture of epoxy resin and powdered salt. These boreholes, 6 in number, were aligned parallel to the deformation monitoring boreholes at points midway between the stations.

In order to allow correction for the thermal expansion or contraction of the components of the deformation measuring system, a further 54 sensors were mounted on the borehole anchors and the extensometers.

**Photographic recording.** In order to detect surface fracturing, provisions were made to photograph selected areas of the cavity wall. This was achieved using a pair of remote controlled cameras mounted so as to rotate about the cavity axis and automatically position themselves opposite the 12 spaces between the heat exchanger pipes. Each revolution was started either manually or automatically by an electric timer (Fig. 6).

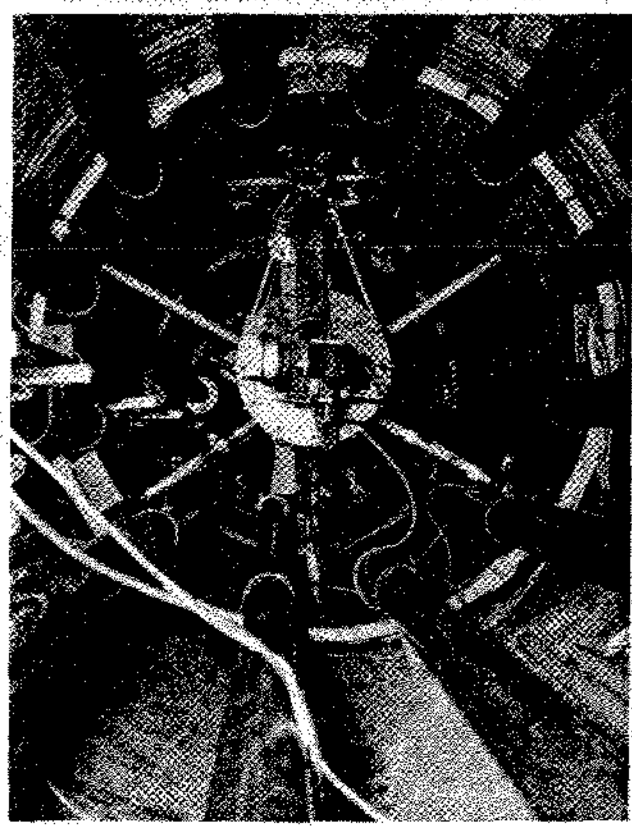

**Figure 6.** Internal view of the cavity showing the heat-exchanger pipes, the diametral extensometers and one of the remote-controlled cameras.

## THE DATA LOGGING SYSTEM

The final instrumentation scheme included 54 L.V.D.T.'s and 138 thermistors which were to be monitored during a test. A data logger with facilities for programmed sequential monitoring of up to 100 voltage and 200 resistance measurements at speeds of up to 10 channels per second was employed for this purpose. All data were recorded on paper tape awaiting computer analysis. A chart recorder was used to provide an instant check on critical items such as movement of the pressure retaining plug, cavity pressure and surface temperature.

**Brief summary of the test program.** Over an 18 month period from the commissioning of the cavity in May 1973, a total of 39 tests were performed. The duration of these tests ranged from about 3 hours up to about 400 hours. The tests fall into two categories, pressure tests and imposed temperature tests, the latter at above and below ambient rock temperature.

The pressure tests, which were carried out at both ambient and elevated temperatures, were conducted to investigate the effects of mechanical loading on the cavity. They also allowed the in situ Shear Modulus to be determined. Pressure was applied to the cavity at a rate judged to be low enough to avoid adiabatic heating. In practice, the pressurization rates ranged from less than 7kPa/minute up to 35kPa/minute. In most of the tests, after reaching the scheduled maximum pressure, the cavity was immediately depressurized at a controlled rate. In four tests the maximum pressure was held steady for between 16 and 200 hours. These extended tests were conducted to investigate the time-dependent response of the salt.

Temperature tests were peformed by heating or cooling the cavity surface at a predetermined rate. Difficulties were encountered when the cavity temperature was changed too rapidly. For practical reasons the temperature distribution around the cavity became asymmetric. In addition the penetration of the temperature field resulting from rapid heating or cooling was too small to give meaningful results. The rate of change of cavity surface temperature in successful tests ranged from approximately 0.2 to 2°C/hour.

**Analysis of data.** With the large amount of data to be handled in any test, in excess of 20,000 data items being common, computer based data handling and analysis was essential. A suite of Fortran IV programs were written specifically for the project[7].

It is beyond the scope of this paper to describe the reduction of data in anything but a grossly simplified manner. Briefly, the plane strain solution for the radial deformation of a hollow cylinder with infinite outer radius and under internal pressure is given by:

$$U = \frac{1 + \nu}{E} \cdot \frac{a^2}{r} \cdot q$$

Where q is the internal pressure, a is the internal radius, E is the Elastic Modulus and $\nu$ is Poisson's Ratio.

Therefore, the Shear Modulus can be obtained by regressing the radial deformation of the cavity against q/r.

The radial displacement caused by an imposed temperature field is given by[10]:

$$U = \frac{1+\nu}{1-\nu} \cdot \frac{\alpha}{r} \int_a^r T\, r\, dr$$

Where $\alpha$ is the Coefficient of Linear Expansion and T is the temperature, which is a function of radial distance r.

Temperature induced deformations were plotted against the integral $\frac{1}{r} \int_a^r T\, r\, dr$, which has been denoted by I(r) in the figures. The integral was evaluated using the radial temperature distribution given by the thermistors. Clearly, the regression line of U against I(r) has the slope $\frac{1+\nu}{1-\nu}\alpha$. Provided that $\alpha$ is known, then the Poisson's Ratio may be determined.

**Experimental results.** All the short-term pressure tests showed good agreement with the elastic response, with a marked linearity between radial deformation and pressure and with an absence of permanent set or separation of the loading and unloading curves. A typical result is shown in Figure 7.

In all the pressure tests the results from the borehole anchors were less consistent than those from the diametral extensometers. The main reason for this was that, at increasing radial distance from the cavity, the magnitude of the measured deformations approached the limit of resolution of the instrumentation.

Three long-term tests with internal pressure of approximately 1.38 MPa showed a departure from linear elasticity. Figure 8 is typical and shows a distinct permanent set. A fourth long-term test at approximately 0.69 MPa did not exhibit permanent set.

In the above ambient temperature tests, the inelastic response of the cavity was more apparent at higher imposed temperatures. For example, for an imposed temperature of +2°C (Fig. 9), anchors at all radii showed a predominantly elastic response as seen in Figure 10, for an imposed temperature of +5°C the three anchors furthest from the cavity displayed elastic behavior but the near surface anchor and the corresponding extensometer exhibited non-linearity of the loading curves, a separation of the loading and unloading curves and a permanent set. The more severe tests at +10°C and +15°C showed the effects of inelastic deformation to a much greater extent.

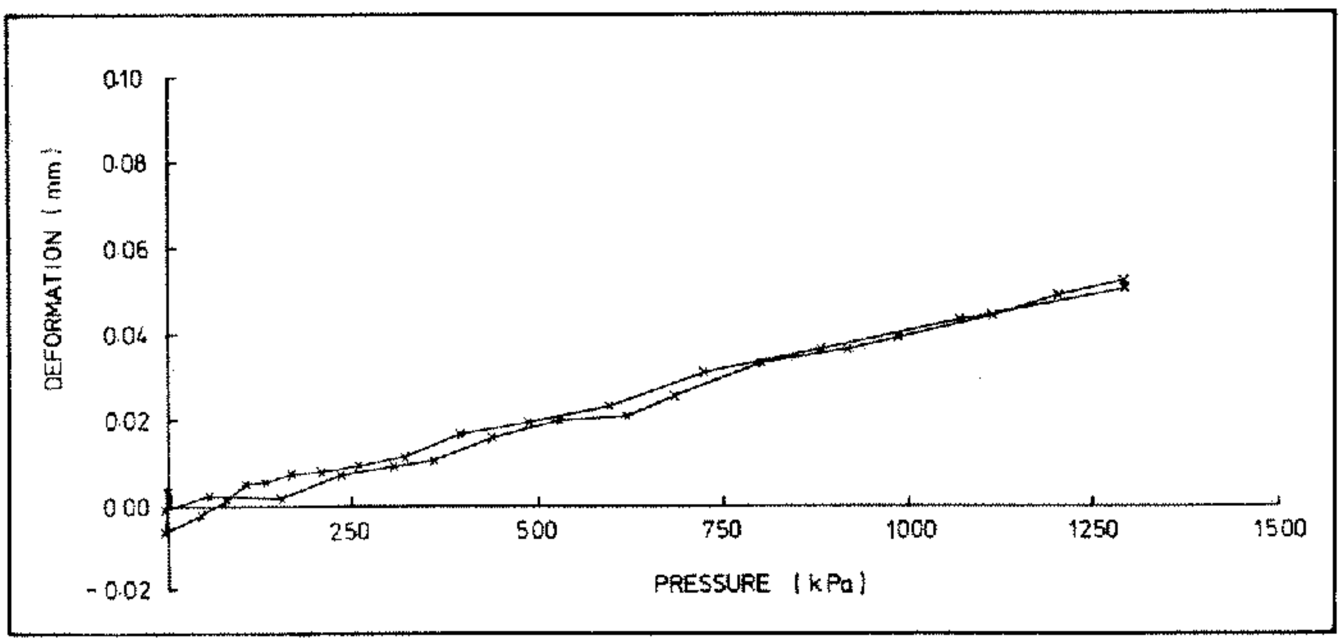


**Figure 7.** Test 22.5, internal pressure = 1290 kPa, ΔT = 0°C. Diametral deformation vs pressure-overall mean.

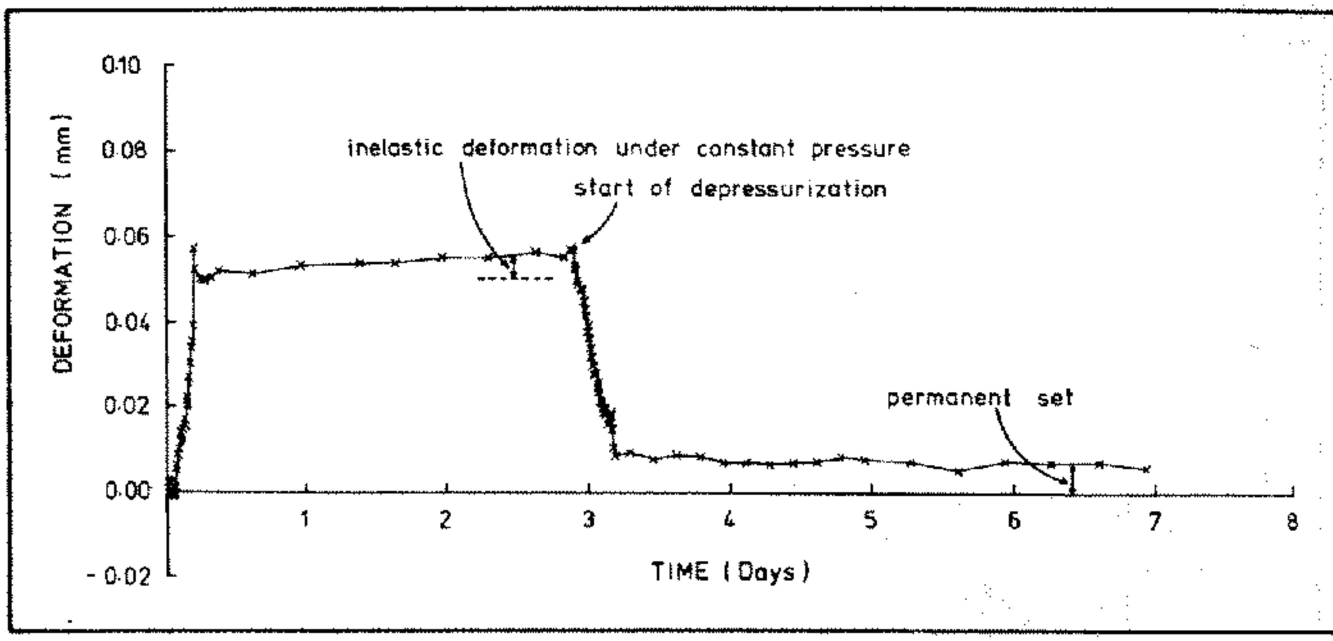


**Figure 8.** Test 7, internal pressure = 1350 kPa, ΔT = 0°C. Diametral deformation vs time-overall mean.

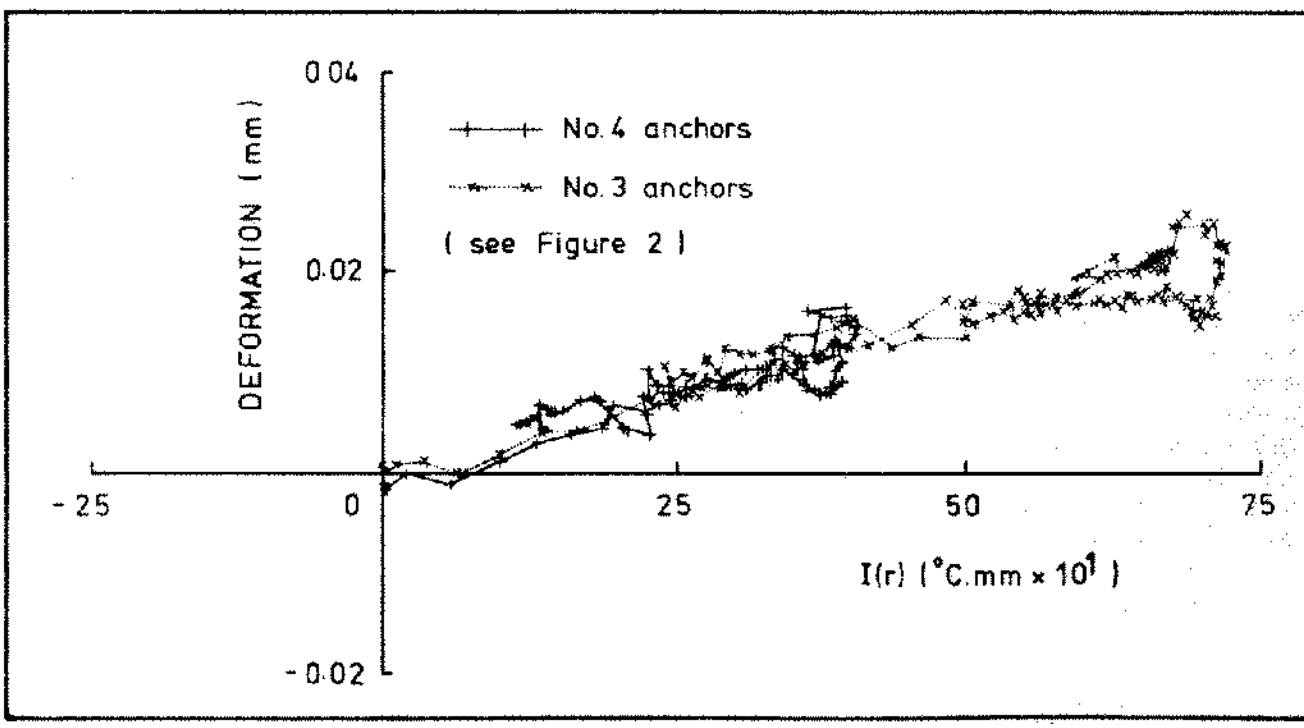


**Figure 9.** Test 21, internal pressure = 1390 kPa, ΔT = +2°C. Anchor movement relative to surface vs I(r)-overall means.

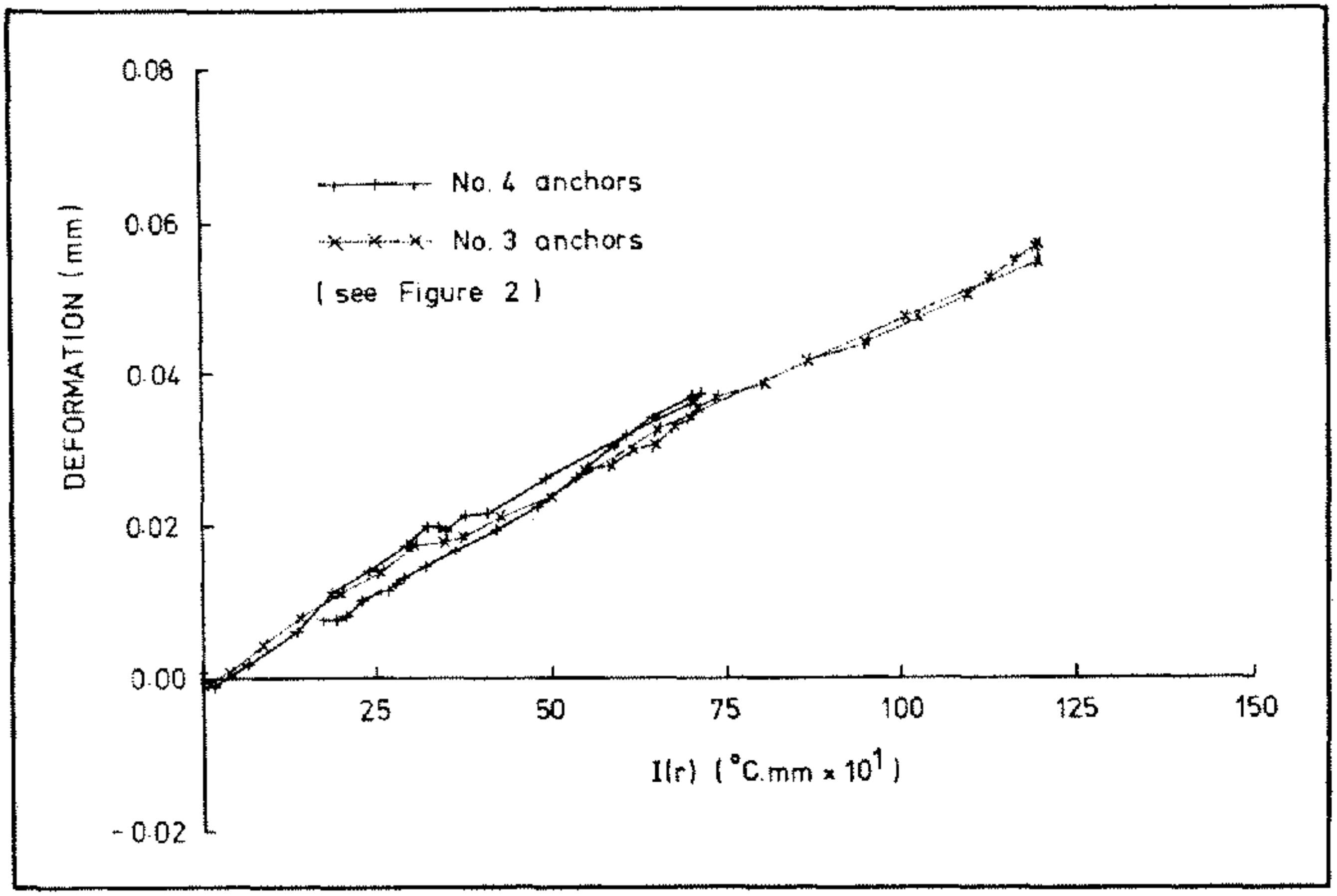


**Figure 10.** Test 10, internal pressure = 0 kPa, ΔT = +5°C. Anchor movement relative to surface vs I(r)-overall means.

The below ambient temperature tests are, perhaps, the most interesting in terms of the gas storage problems. When temperature changes of −5°C were imposed on the cavity, the response was largely elastic. The tensile stress levels associated with an imposed −10° and −14°C temperature change resulted in a response which can be attributed to the development of microfractures in the near surface rock. This localized microfracturing appears to have resulted in dilatancy or "bulking" of the salt in this zone. In a subsequent test, the repeated application of a temperature of +10°C induced high compressive stresses in the near surface salt which seemed to diminish the effect of the previous tensile history (Fig. 11).

The results which are of the most general interest are the in situ measured values for the elastic constants of Cheshire rock salt. The Poisson's Ratio was found to vary with stress, the most distinct differences being between the compressive and tensile stress states. The mean value in the compressive region was 0.21 ± 0.11 and in the tensile

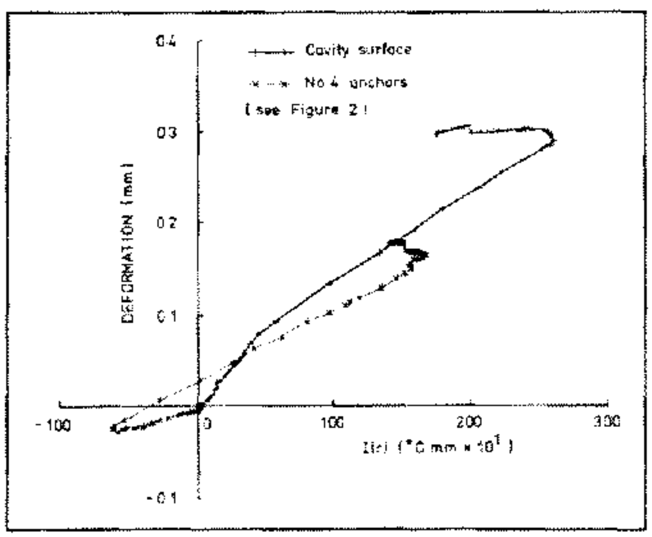


**Figure 11.** Test 5, internal pressure = 0 kPa, ΔT = +10°C. Anchor movement relative to surface vs I(r)-overall means.

region was 0.05 ± 0.16. These values have been based on a laboratory determined Coefficient of Linear Expansion of $2.6 \times 10^{-5}$°C$^{-1}$. The Shear Modulus was determined from the pressure tests at 15.2 GPa ± 20%, giving a value for the Elastic Modulus in compression of 36.5 GPa ± 30%.

This Elastic Modulus is higher than most laboratory determined values. This variation may, in part, be due to the different behavior of the rock in the in situ environment but, more probably, it is caused by the generally higher stress conditions used in the laboratory tests, and the consequent unavoidable incorporation of primary creep deformation in the elastic movement.

## THE STRUCTURAL PERFORMANCE OF DEEP STORAGE CAVITIES

Deep cavities in salt offer greater potential for gas storage than those at shallow depth since the massive overburden permits much higher maximum storage pressures. In practice, this maximum pressure is determined by the strength of the well casing and cementation. In most storage operations this pressure is between 50% and 70% of the geostatic stress at the cavity depth. For preliminary design purposes the vertical geostatic stress may be taken as 22.6 kPa per meter depth. The maximum allowable storage pressure therefore ranges from 11 to 16 kPa per meter below the surface.

The useful storage capacity of a cavity is a function of the free volume of the opening, the difference between the maximum and minimum storage pressure and the compressibility of the gas under cavern conditions. Since the maximum allowable pressure is largely predetermined by the well casing and the operator of the cavity has no control over the gas compressibility, the only scope for optimizing the useful storage capacity of a particular installation is to set the minimum gas pressure as low as possible.

Whilst the internal pressure in shallow cavities may occasionally be reduced to near atmospheric without ill-effect, for cavities situated below about 750 meters consideration must be given to the effect of depressurization on the wall-rocks. The source of primary concern is the flow or creep response of the salt, although other issues such as surface spalling, creep rupture and damage to the overlying strata should be carefully evaluated.

**Creep closure of a cavity.** Most rocks when stressed to near their ultimate strength in compression continue to deform with time after the application of load. In the evaporitic rocks, especially those containing halite or sylvine, time-dependent deformation is pronounced even at comparatively low stress levels. At high stress levels this flow or creep becomes a dominant feature of the mechanical behavior of salt rocks. The creep of salt is a response to applied shear stress. Under a hydrostatic state of stress, that is, one in which no shear stress is engendered in the material, no significant creep can occur, although the application of stress will cause a change in volume.

When the internal pressure in a storage cavity is reduced, the shear stresses in the walls rise accordingly. This increase in the shear or deviatoric stresses in the rock mass causes the material to flow inward into the cavity. The rate of inward flow will be at a maximum during and immediately following the reduction in pressure and thereafter will decay somewhat with time. The exact manner in which the creep deformation rates decay is a matter of great concern and, indeed, of controversy.

If the fall in gas pressure in a deep storage cavity is too severe then the resulting inward flow of the walls of the cavity may be unacceptably large. Because we are dealing with a time-dependent characteristic it is evident that the critical factor governing the closure is not simply the magnitude of the reduction in pressure but also the period of time over which this condition is maintained. Most cavities providing seasonal storage will be at minimum gas pressure each year towards the end of the winter months. If the base pressure is set too low the cumulative closure over a number of years may result in a serious loss of storage capacity.

**Rupture, creep rupture and spalling.** In the earlier sections of this paper considerable emphasis was placed on the operating conditions likely to produce resultant tensile stresses in the wall-rocks of a cavity. The occurrence of tensile stresses in materials which are inherently weak in tension must inevitably be a source of concern. In the case of a deep storage cavity, the possibility of tensile stresses being developed at a point in the normal storage pressure cycle will depend largely on the primitive stress field of the salt formation and the shape of the opening. If, for example, the lateral rock stress around a particular cavity greatly exceeds the vertical stress, as might be the case in a tectonically active salt dome, then zones of tension could well be produced in the walls of that cavity.

In practice the low flow limits of salt lead us to assume, unless there are strong contraindications, that an approximately hydrostatic condition of stress exists in a deep salt formation prior to the excavation of a cavity. Under such a condition the wall-rocks of cavities operated with the normally accepted maximum pressure will be in a state of compression.

The strength of salt under short duration compressional loading has been systematically investigated using the Karman or triaxial cell[11,12]. In an unconfined test, salt exhibits brittle fracture after fairly small inelastic deformation. At low confining pressures the material may endure considerable inelastic deformation but ultimately fails along multiple intersecting "slip planes" or by a general fragmentation. Under conditions of high confining pressure the salt may be distorted indefinitely with no apparent loss of integrity.

The Mohr Envelope of Failure can only be usefully applied to the triaxial response at zero or low confining pressures, that is, for those conditions under which rupture of the specimen can be reasonably defined. At high confining pressure the envelope must be somewhat arbitrarily constructed for points of equal inelastic strain. Despite this difficulty, the Mohr Envelope for salt from most localities shows a broadly similar pattern, namely, a fairly high initial angle of internal friction which progressively decreases with increasing confining pressure. At high confining pressures the angle of internal friction may be low, and, in some cases, even zero.

This behavior may be interpreted in terms of a brittle to ductile transition. In the unconfined, state cracks can readily be formed and can propagate and coalesce to rupture the material. Under high confinement the normal stress acting on incipient fractures inhibits their propagation whilst the large shear stress induces rapid creep deformation. In this condition the stress borne by the material ceases to be an indication of its strength but is more one of its viscosity and state of strain hardening. It is currently believed that the creep response, at least under high confining pressure, is determined by either the deviatoric or the octahedral shear stress in the material. This could adequately explain the very low angle of internal friction exhibited by salt under high confinement.

At the present time only qualitative suppositions can be expressed on the manner in which these short-term strength characteristics might influence the structural integrity of a deep storage cavity. The condition of the wall-rocks remote from the surface approximates to that of the high confinement triaxial test. It seems probable that salt in this position can suffer massive deformation without fracture. It is more difficult to predict the behavior of salt near the cavity surface. A "skin" of material around the opening will have been penetrated by brine during cavity washing. This must enhance the ductility of the salt in this region[13]. Evidence from the Mohr Envelope would suggest that, provided the internal gas pressure is consistently greater than the confining pressure at the brittle to ductile transition in salt, then creep is more likely to occur than short-term rupture.

Creep rupture under a multiaxial state of stress presents a very taxing problem. Tests on essentially brittle rocks suggest that for an increase in confinement from zero to 69 MPa the time to failure for a fixed shear stress increases by many orders of magnitude[14]. Salt under high confinement has a capacity to "heal" any discontinuities which may be produced during deformation, particularly if small amounts of moisture are present. This is evidenced by the manner in which powdered salt can be consolidated by the application of confining pressure.

Evidently the critical areas around a deep storage cavity, in terms of possible creep rupture, are those areas which endure the maximum strain under the minimum confinement. This suggests the rock immediately adjacent to the surface cavity. It has been proposed that excessive tensile strain might induce fracture in this zone[15]. The consequence that was envisaged was a general spalling of the surface.

**Damage to overlying strata by stress redistribution.** As was previously noted the creep response of salt under the conditions which pertain around a deep storage cavity shows a markedly non-linear dependence on stress deviator. This non-linearity may be incorporated in a creep model in a number of different ways using empirical creep equations[16,17], step-wise non-linear rheological models[18] or rheological models with stress-dependent parameters[19].

Non-linear models have one thing in common, they predict stress redistribution around a cavity. Initially the peak tangential and peak deviatoric stresses are situated close to the cavity surface. The salt in this area responds to the high deviatoric stress by very rapid creep. This causes the peak tangential stress to move away from the cavity surface. The volume of rock influenced by the creation of the opening becomes progressively larger until eventually a "steady-state" condition is achieved. In this condition the stress distribution remains constant with time but the cavity may continue to close. Whilst the dynamic effects of stress redistribution can only be quantitatively investigated using numerical stress analysis techniques[20], the steady-state condition around openings of simple geometry can be predicted analytically[21].

The main consequence of stress redistribution is that shear stresses may be imposed on rock formations which lie some distances above or below the cavity. In establishing the operating conditions for a cavity these stresses should be evaluated and the possibility of rupture of the formations assessed.

**The determination of cavity base pressure.** From the preceding sections it is apparent that the minimum allowable gas pressure in any deep storage cavity must be determined by carefully weighing the need to maximize usable storage volume against the possible consequences of creep closure and damage to the cavity walls and surrounding rock formations.

Some guidance in this task is available from the operational experience gained by others. Numerous storage cavities are in use throughout the world. Most of these successfully perform the duty for which they were intended. A small number have shown problems, most of which can be associated with excessive depressurization. Unfortunately, the freely available data on base pressures are, at the present time, insufficient to draw firm conclusions as to what is acceptable and what is unacceptable. Inevitably the factors which influence the performance of a cavity, such as size, shape, depth, the geological structure of the formation and the mechanical characteristics of the wall-rocks, will vary from one location to another. It therefore proves advisable to examine the particular circumstances of a proposed storage cavity in detail.

One possible approach to quantifying the base pressure is to simulate the response of the cavity using finite element techniques employing a digital computer. Numerical methods are sufficiently well developed to model a reasonable approximation to cavity geometry, stratified rock and gravitational loading using elasto-plastic and simple non-linear creep descriptions.

The major difficulty associated with the finite element method in rock engineering is the provision of material properties which adequately describe the response of the rock in situ. This is particularly true for salt rocks which show such conspicuous time-dependent deformation. For the problem in hand, the fundamental material properties must be defined from laboratory tests on samples of core taken from the access wells. The desirability of checking the predicted response against in situ data from "pumping out" tests on the cavity or closure measurements in shafts or mine workings which penetrate the formation is evident.

**The design of a laboratory test program.** It is our firm conviction that the response of a deep storage cavity should be simulated using a non-linear time-dependent description of the creep behavior of salt rocks. Whilst elasto-plastic analyses provide a useful qualitative indication of the effects of stress redistribution around a cavity, the somewhat arbitrary manner in which the yield point must be defined provides a major source of uncertainty. Time is the essential factor in the behavior of salt rocks and rate of closure is the essential factor in predicting useful cavity life.

The only effective laboratory test for determining creep response over extended periods of time is the long-term creep test. Alternatives to the creep test may provide useful short-term information on the inelastic behavior of salt, but this cannot be extrapolated in a satisfactory manner. Creep testing is necessarily a time-consuming and tedious procedure. In general, the longer the tests are, the better will be the predictions of the creep model.

In order to use creep test data in a quantitative manner a number of fundamental questions arise. The main issues that have influenced the design of the test program at Newcastle are discussed below.

**Test temperature.** The creep of rock salt is a temperature dependent process. It is therefore important that the tests should be conducted at the down-hole rock temperature. An isothermal rock condition is assumed in the present study.

**Relative humidity of the atmosphere.** The creep response of laboratory test specimens varies considerably with changes in the relative humidity of the atmosphere. This poses the very difficult problem of what atmospheric humidity produces a specimen moisture content equal to that of the salt in situ. Our approach to the problem has been firstly to qualitatively investigate the influence of moisture on the creep response and secondly to review published data on the moisture content and permeability of deeply buried salt formations.

Our conclusions are that at above 75% R.H. at 60°C the influence of humidity on the creep behavior is dramatic and is accompanied by solution of the surface of the test specimens. The figure of 75% R.H. corresponds with the partial vapor pressure of saturated brine and is almost independent of temperature in the range under consideration[22]. Tests at approximately 42% and 13% R.H. have shown that the influence of humidity on the creep response in this range is still apparent but no solution takes place. The influence at low humidity is largely confined to the initial stages of the creep curve[13].

A number of studies have been made elsewhere on the permeability of rock salt[23,24]. Under conditions of high confinement the general conclusion is that salt is effectively impermeable. From this we surmise that, provided the salt around a cavity is fairly homogeneous, the penetration of brine during solution-mining will be restricted to a zone of disturbed salt near the surface.

It is not possible to assess the in situ moisture content of the salt formation from cores, by virtue of the manner in which the wells were drilled, that is, using a brine flush. Although it is difficult to generalize, the moisture content of a deeply buried, thick horizon of salt is probably very low. Inclusions of connate brine are unlikely to be influenced by moderate temperatures during testing.

After careful consideration of all these factors we concluded that the moisture introduced during drilling, transport and storage of the core should be removed by "preconditioning" in a low humidity environment and that testing should be conducted under low humidity conditions.

**Influence of the mean normal stress.** The published evidence for the influence of mean normal stress on the creep response was regarded as insufficiently conclusive for the purpose of design. It was therefore included as a parameter in the test program. Uniaxial and triaxial tests were scheduled, the latter at two levels of confining pressure. Uniaxial testing has recently been abandoned.

**Influence of deviatoric stress—non-linearity.** The precise description of the non-linear effect of deviatoric stress on the creep respone of salt assumes great importance for it largely determines the pattern of stress redistribution around a cavity. We chose to test at six levels of deviator typical of the conditions in the cavity wall-rock.

**Material variability—number of tests.** If core is taken from a vertical borehole through bedded salt the varying petrology of the material will produce considerable scatter in the measured mechanical properties. The number of tests that can reasonably be performed must be a compromise between the number of rigs, the duration of each creep test, and the total time of the test program. We concluded that a battery of uniaxial and triaxial rigs would be required enabling multiple simultaneous tests to be performed.

**Instrumentation.** Although desirable, stress control of a large number of test rigs was ruled out because of the staggering cost of a servo-controlled system. We opted for the more usual load-controlled creep test and have to be content with the imprecisions of engineering stress and strain. The effects are only significant at high levels of deviatoric stress.

Volumetric behavior and "platen-effects" are considered important. We have shown that high-yield strain gauges carefully applied to dry salt will perform satisfactorily and can provide useful information on these two issues. The test apparatus has been designed accordingly.

Conventional resistance strain gauges are, however, of little use in monitoring the large strains experienced by salt at high deviatoric stresses and in such circumstances calculation of strains from displacement measurements proves advisable. Ideally, to avoid end-effects, displacement measurements should be made over a gauge-length straddling the centerline of the specimen. Difficulties of specimen jacketing and the high cost of instrumenting a "bulk-testing" facility precluded such sophistication. In order to provide conformity, platen to platen displacement measurement has been adopted in both uniaxial and triaxial testing.

The unpleasant temperature of the test atmosphere, the large number of tests coupled with the use of multiple strain gauges and transducers and the extended time span of the project prompted the adoption of a remote monitoring and logging system.

**Other considerations.** The creep response of a material is incompletely defined by tests at a single load. The effects of strain history are paramount in salt rocks. Whilst acknowledging the major theoretical and experimental problems associated with "history effects" we decided to include a number of step-load tests in the program. The unloading behavior of salt is important not only in predicting the response of a cavity to cyclically varying pressures, but also in testing the appropriateness of a particular rheological model. We concluded that unloading behavior should be studied in some detail.

**The development of a creep testing facility.** In order to provide a suitable testing environment, a firm of heating and ventilation engineers were commissioned to design and construct an insulated air-conditioned chamber. This chamber, which is approximately 5 m × 1.5 m and 2.1 m high, houses a 7kW forced-air heater. Air is ducted to this heater from an external chemical dehumidifier and pre-chiller unit. The temperature and humidity are thermistor controlled. The air is maintained at the down-hole rock temperature, which for the problem under consideration is 57°C, and at less than 5% Relative Humidity. The chamber, which is metal clad, vapor-sealed and equipped with a heavy sliding door, has been constructed inside an insulated room which contains the pressure control and monitoring equipment.

**Development of uniaxial creep rigs.** The main criteria in the development of the uniaxial rigs were that they should enable constant and easily determined loads to be applied to the specimens, should be sufficiently robust for their duty and should be of a construction that could be readily "mass-produced" at reasonable unit cost in our department workshops. We opted for the very simple yet effective design shown in Figure 12. The reaction to the hollow hydraulic ram is provided by the machined tubular body of the rig. The hollow ram enables axial deformation to be determined by a single measurement along the specimen centerline.

**Development of triaxial creep cells.** After a number of preliminary tests on several existing designs of triaxial cell we concluded that the high frictional restraint and associated "stick-slip" of the hydraulic packings would be unacceptable for the quantitative study in hand. We therefore embarked on the somewhat awesome task of designing and manufacturing triaxial cells to meet the particular requirements of the test program.

The triaxial creep cell, shown in Figure 13, consists of five basic components, the cylindrical cell body, a hollow hydraulic ram threaded into the cylinder, a plunger which transmits thrust to the platen, a collar housing the main

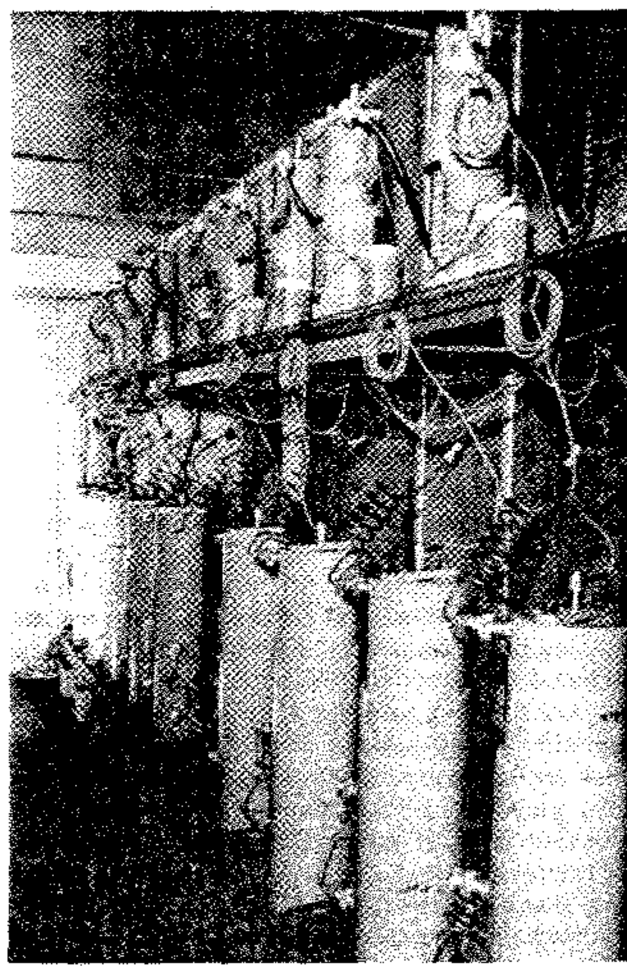

**Figure 12.** Internal view of the heated test chamber showing the uniaxial creep rigs (at top) and the battery of triaxial cells (below).

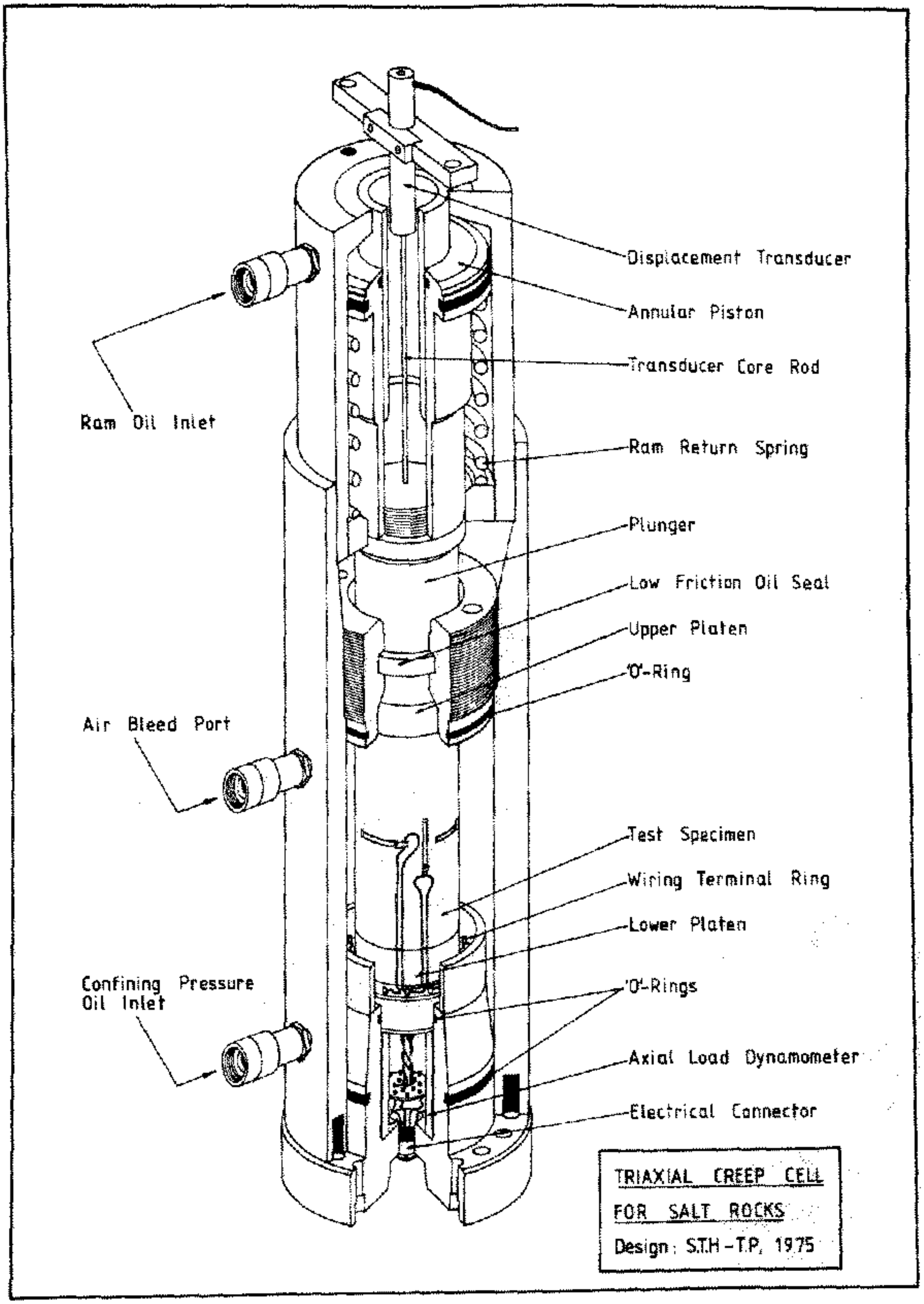


**Figure 13.** The Newcastle triaxial creep cell is self-contained and incorporates an axial load dynamometer and strain gauging facilities.

oil-seal and a removable base-assembly. The cell is unusual in that the reaction to the axial load is carried by the cell body. This eliminates the need for a heavy H-section frame.

The cylindrical cell body is threaded to accept the hydraulic ram. The ram is 550kN capacity and is spring-loaded. The plunger, which is case-hardened, is threaded into the ram. A conical recess on its lower surface accepts a boss on the upper platen providing for positive centering of the test specimen.

The bearing-surface of the cell collar on the sliding plunger is deliberately restricted to avoid metal to metal binding at this point. Plunger alignment is ensured by combined guidance of the ram and collar.

Considerable attention has been paid to the selection of a packing for the main oil-seal. This seal is of the P.T.F.E. composite-type which offers low frictional restraint even at high confining pressures. The seals have been usefully applied in fatigue testing machines for metals testing.

The removable base-assembly seals into the body of the cell with an 'O'-ring and is retained by sixteen capscrews. The assembly is hollow and incorporates an axial load dynamometer which is isolated from the confing oil. The cylindrical load-sensing element has a full-bridge of four lateral and four axial strain gauges.

The cell has provisions for up to fourteen specimen strain gauges. A ring of turret-lugs around the lower platen is connected via ducts in the cap of the dynamometer to an internal wiring terminal board. The ducts are tapered and are sealed-off with nylon plugs. Dynamometer and strain gauge wiring is terminated at a 19-pin socket which is recessed into the lower surface of the base-assembly.

Axial deformation is monitored by a single Linear Variable Displacement Transformer which is clamped to the ram and senses the movement of the cell plunger. Corrections have to be made for the strain of the body of the rig if the Elastic Modulus is to be determined.

The cell has a maximum working pressure of 40 MPa. The maximum axial load is determined by the dynamometer and is 300kN. The sensitivity of the dynamometer is approximately 3.9 $\mu$V/kN/Volt. The specimens, which are 76 mm in diameter and 152 mm long, are enclosed in a nitrile rubber jacket.

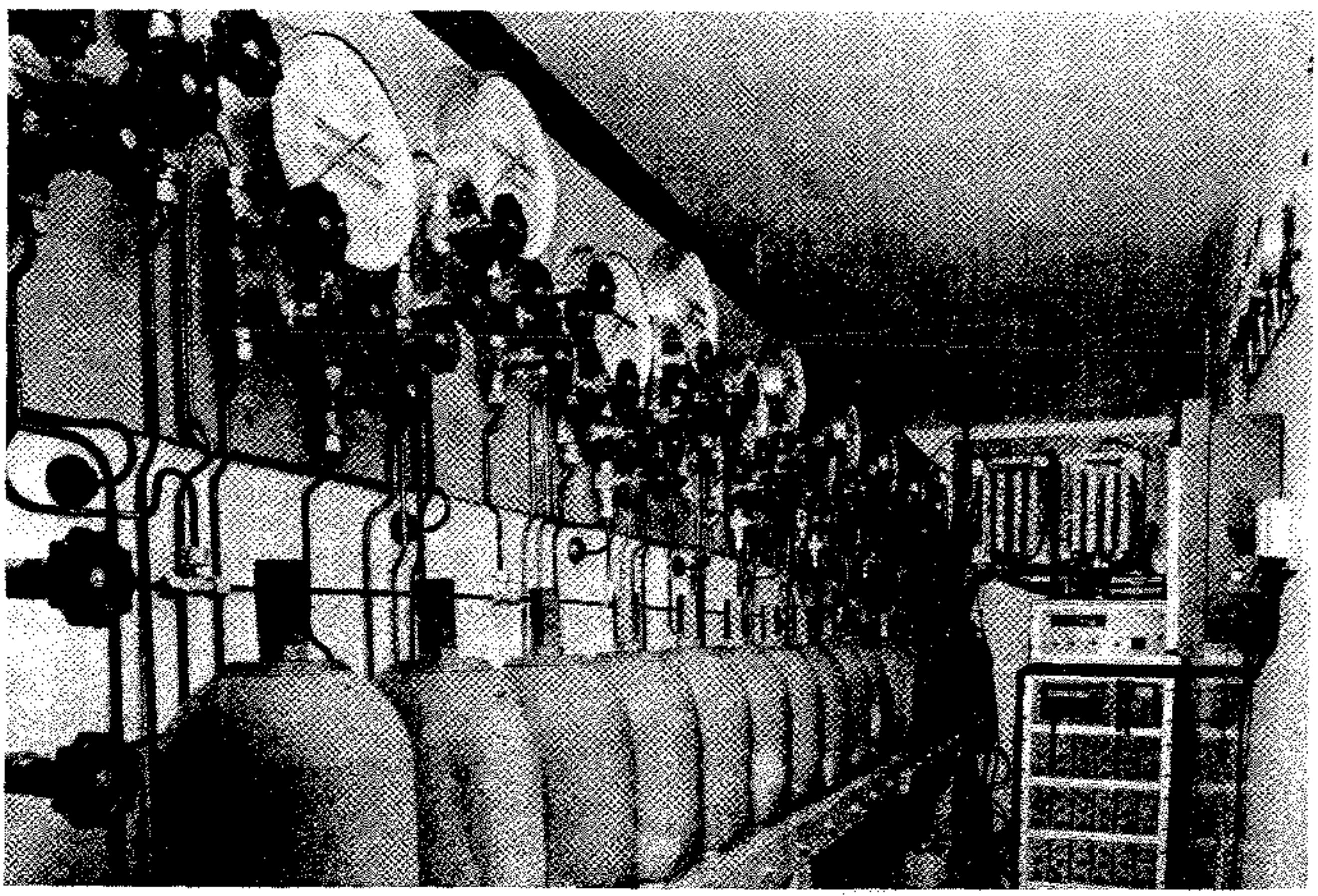

**Figure 14.** External view of the chamber showing the pressure controls, hydraulic accumulators and logging system.

**Pressure control and monitoring.** A battery of ten triaxial and eleven uniaxial rigs are in use inside the heated chamber. The rigs, which are rack-mounted for easy handling, are shown in Figure 14.

Pressure is applied to the ram and confining pressure circuits using a portable electric pump. The hydraulic circuits are shown in Figure 15. The pressure is maintained by thirty-one nitrogen-filled hydraulic accumulators. The pressures have to be corrected from time to time using a hand pump.

The bus-bar arrangement of the pipework enables the specimens to be "cycled" simultaneously to determine the elastic properties of the core. Most rigs are piped in pairs so that duplicate creep tests can be performed for each condition of stress. These arrangements also enable multiple tests to be conducted under, as near as possible, identical deviatoric stresses.

All test parameters are recorded using a 300-channel data logger equipped with a paper-tape punch and remote monitor. The tapes are processed and plotted using the University's I.B.M. 360/370 computer.

**Typical results from laboratory testing.** Figure 16 shows the results from a series of triaxial creep tests. We feel that they adequately demonstrate the benefits of the "bulk-testing" applied to the creep of rock salt. The ten tests shown here were performed simultaneously. The confining pressure was 18 MPa and the stress difference 21 MPa for each test. By connecting the hydraulic circuits providing axial load and those providing confining pressure we have ensured that the conditions of testing were, as near as possible, identical.

Earlier in this paper we noted the problems associated with testing core from a vertical borehole through a bedded salt deposit. The size of test specimen is inevitably dictated by the diameter of the core. It is our experience that, when viewed on this scale, salt is often quite inhomogeneous. Thus the results of no one test can be taken as typical of the particular conditions of testing. For the job in hand there

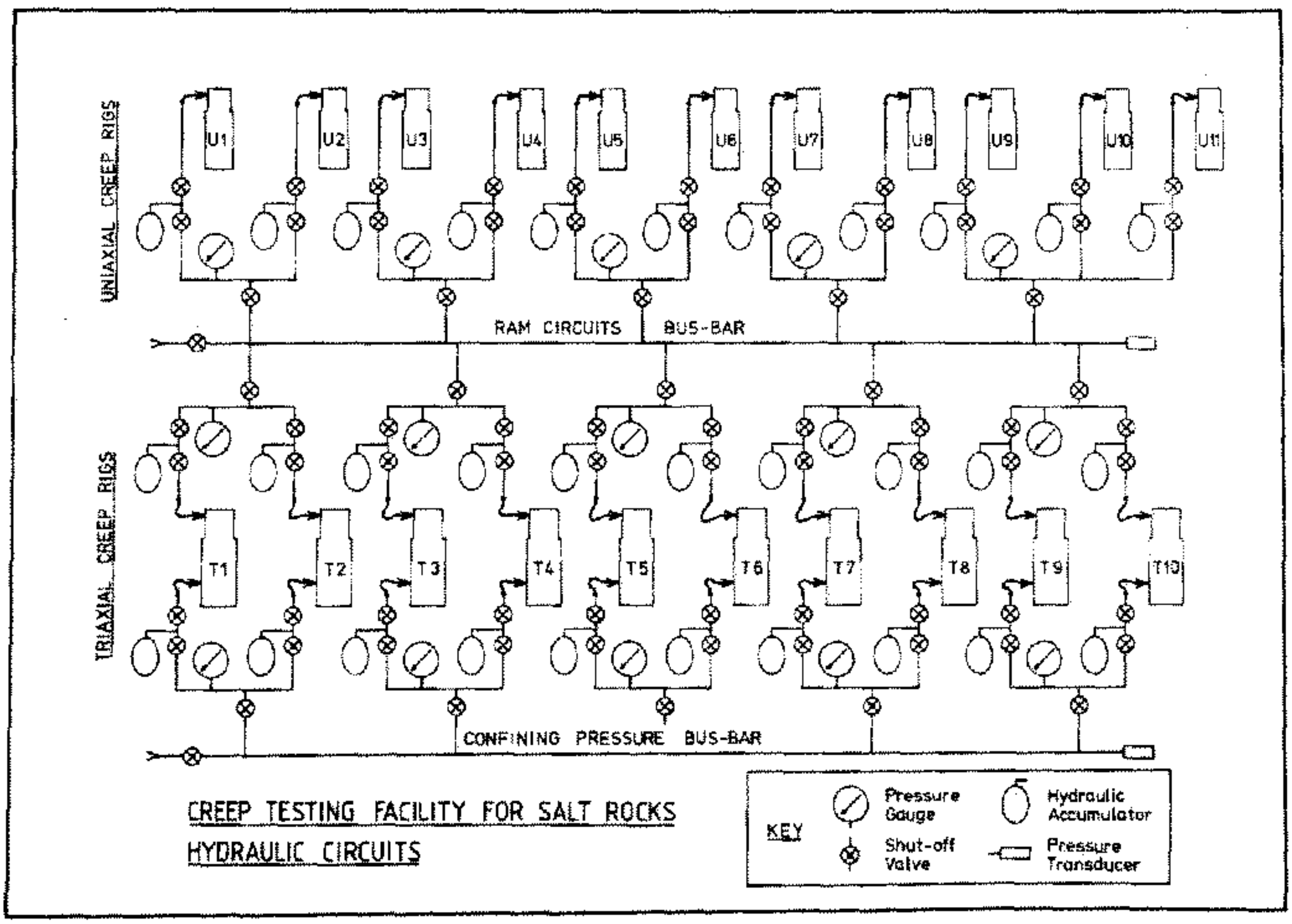


**Figure 15.** Pressure control and monitoring arrangements for the testing facility.

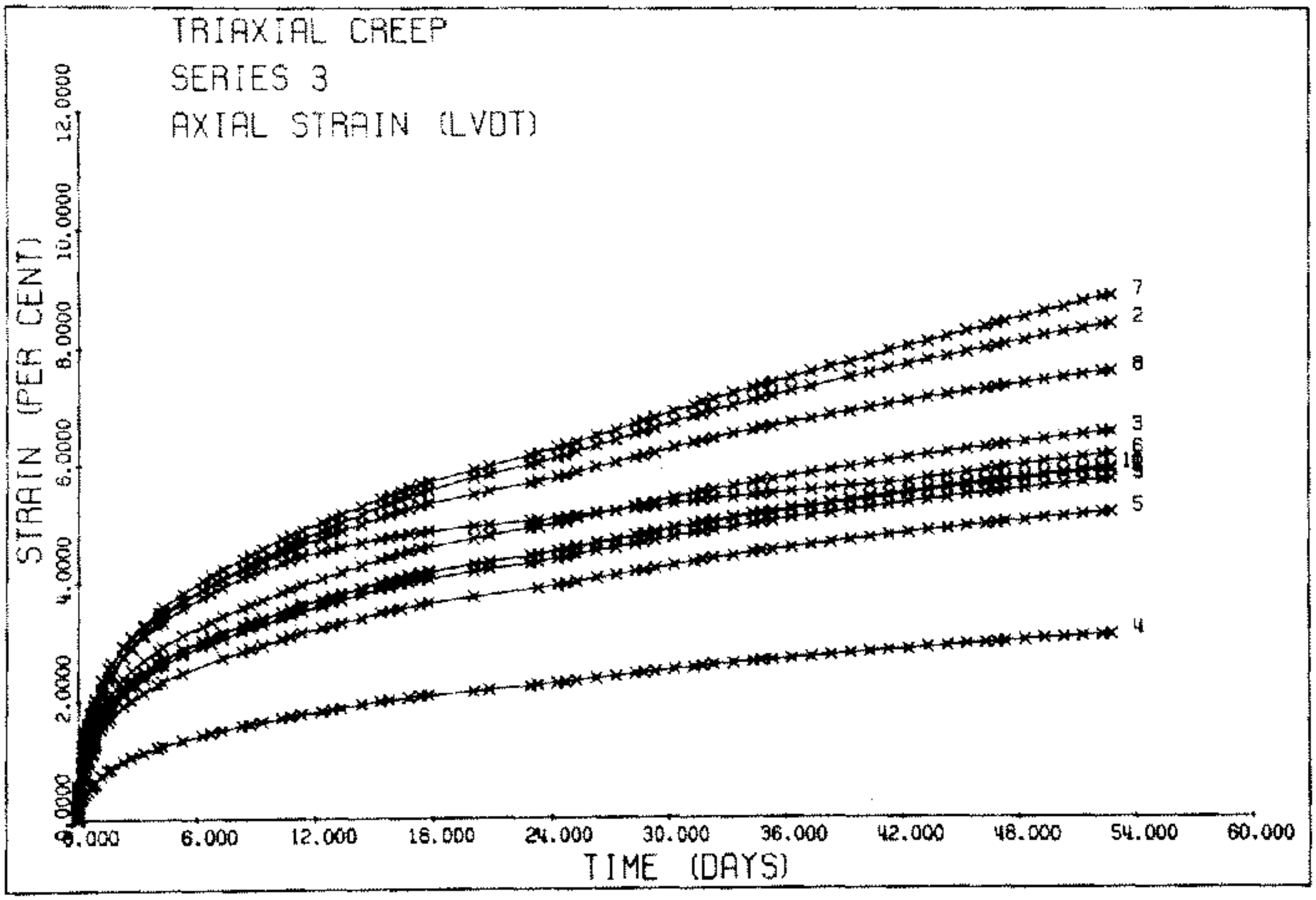


**Figure 16.** Typical triaxial creep results for rock salt of Permian origin. $\sigma_1 - \sigma_2 = 21$ MPa, $\sigma_2 = 18$ MPa.

can be no alternative but to repeat tests until significant material trends emerge from the results.

## GENERAL CONCLUSIONS

The main conclusion of the earlier work described here is that low temperatures produced by the rapid withdrawal of gas from a brine well cavity at shallow or intermediate depth may produce tensile resultant stresses in the near surface rock. The magnitude of these stresses may be greater than the uniaxial tensile strength of salt and may produce localized microfracturing of the cavity walls. Our tests indicated that the repeated application of compressive stress to the salt by pressure loading or above ambient imposed temperatures may close up previously formed microfractures. There is some evidence to suggest that a form of "stress-healing" may take place in the wall-rocks.

In considering the implication of these results to the performance of a storage cavity we are anxious to distinguish between a localized weakening of the wall-rocks and gross failure of the salt. We have no evidence of progressive gross failure of the salt when subjected to repeated cycles of tensile loading over a number of years nor can we say whether the damage to the salt accumulates or whether a stress-healing mechanism nullifies its effect. However, we suggest that in establishing the maximum withdrawal rates for a particular storage cavity the possibility of damaging the cavity walls should be carefully examined.

In the latter part of this paper we have outlined the difficult problem of determining an operational base pressure for cavities at depth. We have discussed the possibility of rupture of the wall-rocks, the influence of stress redistribution and the important issue of creep closure. We have described one possible approach to quantifying the base pressure. Finally we have described the design of a test program to determine the fundamental material properties of rock salt and we have indicated how this has been implemented at Newcastle University.

The writers wish to state that the statements, theories and methodologies expressed in this paper are those of the staff, past and present, of the Department of Mining Engineering and as such do not necessarily coincide with those of the sponsors of the research.

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It is difficult to single out names from all those who have materially contributed to the work but those of Dr. M. Thompson, Mr. A.C. Talbott and Dr. E. Dack stand out, for their assistance during the development and operation of the experimental cavity has been of inestimable value.

Particular acknowledgement must be made to Mr. T. Pollock and his technical staff at the Department of Mining Engineering whose efforts, sometimes over long hours and in adverse conditions, have contributed much to the success of the work described here.

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