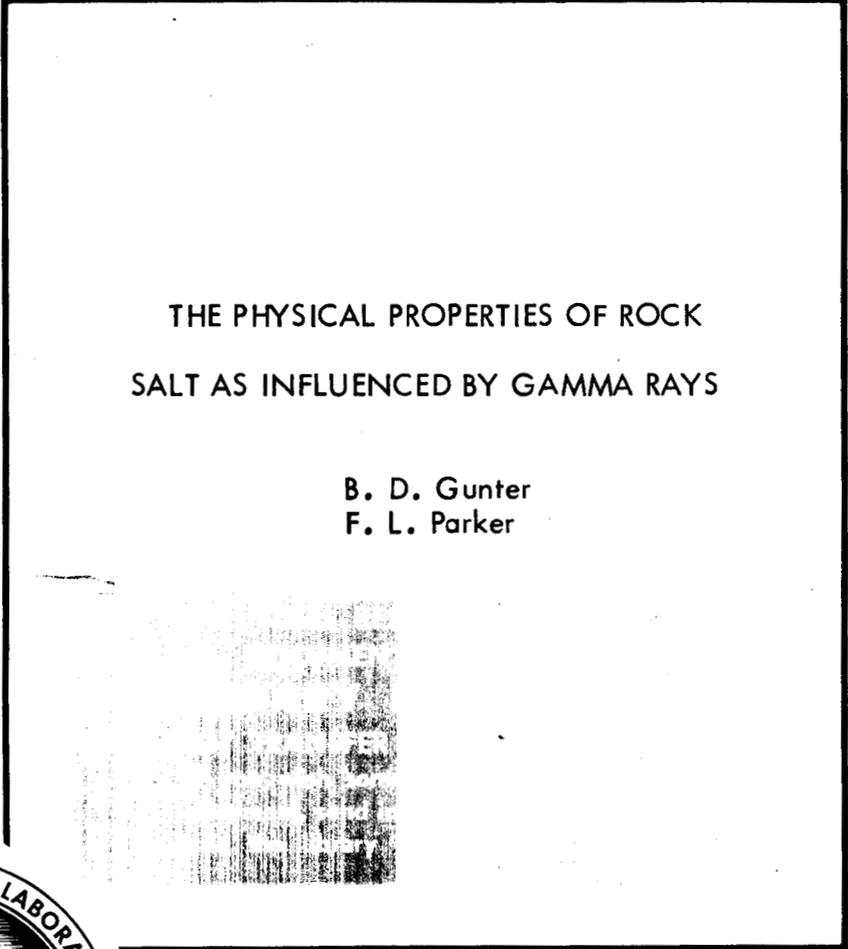




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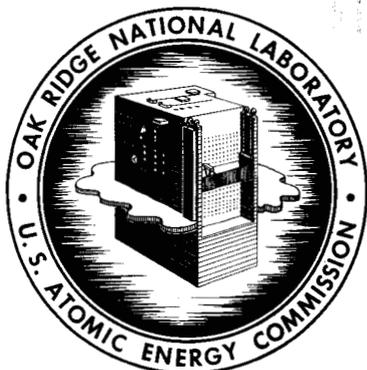
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ORNL-3027
UC-70 - Waste Disposal and Processing



THE PHYSICAL PROPERTIES OF ROCK
SALT AS INFLUENCED BY GAMMA RAYS

B. D. Gunter
F. L. Parker



OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

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HEALTH PHYSICS DIVISION

THE PHYSICAL PROPERTIES OF ROCK SALT AS

INFLUENCED BY GAMMA RAYS

B. D. Gunter and F. L. Parker

Submitted as a thesis to the Faculty of the Graduate
School of Vanderbilt University in partial fulfill-
ment of the requirements for the degree of MASTER OF
SCIENCE in Physics

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ABSTRACT

The response of aggregates of natural rock salt crystals to gamma radiation was determined for a spectra of exposure doses from 10^6 to 5×10^8 roentgens. Emphasis was on those physical properties which determine the structural stability of salt. The compressive strength, yield strength, modulus of elasticity, and apparent elastic limit were investigated. Short-term creep tests were also made. Data are presented in both tabular and graphic form.

Both bedded and dome salt were studied. Bedded salt was studied with force applied both parallel to and perpendicular to the planes of stratification.

Specimens were tested at room temperature and at 200° C to establish temperature effects. The plasticity of both unirradiated and irradiated rock salt exhibited a pronounced increase with temperature.

Within the statistical variation of the experiment, radiation causes only minor changes in the physical properties of rock salt.



I. INTRODUCTION

This thesis is a study of the effects of radiation upon the physical properties of aggregates of natural rock salt crystals. This study is part of a seven-point program¹ at Oak Ridge National Laboratory to investigate the possibility of disposing of radioactive wastes in cavities in natural rock salt formations.

The disposal of large quantities of radioactive wastes is one of the most vexing problems of the nuclear age. Radioactive wastes must be segregated from man's environment until they are no longer a hazard. Radioactive waste disposal must be both safe and permanent.

To date, the chief source of radioactive wastes has been production reactors. The spent fuel elements from these reactors are reprocessed to recover unfissioned fissionable material. In present reprocessing operations, the radioactive fission products become part of the liquid wastes. Since relatively few nuclear power reactors have been in operation up to the present time, the volume of fission product wastes has been small.

These small volumes of fission products have been stored in underground steel and concrete tanks. Located just below the earth's surface, these tanks are subject to earthquakes, sabotage, explosions, and other

¹F. L. Parker, L. Hemphill, J. Crowell, Status Report on Waste Disposal in Natural Salt Formations, ORNL-2560, p. 24.

forms of release. Furthermore, the life of many fission products is much greater than the tank life. Tank disposal provides neither safe nor permanent disposal.

Although the volume of fission-product wastes has been small in the past, a substantial increase in the volume of fission-product wastes may be expected once nuclear power is an important portion of total power generated. Lane² has predicted that by the year 2000 there will be 700,000 megawatts (thermal) of installed nuclear capacity. Assuming a waste of 820 gallons per ton of spent fuel reprocessed and a burnup of 4000 megawatt days per ton, a nuclear generating capacity of 700,000 thermal megawatts will produce an accumulated volume of one-half billion gallons and 3.5×10^{11} curies of fission products by the year 2000.³

Even though the present method of storing fission-product wastes in underground tanks is probably the safest and most economical available to date,⁴ the cost (\$1.00 to \$3.00 per gallon)⁵ and hazard renders this method impractical from a power production viewpoint. If nuclear fission is to become a major source of public power, cheaper, safer, and more permanent means of radioactive waste disposal are needed.

²J. A. Lane, *Nucleonics* 12, 10, 64 (1954).

³H. R. Zeitlin, E. D. Arnold, and J. W. Ullmann, *Nucleonics* 15, 1, 58-62 (1957).

⁴Committee on Waste Disposal - Division of Earth Sciences, Disposal of Radioactive Wastes of Land, National Academy of Sciences, National Research Council Publication 519, April 1957, p. 6.

⁵Anonymous, Summary Report: AEC Reference Fuel-Processing Plant, Division of Civilian Application, Washington, D. C., WASH-743, Oct 1957, p. 11.

Recognizing the necessity for ultimate radioactive waste disposal sites, a Committee of the National Academy of Sciences suggested the most promising methods of storage on land.⁶ In particular, the report said: "Disposal in salt is the most promising method for the near future."⁷

Salt cavities have been found to be safe and economical in storing liquified petroleum gases. The advantages of storing petroleum gases in salt cavities are such that the volume of petroleum gases stored in salt cavities has soared from zero gallons in 1950 to over one billion gallons in 1957⁸ - twice the predicted volume of radioactive wastes by the year 2000.

Despite the success enjoyed by the petroleum industry, the storage of radioactive wastes in salt formations has not yet taken place. Obviously, the risks associated with radioactive wastes are much greater than those associated with petroleum gases, and a more cautious approach is necessary.

This thesis presents the results of an investigation of the effect of radiation and temperature upon the physical properties of aggregates of natural rock salt crystals. The primary emphasis has been to determine those physical properties which influence the stability of a cavity in a rock salt formation. The stress-strain relationship was studied to determine the effect of radiation upon the compressive strength, yield strength,

⁶Committee on Waste Disposal, op. cit., p. 6.

⁷Ibid., p. 6

⁸F. L. Parker et al., op. cit., p. 9.

modulus of elasticity, and apparent elastic limit*. The creep rate was studied to determine the response of rock salt aggregates to constant pressure application.

*These terms are defined in Section III, Stress-Strain Relationship.

II. PREVIOUS WORK ON ROCK SALT

A. Unirradiated Rock Salt

Previous work on the physical properties of unirradiated rock salt has shown that experimental conditions and type of salt influence the results. In general though, the plasticity of rock salt increases rapidly with temperature.⁹ Increased temperature also decreases the modulus of elasticity and yield strength. A marked increase in plasticity is also shown by salt which has been immersed in water.¹⁰

The addition of small amounts of impurities to synthetic salt crystals increases the tensile and yield strengths.¹¹ These studies are not applicable to natural crystals or single crystal studies, because results obtained for synthetic and natural crystals and single and aggregates of crystals are quite different. Stamatiu,¹² for example, has reported an average value of 170 pounds per square inch for the tensile strength of natural crystals, while Kuznetsov and Sementzov¹³ have reported an upper

⁹W. Theile, Zeit. für Physik 75, 770 (1932).

¹⁰R. B. Barnes, Phys. Rev. 44, 898 (1933).

¹¹W. Metag, Zeit. für Physik 78, 363 (1932).

¹²M. Stamatiu, Anuarul Institutului Geologic Al Romaniel 17, 501 (1932).

¹³W. D. Kuznetsov and W. A. Sementzov, Zeit. für Krist. 78, 443 (1931).

limit of 5975 pounds per square inch for the tensile strength of single crystals of NaCl. Studies of the physical properties of single and synthetic crystals, therefore, have little pertinence to the physical properties of aggregates of natural rock salt crystals.

Results reported for the physical properties of natural rock salt crystals also vary considerably. This is not surprising. Geological formations, such as rock salt deposits, are now homogeneous and would be expected to exhibit variations in properties. In fact, the work of Stamatiu¹⁴ has shown that the physical properties of rock salt vary for specimens taken from different locations in the same deposit.

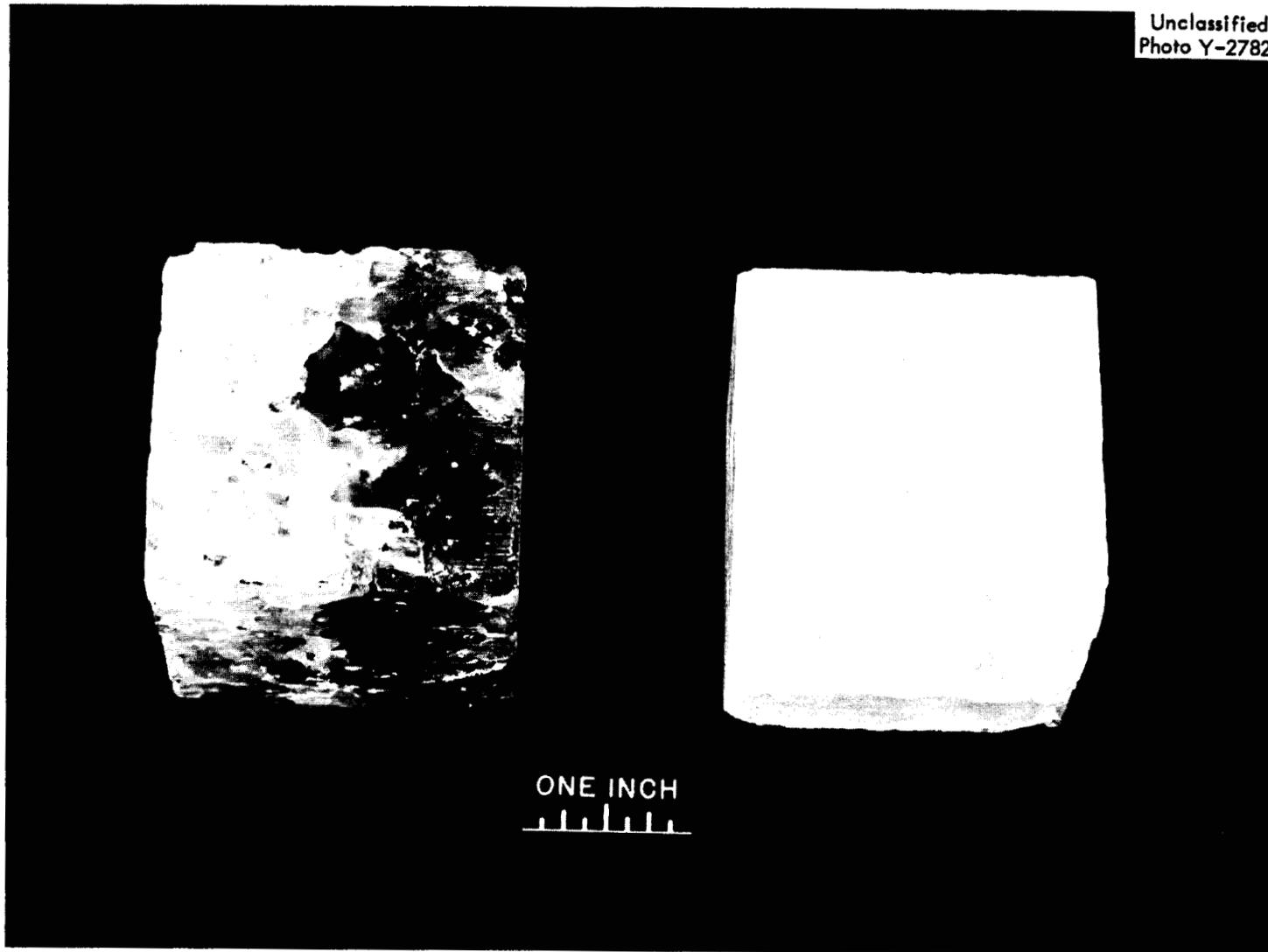
Rock salt deposits consist of two basic types, bedded and dome.¹⁵ The bedded deposits, which were formed by the precipitation of salts from saline waters, are interstratified with other sediments. Domes were formed by the upward flow of older salt deposits through cracks, fractures, and weak sections in the overlying structure and contain few stratification planes. Because of the sediment layers, the bedded salt contains more impurities than the dome salt. Figure I shows specimens of dome and bedded salt, and the difference in purity is evident. Table I gives the chemical composition of rock salt from several locations in the United States.¹⁶

¹⁴M. Stamatiu, op. cit., pp. 501-525.

¹⁵F. L. Parker, L. Hemphill, and J. Crowell, op. cit., p. 14.

¹⁶Salt, Encyclopedia of Chemical Technology (The Interscience Encyclopedia, Inc., New York, New York, 1954), Vol. 12, p. 68.

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Photo Y-27822



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Figure 1. Unirradiated Bedded and Dome Salt.

Table 1

COMPOSITION OF AMERICAN ROCK SALT

Type of Salt	Bedded	Bedded	Dome	Bedded	Brine
Location	Retsof New York	Detroit Michigan	Avery Island Louisiana	Hutchinson Kansas	Natrium West Virginia
NaCl	98.262	98.181	99.026	96.970	96.440
Na ₂ SO ₄	----	----	----	----	----
MgCl ₂	0.002	0.024	0.009	0.066	----
MgSO ₄	----	----	----	----	----
CaCl ₂	0.006	0.053	0.010	0.034	0.230
CaSO ₄	0.743	0.872	0.225	0.875	1.600
H ₂ O	0.015	0.114	0.019	0.670	0.350
H ₂ O Insoluble (N)	0.962	0.756	0.711	1.407	1.070
KCl	----	----	----	----	0.310
Totals ----	99.990	100.000	100.000	100.022	100.000

Even though only the purest bedded deposits are mined, the dome deposits still have a greater purity.

Previous work on the physical properties of unirradiated rock salt aggregates is inadequate to establish a baseline for studying radiation effects. The physical properties of the salt to be irradiated must be known before radiation effects can be evaluated.

B. Radiation Effects on Rock Salt

The effect of radiation on single and synthetic crystals of NaCl has been widely studied, because NaCl crystals are among the simplest known. The solid state physicists have found alkali halide crystals particularly well-suited to their studies of radiation damage in ionic crystals. The main emphasis has been on the mechanism by which radiation damages ionic crystals, and formulating a theory to explain, at an atomic level, the nature of radiation damage in solids.

The results obtained for single and synthetic crystals are not directly applicable to the problems encountered in radioactive waste disposal where we are concerned with the damage to aggregates of natural crystals rather than the method by which the damage is introduced into the crystal. Quite different results have been reported for synthetic and natural crystals.^{17,18} This has been attributed to the presence of impurities in the

¹⁷E. E. Schneider, "Symposium on Photographic Sensitivity," Bristol, 1951, p. 13.

¹⁸J. H. Schulmann, J. Phys. Chem. 57, 749 (1953).

natural crystals. Mined rock salt of the United States contained from about 1 per cent to over 3 1/2 per cent impurities (Table I), depending on the location of the deposit.

Even though numerical values obtained by the solid states physicists are not applicable to the problem under investigation, a knowledge of radiation effects is helpful in evaluating radiation damage. It is therefore worthwhile to consider briefly the findings of the solid state physicist.

It is now believed that the effect of radiation is to disturb the crystal lattice and to form color centers. The most prevalent of these are the F-center, which is an electron trapped at a negative ion vacancy, and the V-center, which is a hole (vacancy) trapped at a positive ion vacancy. The mechanisms of color center formation are not well known, and the very nature of these centers remains uncertain.^{19,20} Consequently, no effort will be made to describe color center formation.

Although radiation effects should accumulate with dose, there appears to be a finite limit to the F- and V-center concentration which can be obtained in a crystal. A practical upper limit to the concentration of color centers is set by the fact that when an F-center gets close enough to a V-center, the electron in the F-center can tunnel through to the V-center

¹⁹I. L. Mador et al., Phys Rev. 96, 617 (1954).

²⁰I. Eastermann, W. J. Levio, and O. Stern, Phys. Rev. 75, 633 (1949).

and annihilate the positive hole.²¹ The upper limit of F-center concentration in NaCl crystals is approximately 10^{19} F-centers per cubic centimeter²² and appears to be very little influenced by the energy of the dose. The value of greater than 0.8×10^{-3} F-centers per molecule at saturation given by Schneider²³ for filtered x-rays compares favorably with the value of 2×10^{-3} F-centers per molecule reported by Easterman et al.²⁴ It has been suggested that each F-center is accompanied at a distance of from 10 to 30 lattice spacings by a V-center.²⁵ This suggests a maximum degree of decomposition of the order of a tenth of a per cent.²⁶

The physical properties can, however, change to a greater extent. The effect of radiation on NaCl crystals has been to decrease the density²⁷ and the internal friction,²⁸ increase the modulus of elasticity,²⁹ hardness, and tensile strength.³⁰ Removal of the F-centers by optical bleaching does not return these properties to their original values. F-centers

²¹E. E. Schneider, op. cit., p. 13.

²²F. Seitz, *Revs. Mod. Phys.* 18, 408 (1946).

²³E. E. Schneider, op. cit., p. 14.

²⁴I. Eastermann et al., op. cit., p. 627.

²⁵E. E. Schneider, op. cit., p. 13.

²⁶H. G. Heal, *Atomics*, August 1955, p. 241.

²⁷I. Eastermann et al., op. cit., p. 627.

²⁸D. R. Frankl and T. A. Read, *Phys. Rev.* 89, 663 (1953).

²⁹R. B. Gordon and A. S. Nowich, *Phys. Rev.* 98, 1540 (1955).

³⁰D. R. Westervelt, NAA-SR-288, Feb. 3, 1954, p. 13.

are, therefore, not responsible for the changes in the physical properties. It has been suggested that free positive ion vacancies diffuse and interact with crystal lattice imperfections (dislocations) and are trapped at these dislocations.³¹ Trapping of positive ion vacancies causes dislocations to become firmly pinned, and, therefore, they are harder to move. The increase in the modulus of elasticity is permanent at room temperature, but returns to normal when annealed at 350° C.³² Therefore, the binding energy of the pinning vacancies is small, and at slightly elevated temperature they diffuse and recombine with negative ion vacancies.³³

There is clear evidence that radiation effects (excitons) are mobile in some organic compounds,³⁴ and it is now accepted that the same is true for the alkali halides.³⁵ Therefore, many of the observed effects of radiation occur largely at crystal lattice imperfections.

³¹R. B. Gordon and A. S. Nowich, *ACTA Metallurgica* 4, 514 (1956).

³²R. B. Gordon and A. S. Nowich, *Phys. Rev.* 101, 977 (1956).

³³D. R. Frankl and T. A. Read, *op. cit.*, p. 663.

³⁴H. G. Heal, *Atomics*, July 1955, p. 206.

³⁵F. Seitz, *Revs. Mod. Phys.* 26, 93 (1954).

III. STRESS-STRAIN RELATIONSHIP³⁶

The physical stability of a salt cavity may be predicted by determining the response of aggregates of rock salt crystals to the application of forces. Force is defined as the cause of the changes in the state of rest or motion of matter. Therefore, the application of a force to a stationary body will cause a change in the shape of the body. The degree to which the shape of a body is changed is dependent on the magnitude of the force, the manner in which the force is transmitted, and the rate of force application. This discussion will be limited to axial forces (those forces which coincide with the structural axis of the body) and to those forces which are considered to be time independent. In the testing of materials, forces are customarily given in mass units, and the force applied to a body is called the "load." Technically, this terminology is incorrect, because this usage does not include the acceleration of the body. The

³⁶References consulted:

- a. F. R. Shanley, Strength of Materials (McGraw Hill Book Company, Inc., New York, 1957).
- b. I. H. Cowdrey and R. G. Adams, Materials Testing (John Wiley and Sons, Inc., New York, 1945).
- c. H. E. Davis, G. E. Troxell, and C. T. Wiskocil, The Testing and Inspection of Engineering Materials (McGraw Hill Book Company, Inc., New York, 1941).
- d. R. Houwink, Elasticity, Plasticity, and the Structure of Matter (Harrow Press, Washington, D. C., 1955).
- e. A. H. Cottrell, Dislocations and Plastic Flow in Crystals (Oxford Press, London, 1953).

acceleration of body is small, however, and the movement of the body is given in the force value.

The force-induced change in the shape of a body is called deformation. Deformation is the relative change in the location of a specific point on the body and may be rotational, translational, or both, depending on the manner in which the force is transmitted to the body. However, with axial forces, the deformation will be parallel to the axis of force application and translational. With axial forces, deformation is a change in the length of the body parallel to the axis of force application.

It is evident from the above discussion that a relationship exists between force and deformation; the greater the force the larger the deformation. The application of a sufficiently large force to a solid body will cause a brittle body to break. The force necessary to break a body of a given material or to cause the degree of distortion that is regarded as the effective failure of the material, called the compressive strength, is an important characteristic of that material.

The relationship between force and deformation may be expressed mathematically and is given by the following formula:

$$\delta = f(P) \quad (1)$$

where

δ = deformation,

P = force,

f() = function of ().

The relationship between force and deformation is usually quite complicated, and the solution of equation (1) becomes difficult. It is

desirable, therefore, to determine the relationship experimentally. This is done by applying known forces of increasing magnitude and measuring the resulting deformation. This data may then be presented in graphical form, and the behavior of a given material of given size is known.

The usefulness of force-deformation relationships is limited, as it would entail the individual measurement of every material and shape of material studied. It is, therefore, desirable to normalize the force-deformation curve so as to have a relationship which can be applied to a member of any length and cross-sectional area. Dividing the total force by the cross-sectional area (stress) and the total deformation by the length of the member deformed (strain) normalizes the force-deformation curve to a stress-strain curve.

Stress and strain are defined mathematically by the following formulae:

For axial stress assuming uniform stress over the cross-sectional area,

$$\sigma = \frac{P}{A} \quad (2)$$

where

σ = stress,

P = total force,

A = cross-sectional area taken normal to the line of force application.

For axial strain measured along the axis of force transmission,

$$\epsilon = \frac{\ell}{L_0} \quad (3)$$

where

ϵ = strain,

l = total change in length of the reference length,

L_0 = original reference length*.

A typical stress-strain relationship is shown graphically in Fig. 2.

For most materials the stress-strain curve may be conveniently divided into two sections. These are:

A. The Linear (elastic) Portion of the Curve (A - B)

The linear portion of the stress-strain curve, A - B, is attributed to the elastic action of the material. By elastic action we mean that there is no permanent deformation (strain) upon complete removal of the force (stress). Davis³⁷ defines elasticity "as that property of a material by virtue of which deformations caused by stress disappear upon removal of the stress." Elastic action is, therefore, reversible.

Elastic action involves a change in the distance between constituent atoms or molecules of the material. The mechanical stability of solids is due to cohesive forces which exist between atoms and molecules. However, the total force which exists between two atoms must be thought of as the resultant of attractive and repulsive forces; attractive forces cause the atoms to cohere to one another, while repulsive forces prevent the

*The change in length is often measured between two points of reference rather than over the entire length of the specimen. The definition of strain justifies this method of measurement.

³⁷H. E. Davis et al., op. cit., p. 23.

atoms from coming completely together. In an undisturbed condition the attractive and repulsive forces are balanced. The application of an external force upsets the equilibrium of forces, and the atoms move slightly to establish a new balance between attractive, repulsive, and external forces. Removal of the external force (before the atoms are completely separated) will disturb the new balance of forces, and the atoms will return to their original positions; thus elastic action is reversible.

The ability of a material to completely recover from force-induced changes in shape is a desirable physical characteristic, and the stress a material will support and still remain elastic is of importance in determining the stability of a structure. The precise determination of the stress at which a material ceases to be elastic is tedious and time consuming. It is desirable, therefore, to have a quick, easy method which closely approximates this value. Two such methods have been developed:

(1) Yield Strength.-- The yield strength is the maximum stress which can be applied to a material before the material ceases to be elastic. As already mentioned, it is difficult to obtain the true value of stress at which inelastic action begins. The yield strength is, therefore, defined³⁸ by some specified degree of inelastic strain above which the material may be considered damaged and below which the damage may be considered negligible. The most commonly used yield strength is determined by passing a line parallel to the elastic part of the curve through a strain of 0.2 per cent

³⁸H. E. Davis et al., op. cit., p. 26.

of the reference length. The point of intersection of the line and the stress-strain curve is taken as the yield strength and is called the 0.2 per cent offset yield strength.

(2) Elastic Limit.-- The elastic limit is the greatest stress a material is capable of developing without a permanent strain remaining after complete removal of the stress.³⁹ The determination of the elastic limit within this definition would require successive application and release of greater and greater loads until a load was found at which a permanent strain was observed. This is not practical from a materials testing viewpoint. Consequently, an apparent elastic limit is used and defined⁴⁰ as that stress at which the rate of deformation is 50 per cent greater than the initial rate of deformation.

In Fig. 2, the initial rate of deformation is $\frac{\overline{FB}}{\overline{AF}}$. Therefore, when $\overline{BB}' = 0.5 \overline{FB}$, the slope of \overline{AB}' represents a rate of deformation 50 per cent greater than the initial rate, \overline{AB} . The line $\overline{A''B''}$ is then drawn parallel to \overline{AB}' and tangent to the stress-strain curve. The point of tangency locates the apparent elastic limit.

Although the yield strength and elastic limit are valuable in determining the stress a material will support and remain elastic, neither offers any indication of the strain increase with increasing stress. This property, given by the slope of the linear part of the curve, $\frac{\overline{AF}}{\overline{FB}}$, is known as the modulus of elasticity, and is a measure of the stiffness of the material.

³⁹I. H. Cowdrey and R. G. Adams, op. cit., p. 13.

⁴⁰Ibid., p. 14.

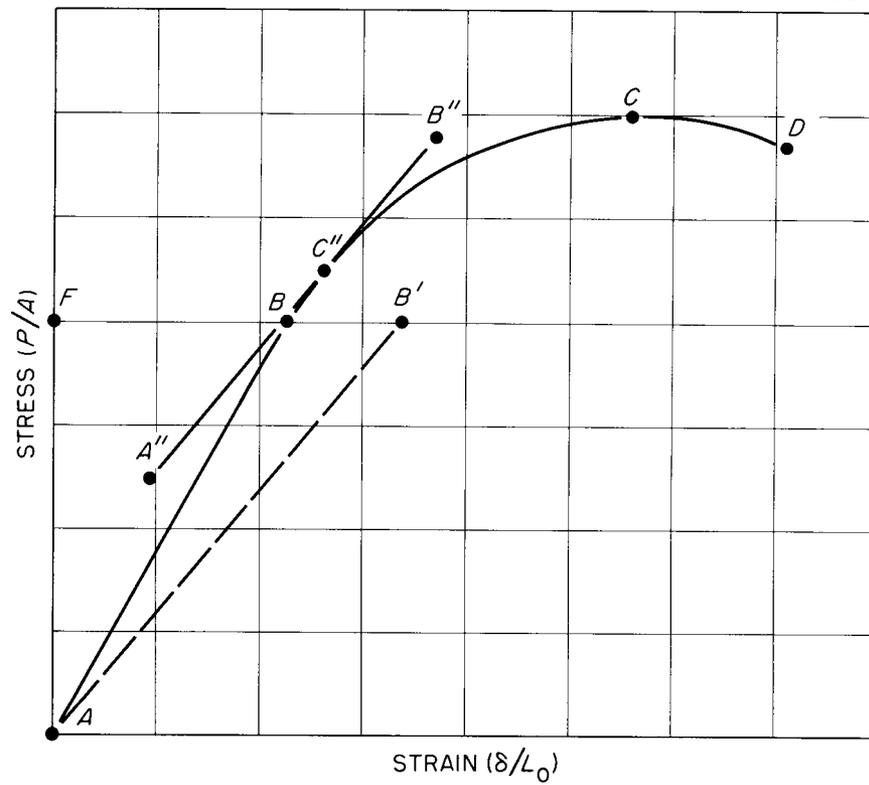
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Figure 2. Stress Strain Relationships.

B. The Nonlinear (inelastic) Portion of the Curve (B - D)

The nonlinear portion of the stress-strain curve, B - D, is attributed to the plastic action of the material. Plasticity is defined⁴¹ as that property of a material by virtue of which it can undergo permanent deformation without breaking. Therefore, unlike elastic action, plastic action is not reversible, and complete removal of the applied force will not cause a return to zero deflection.

Plastic strain involves a change of position of atoms of molecules with negligible change of atomic spacing. Crystals deform plastically by means of translational glide in which one part of the crystal slides, as a unit, across a neighboring part. This movement is known as slip, and the planes of movement are known as slip planes or slip surfaces. Most atoms do not move relative to their neighbors; only on an occasional slip plane is there any movement, and the crystals lying between these slip planes remain practically undeformed.

The theory of plasticity is not as straightforward nor as well developed as that of elasticity. The main point of interest for our purposes is that slip starts from structural irregularities or dislocations in the crystal. Assuming that radiation increases the modulus of elasticity of rock salt by pinning dislocations, then plastic action is responsible for an appreciable part of the strain at low values of stress. The fact that the stress-strain curve deviates gradually from a straight line further substantiates this proposal.

⁴¹H. E. Davis et al., op. cit., p. 26.

IV. CREEP

The stress-strain relationship and the properties derived from this curve are considered to be time independent and, therefore, offer no indication of the strain to be expected from applying a constant force to a body for a period of time. The continual increase in strain with time under constant stress is known as creep.

Creep results from elastic strains imposed in the body. Consider the case where a static force is allowed to remain on the body for a relatively long period of time. The intermolecular force field will be disturbed, and the system will absorb a quantity of potential energy which will give rise to internal forces to balance the external forces. Although the interatomic forces are balanced and the atoms are in equilibrium, the atoms are not stationary; the atoms in a crystal are in continuous motion as a result of thermal agitation. As soon as the impulse due to thermal agitation is of the same energy as that with which the intermolecular force field has been disturbed, the atoms may be forced back into their positions with smaller energy content. In this way internal tensions disappear, and a continual decrease in force will be necessary to keep the crystal in a deformed state. This mechanism of reducing internal strain by thermal agitation is called relaxation.

If, however, the external force is constant, an increase in length will occur until internal and external forces are balanced, and equilibrium

restored. If relaxation continues, this process will be repeated, and a state of flow will be reached. This flow is known as creep.

The importance of creep in actual practice where structural components are subjected to constant forces for extended periods of time is evident. The force applied to a member must be below that at which appreciable creep occurs. Fortunately, at moderate loads creep is negligible for most structural materials.

V. TEST SPECIMENS

A. General

Values of physical properties are influenced by experimental procedures,^{42,43} and the choice of specimen size and shape, preparation of specimens, and testing procedure are of importance. So that results obtained in different laboratories might be compatible, the American Society for Testing Materials has established standard procedures for commonly tested materials.

However, no standard testing procedure has been established for rock salt. A literature search showed that no trend has been followed by experimenters who have worked with rock salt. A study was made of the procedures for materials which behave similar to rock salt, and the more pertinent provisions applied to the testing of salt.

Salt has a compressive strength comparable to that of concrete, and in many ways rock salt behaves as a good concrete.⁴⁴ The testing procedures for concrete were studied carefully. Salt is brittle, and the testing procedures of natural building stone were investigated to determine the testing

⁴²H. E. Davis et al., op. cit., pp. 75-103.

⁴³I. H. Cowdrey and R. G. Adams, op. cit., pp. 31-34.

⁴⁴F. L. Parker et al., op. cit., p. 41.

of brittle materials as were the testing procedures for wood, a more plastic material.

B. Specimen Size and Procurement

During the investigation of standard testing procedures, it became apparent that the size of the specimen would influence the results. Although rock salt has no standard test specimen size, Stamatiu⁴⁵ studied the effect of specimen size on the compressive strength of rock salt by investigating cubes of 5, 10, 15, and 20 centimeters. These results were not statistically analyzed, and a computation of the standard deviation of the difference showed the variations attributed to size to be within the limits expected statistically. Therefore a cubic specimen in this size range would be satisfactory.

Two-inch cubes were used for test specimens. This was thought large enough to give meaningful results and small enough to allow efficient use of the irradiation chamber (one cubic foot). All dome specimens were taken from a large hand-drilled block of salt from the Morton Salt Company's mine at Grand Saline, Texas. Bedded specimens were taken from a hand-drilled block of salt from the Carey Salt Company's mine at Hutchinson, Kansas. The purity of the dome salt was given as 99.026 per cent NaCl, and the purity of the bedded salt was given as 96.970 per cent NaCl.

⁴⁵M. Stamatiu, op. cit., p. 513.

C. Specimen Preparation

Compression tests require the application of a uniform force. Any departure of the surfaces to which the force is applied from planeness and parallelism will cause eccentric loading, and values obtained under eccentric conditions are not true measures of strength. Specimens were machined so that eccentric loading conditions would be kept at a minimum.

D. End Friction

Friction between the machine and the end surfaces of the specimen due to the lateral expansion of the specimen can give anomalous results in compression tests. The ASTM offers no solution to this problem.

Serata⁴⁶ developed an end friction reducer, consisting of alternate layers of aluminum foil and vaseline, for compression specimens. Efforts to apply this technique in this experiment were unsuccessful. Specimens with the friction reducer were observed to slide under force application. Sliding, of course, resulted in eccentric loading. Furthermore, it is difficult to determine a value of zero deformation when using the friction reducer. The application of force to the specimen not only deforms the specimen, but also compresses the vaseline. This gives a false impression of total strain, and it is difficult to determine the point at which the deformation of the specimen begins. The end friction reducer was not used in this experiment.

⁴⁶S. Serata and E. Gloyna, Technical Report to the Atomic Energy Commission, AEC Contract AT (11-1) - 490, University of Texas, Jan. 1, 1959, p. 150.

VI. IRRADIATION FACILITY AND DOSE MEASUREMENT

The machined specimens were irradiated in the Co^{60} storage facility of the Isotope Production Division at Oak Ridge National Laboratory. This facility was constructed primarily for the storage of Co^{60} to be sold to users outside the Laboratory, and the amount of cobalt present varies as shipments are made. However, in anticipation of the need for a high-level radiation field, the cobalt is stored in such a way that an irradiation chamber 1 cubic foot in size can be raised and lowered independently of the cobalt. A cutaway schematic drawing of the Co^{60} storage facility, known as the cobalt garden, is shown in Fig. 3.

Approximately 200,000 curies of Co^{60} are stored in the garden, and the gamma field at the time of irradiation was 3.2×10^6 roentgens per hour. The temperature inside the chamber is near 70°C .

Cobalt-60 exists in an isomeric state. The half lives of the isomers are 10.5 minutes and 5.3 years. Because of its short half life, the 10.5-minute isomer contributes very little to the dose received by a specimen irradiated in the cobalt garden. The 5.3-year isomer emits one beta particle of 0.31 Mev energy and two gamma rays of 1.33 Mev and 1.17 Mev energy.

A ceric sulfate chemical dosimeter is used for dose determination. Radiation reduces the ceric ions (Ce^{+4}) to cerous ions (Ce^{+++}). The yield

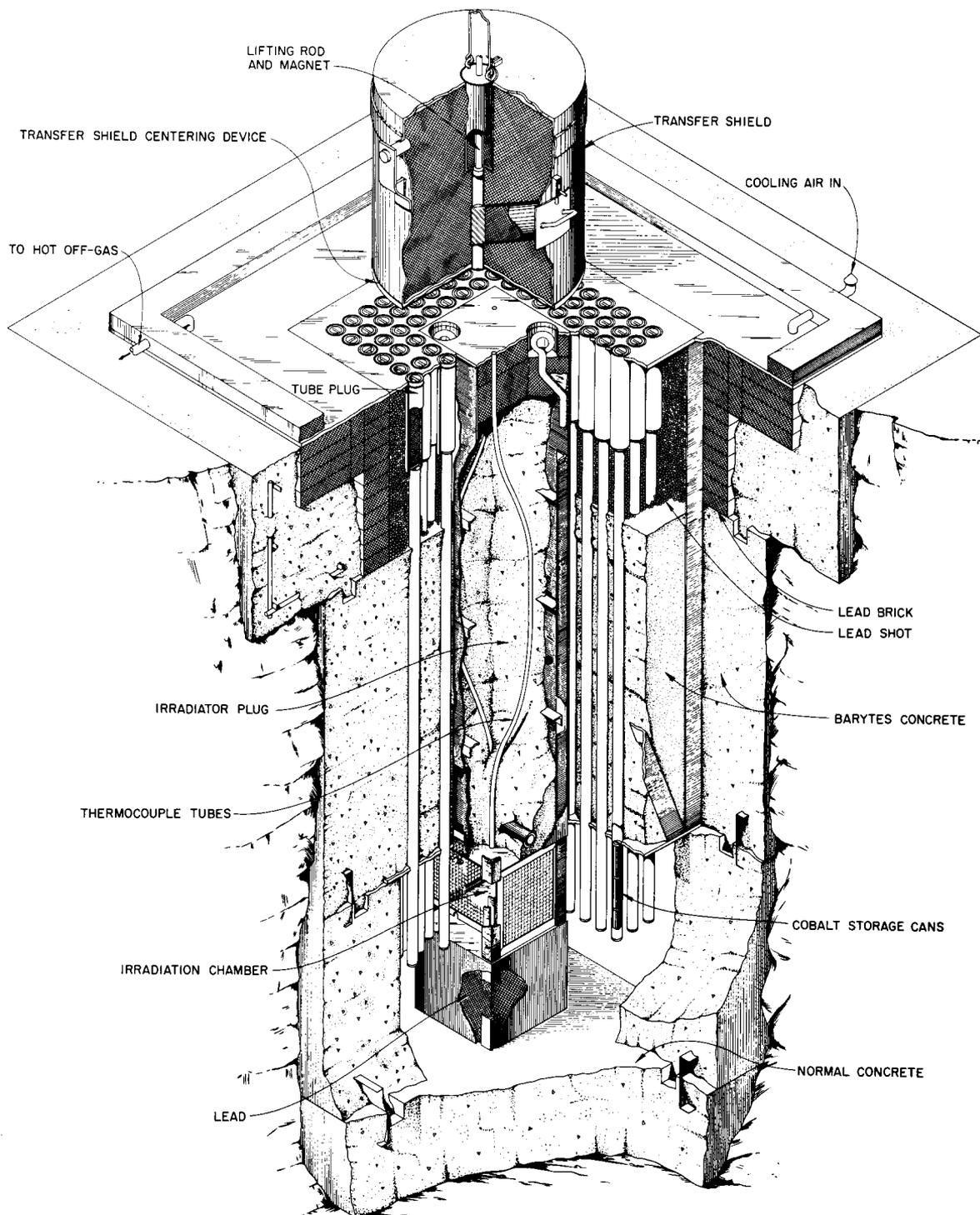


Figure 3. Cobalt Storage Garden.

of cerous ions is independent of the concentration of ceric ions from 3.2×10^{-2} molar to approximately 10^{-5} molar, energy independent from approximately 100 kV x-rays to 2 Mev gamma rays, and independent of the dose rate from one-half roentgen per second to greater than 500 roentgens per second.⁴⁷

In calibrating the cobalt garden a standardized ceric ion solution is placed in the garden for a known period of time. After removal, the solution is titrated with a standardized oxidizing solution which oxidizes the cerous ions formed during irradiation to ceric ions. The amount of oxidizing agent needed for the oxidation reaction is a measure of the number of cerous ions formed. This value may be converted to dose by the G-factor, which is the number of ceric ions reduced per 100 e.v. of energy absorbed. The G-factor has been determined experimentally as 2.34 ions per 100 e.v.⁴⁸ Since the total number of ions reduced is known, the total number of electron volts absorbed may be calculated. This may easily be converted to ergs, and by assuming 93 ergs per roentgen in the solution,⁴⁹ the total number of roentgens may be computed. The exposure dose rate is obtained by dividing the total number of roentgens by the exposure time. (Because of the difficulty in converting ergs of absorbed dose in the solution to ergs of absorbed dose in a specimen, the exposure dose in roentgens is used.)

⁴⁷J. Weiss, *Nucleonics*, 10(7), 28 (1952).

⁴⁸Isotope Division, ORNL, private communication.

⁴⁹J. Weiss, op. cit., p. 29.

VII. TESTING APPARATUS

Three separate test systems are necessary to determine the stress-strain relationship and creep rate of rock salt. These are:

A. Force Application

A 120,000-pound capacity Baldwin-Tate-Emery Universal Testing Machine, shown at the left in Fig. 4, was used for force application. This machine contains a hydraulic capsule, connected through a pumping station to a reservoir of fluid, beneath a piston (which can be seen in Fig. 4) which is free to move in the vertical direction.

The hydraulic capsule is not visible in Fig. 4, but the cylindrical frame containing the piston is visible. The upward movement of the piston raises the flat surface immediately above the piston, the two unthreaded columns, and the crosshead supported by these columns. The two threaded columns are supported by the frame of the machine and are stationary. The lower crosshead may be raised or lowered to position specimens, but is stationary during force application. Compression specimens are placed between the lower crosshead and the top of piston, and tensile specimens are placed between the two crossheads.

Special equipment is required to hold specimens in position. The compression "rig" used for the experiments at room temperature is shown in

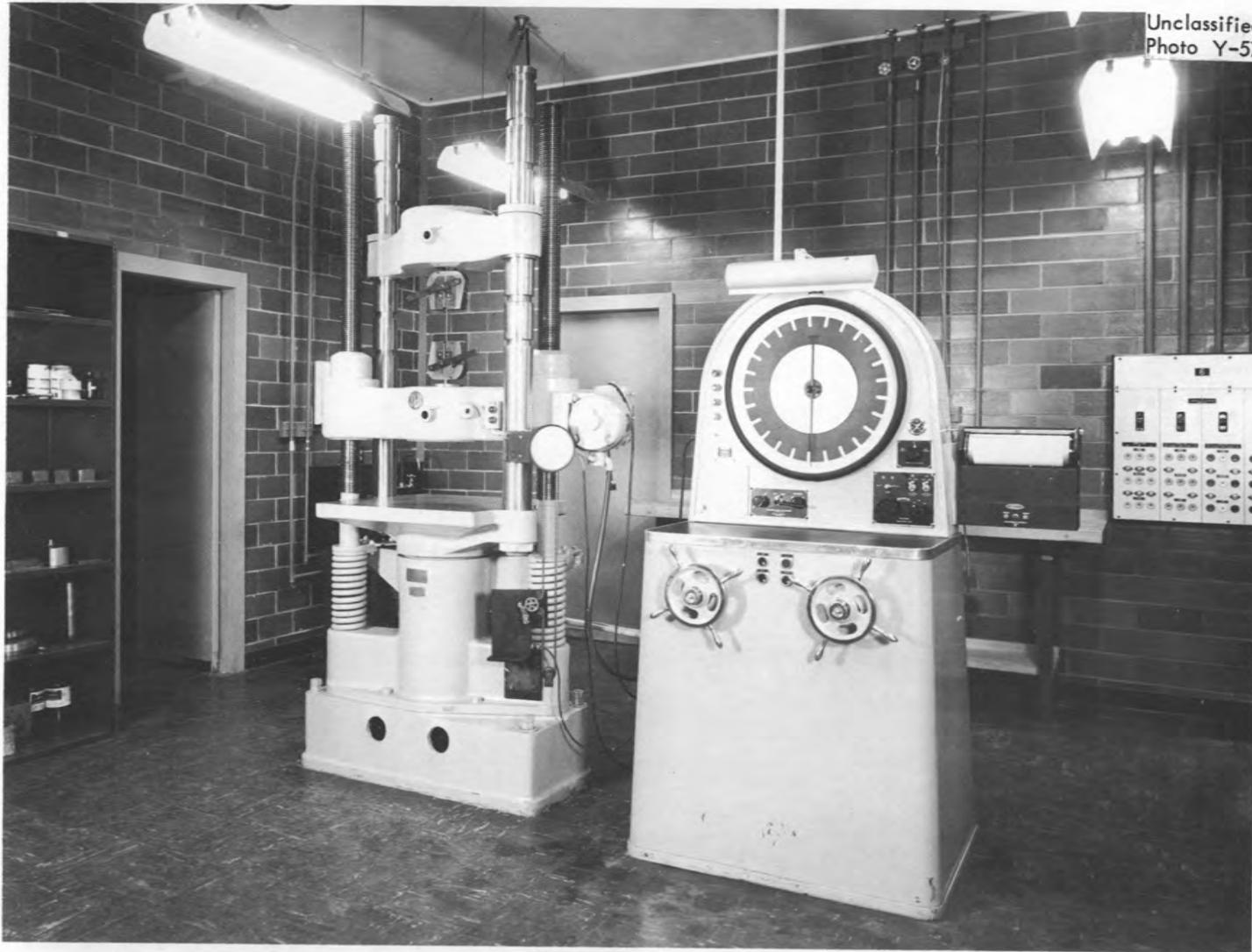


Figure 4. Baldwin-Tate-Emery Universal Testing Machine.

Fig. 5 with a specimen in position for force application. A different compression rig was used for work at elevated temperature, so that the specimen could be surrounded by a heat source. The disassembled equipment used for work at 200° C is shown in Fig. 6. In this case one metal block extends up from the top of the piston, and another down from the lower crosshead. The specimen is placed on the lower block, and the oven, shown in the left in Fig. 6, is placed in position so that it surrounds the specimen. When assembled, this equipment provides a source of heat in such a way that the force applied to the salt is uninfluenced by the presence of the oven.

The oven was electrically heated and controlled. In order to determine the temperature gradient across a specimen, holes were drilled in a specimen and thermocouples inserted into the holes. The thermocouple readings (on a Brown recorder) were observed to detect temperature variations across the specimen. The temperature across the control was constant to plus or minus 5° C. This variation is probably due in part to varying crystal size and purity across the specimen.

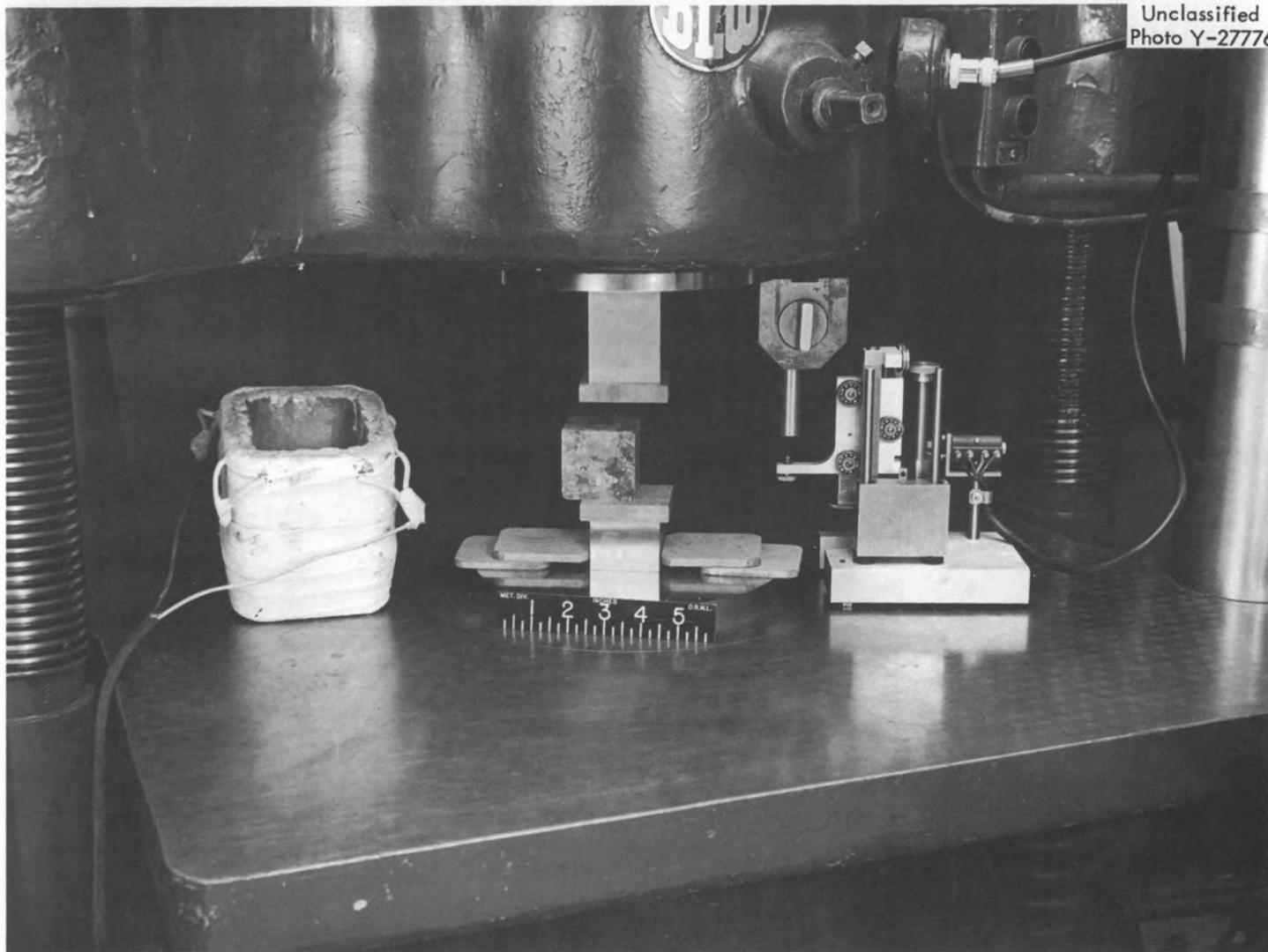
B. Force Measurement

The force measuring system is also a hydraulic device. The main component is a "Bourdon tube," which is a closed end, curved metal tube, connected to the capsule in the force applying machine. This tube contains hydraulic fluid and tends to straighten as the pressure on the fluid is increased. Therefore, as the pressure in the capsule increases, it also increases in the tube. By mechanically magnifying the movement of the end

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Photo Y-27775



Figure 5. Room Temperature Compression Rig.



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Photo Y-27776

Figure 6. Elevated Temperature Compression Rig.

of the tube, a pointer can be rotated over a scale calibrated to read the magnitude of the force. Furthermore, the force-indicating device may be arranged to actuate a stylus, and, therefore, record the force.

The combination force-applying, force-measuring device is remarkably accurate and is guaranteed by the manufacturer to be within 1 per cent of the applied force. The particular apparatus used in this experiment was correct to within $1/4$ of 1 per cent of the applied force.⁵⁰

C. Deformation Measurement

Deformation was measured by a Bell-Crank-Anvil extensometer. This instrument, shown in the foreground of Fig. 5, measures the movement of the piston and not the direct deformation of the salt. This gives a better measurement of the total deformation than could be obtained by connecting a deformation measuring instrument directly to the specimen, because the deformation of the salt is not uniform over the cross-section of the specimen.

Two miniature transformers are the major components of the Bell-Crank-Anvil extensometer. One transformer is located in the extensometer and the other in the recording device. When the extensometer is not in operation, the outputs of the two transformers are balanced. As the specimen is deformed a lever on the extensometer displaces one of the transformers. This movement causes a change in the output of the transformer, and upsets the

⁵⁰ Calibration data, Mechanical Testing Laboratory, ORNL.

balance between the two transformers. The unbalanced signal is amplified and drives a servo motor. The motor rotates a drum and at the same time moves the second transformer to a position where the balance is re-established. As the specimen continues to deform, this process is repeated. Although this is a step-by-step process, the rotation of the drum is essentially continuous and offers a record of the deformation.

By having the force-actuated stylus move on the rotating drum, a total force versus total deformation curve is obtained. This curve may then be reduced to a stress-strain diagram.

The equipment discussed above was also used for creep measurement. A constant force was applied, and the deformation was read from the rotating drum at regular time intervals. The strain as a function of time was then plotted from this data.

VIII. EXPERIMENTAL RESULTS

A. Introduction

Deformation-force curves were obtained for three samples each of dome salt, bedded salt where the force was applied perpendicular to the planes of stratification, and bedded salt where the force was applied parallel to the planes of stratification at radiation exposures of 0, 10^6 , 10^7 , 10^8 , and 5×10^8 roentgens at room temperature. In addition, similar tests were run on the same species of salt at 200° C at radiation exposures of 0 and 5×10^8 roentgens. Creep tests were run on the same species of salt at room temperature and at radiation exposures of 0 and 5×10^8 roentgens. The deformation-force curves were normalized to stress-strain curves and the compressive strength, yield strength, apparent elastic limit, and modulus of elasticity and their standard deviations computed.

B. Stress-Strain Relationship

1. Room Temperature

(1) Unirradiated Dome and Bedded Salt.-- Specimens of dome salt, bedded salt loaded parallel to the planes of stratification, and bedded salt loaded perpendicular to the planes of stratification were tested to establish a control with which to compare irradiated specimens. The results of these tests are shown graphically in Fig. 7 and in tabular form in Table 2.

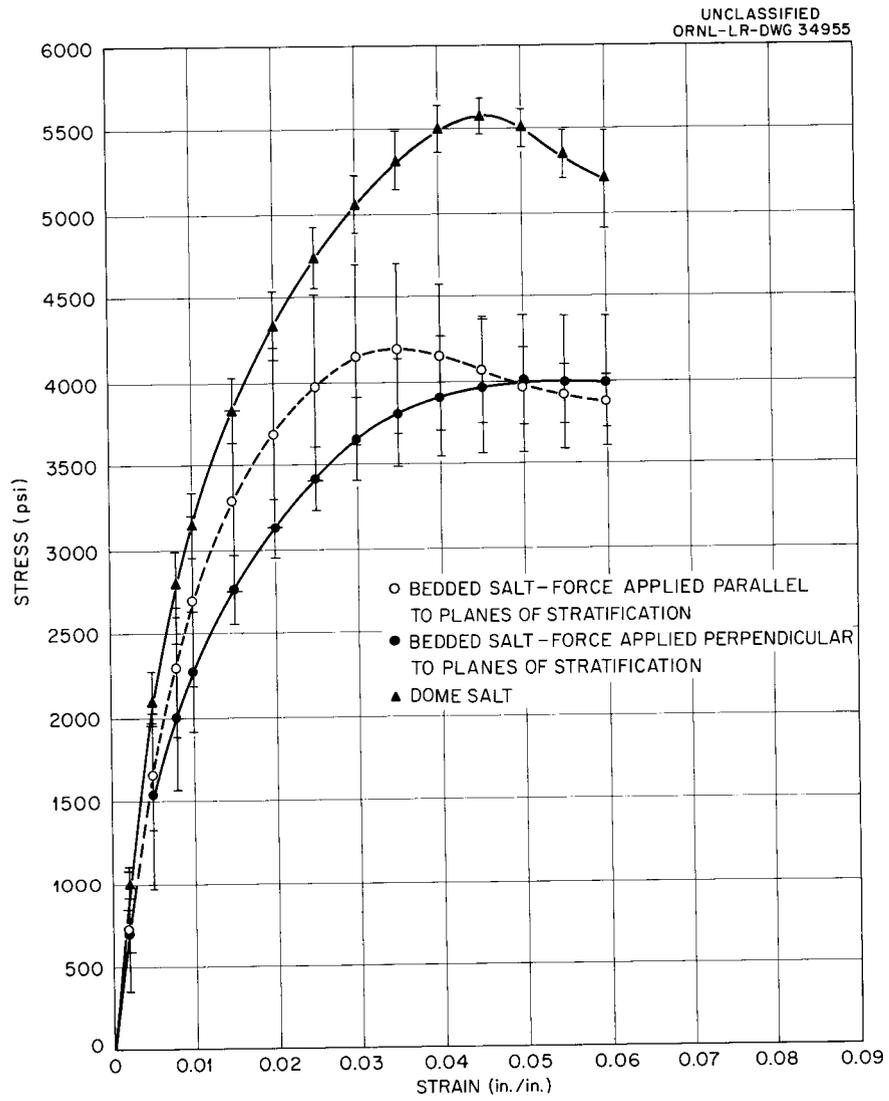


Figure 7. Compression Test of Unirradiated Salt at Room Temperature.

TABLE 2

PHYSICAL PROPERTIES OF ROCK SALT^a

Type of Salt	Exposure Dose (r)	Compressive Strength (psi)	Yield Strength (psi)	Apparent Elastic Limit (psi)	Modulus of Elasticity ₆ (psi) x 10 ⁶
At 20° C					
Bedded Parallel*	0 ₆	4200 ± 500	2500 ± 300	1900 ± 300	0.35 ± .06
	10 ₇	4500 ± 500	2500 ± 150	1900 ± 200	0.32 ± .06
	10 ₈	4600 ± 400	2700 ± 250	2100 ± 200	0.35 ± .02
	10 ₈	4600 ± 150	3400 ± 250	2800 ± 200	0.36 ± .09
	5 x 10 ⁸	3500 ± 50	2700 ± 200	2000 ± 300	0.39 ± .07
Bedded Perpendicular**	0 ₆	4000 ± 400	2300 ± 300	1700 ± 200	0.36 ± .17
	10 ₇	3800 ± 500	1800 ± 250	1400 ± 250	0.35 ± .10
	10 ₈	4100 ± 400	2300 ± 500	1800 ± 500	0.38 ± .04
	10 ₈	4000 ± 400	2400 ± 500	1900 ± 300	0.38 ± .06
	5 x 10 ⁸	3500 ± 400	2400 ± 300	1900 ± 250	0.37 ± .11
Dome	0 ₆	5600 ± 100	2900 ± 150	2000 ± 100	0.50 ± .05
	10 ₇	5300 ± 100	2900 ± 150	2000 ± 300	0.51 ± .12
	10 ₈	5100 ± 200	3000 ± 100	2100 ± 300	0.62 ± .06
	10 ₈	4100 ± 200	2700 ± 100	1800 ± 200	0.48 ± .04
	5 x 10 ⁸	3600 ± 500	2600 ± 200	1900 ± 50	0.59 ± .12
At 200° C					
Bedded Parallel	0 ₈	3900 ± 200	1600 ± 200	1400 ± 100	0.09 ± .01
	5 x 10 ⁸	3400 ± 400	1900 ± 250	1800 ± 250	0.12 ± .02
Bedded Perpendicular ^b	0 ₈	3600 ± 100	1600 ± 100	1500 ± 150	0.11 ± .01
	5 x 10 ⁸	3300 ± 400	2100 ± 150	1800 ± 100	0.13 ± .01
Dome	0 ₈	3600 ± 500	1900 ± 150	1600 ± 200	0.14 ± .01
	5 x 10 ⁸	3100 ± 300	2300 ± 150	1800 ± 200	0.16 ± .01

*Bedded Parallel - bedded salt, force applied parallel to the planes of stratification.

**Bedded Perpendicular - bedded salt, force applied perpendicular to the planes of stratification.

^aAll results have been rounded off to the nearest 100 psi and the standard deviation to the nearest 50 psi.

^bTwo samples only tested.

The dome salt has greater compressive and yield strengths, apparent elastic limit, and modulus of elasticity than the bedded salt (Table 2). Previous experiments on synthetic crystals have indicated that small amounts of impurities added to the sodium chloride increases the yield strength of rock salt. However, as previously noted, results obtained for synthetic crystals are not directly applicable to aggregates of natural crystals. It was also noted that the binding energy between atoms and the presence of lattice imperfections determines the strength of a material. The presence of impurities (mostly anhydrites and shale) is at least partially responsible for the greater statistical variation exhibited by the bedded salt. The dome salt, although neither isotropic nor homogeneous, is much more uniform with respect to impurities than the bedded salt. The original block of bedded salt was interstratified with anhydrite and shale bands of various thicknesses, and machining resulted in specimens of varying impurity content.

Unirradiated bedded salt appears to be slightly stronger when loaded parallel to the planes of stratification than when loaded perpendicular to the planes of the stratification.

(2) Irradiated Bedded Salt Loaded Parallel to the Planes of Stratification.-- The effect of radiation on the stress-strain relationship of bedded salt exposed to 10^6 , 10^7 , 10^8 , and 5×10^8 roentgens and loaded parallel to the planes of stratification is shown graphically in Fig. 8 and in tabular form in Table 2.

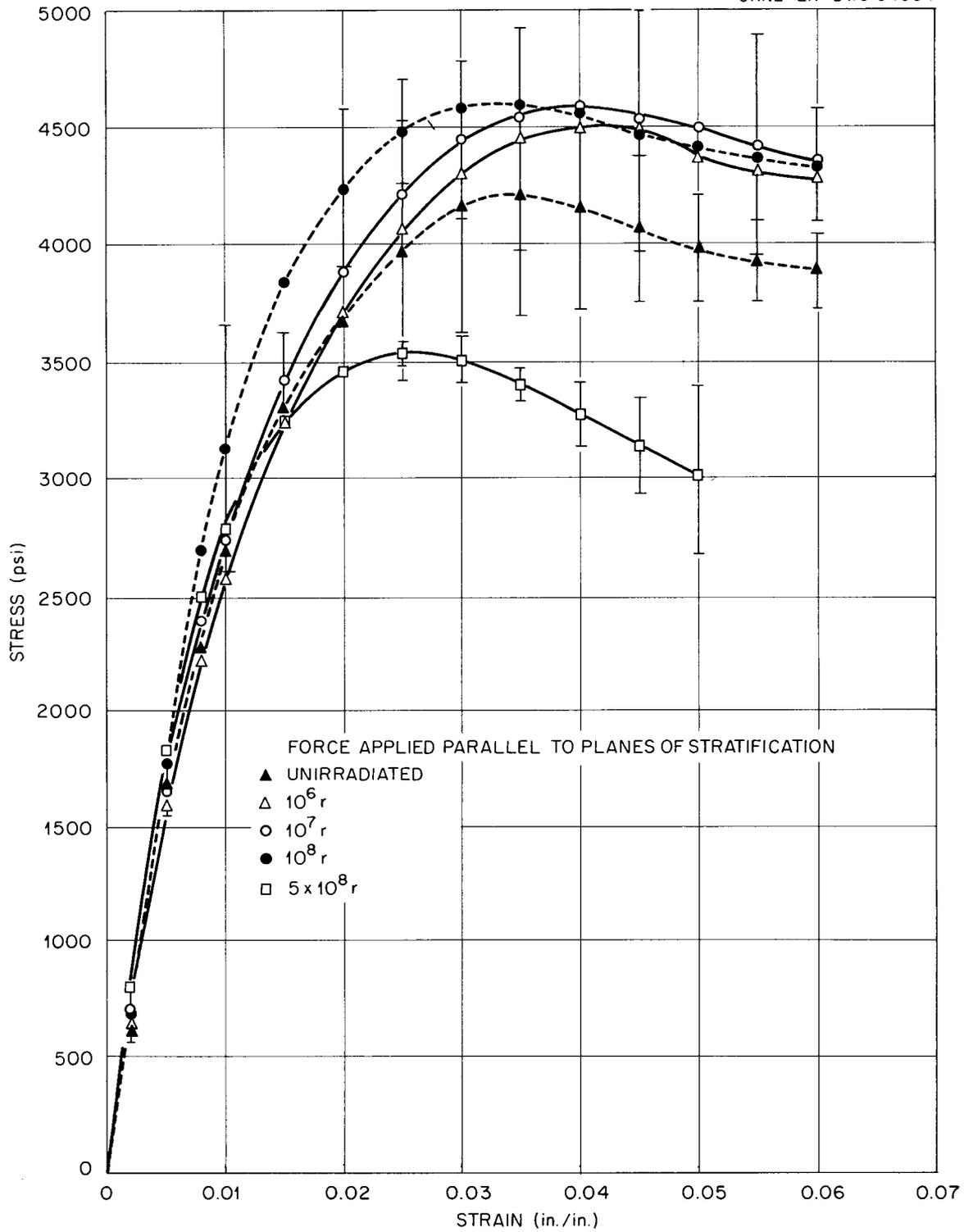
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Figure 8. Compression Test of Bedded Salt at Room Temperature.

It is apparent from Fig. 8 that there is little difference in the stress-strain curves up to a stress of 2000 pounds per square inch. Therefore, the increase in the modulus of elasticity, expected on the basis of positive ion vacancies pinning dislocations, is not evident. Only at the highest dose (5×10^8 r) is there any increase in the modulus of elasticity. In fact, at an exposure of 10^6 roentgens the modulus of elasticity is lower than the unirradiated specimens. The lack of any appreciable change in the modulus of elasticity could be the result of the wide variations in individual specimens.

The compressive strength increases with exposure until the 5×10^8 roentgen exposure dose, where a decrease is observed. The yield strength and apparent elastic limit reach a maximum at an exposure of 10^8 roentgens. However, when exposed to 5×10^8 roentgens, the yield strength and apparent elastic limit, unlike the compressive strength, are greater than the unirradiated specimens.

(3) Irradiated Bedded Salt Loaded Perpendicular to Planes of Stratification.-- The effect of radiation on the physical properties of bedded salt loaded perpendicular to the planes of stratification is shown graphically in Fig. 9 and in tabular form in Table 2.

These stress-strain curves are not appreciably different from those for bedded salt loaded parallel to the planes of stratification. Again there is very little difference in the curves up to a stress of 2000 psi.

There is some increase in the modulus of elasticity at exposures of 10^7 and 10^8 roentgens. The modulus of elasticity is less for an exposure

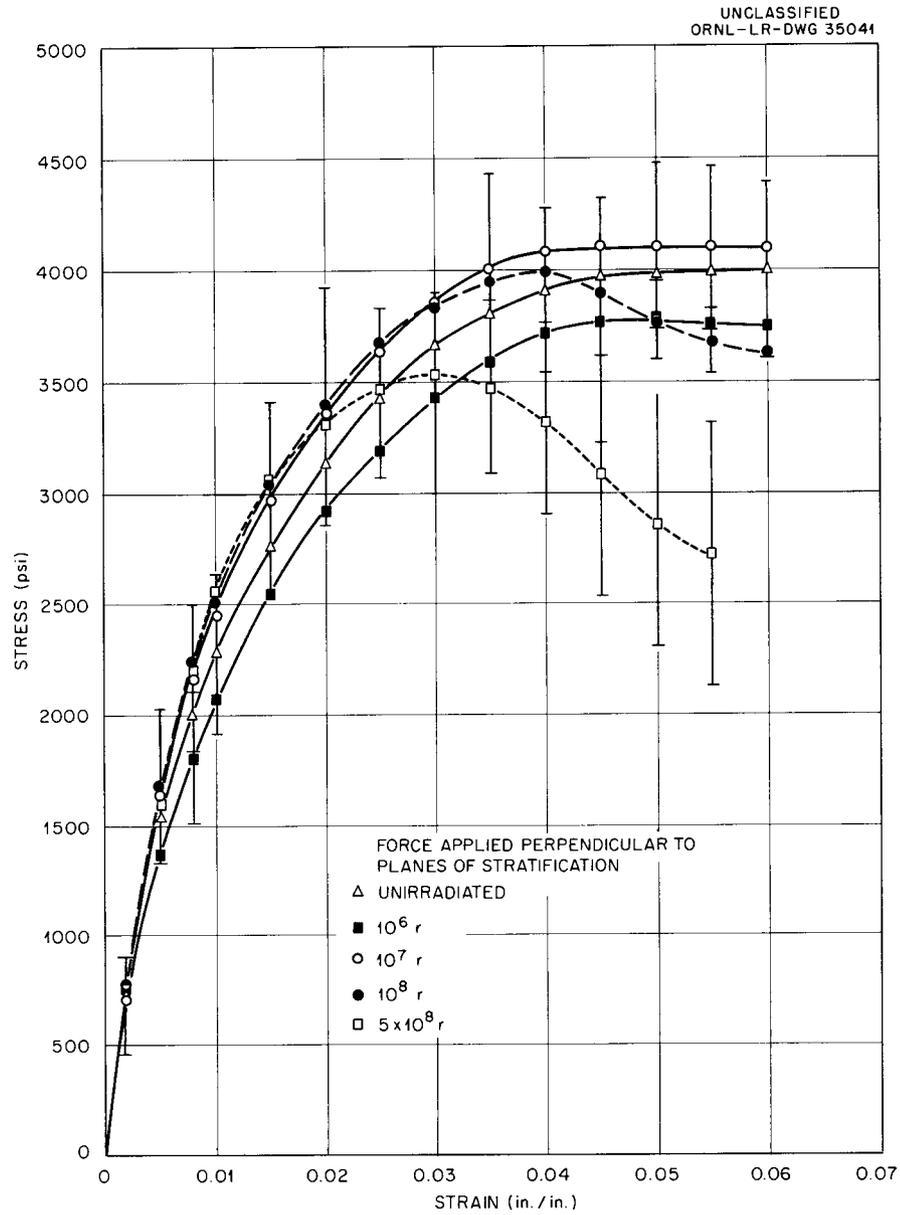


Figure 9. Compression Test of Bedded Salt at Room Temperature.

of 10^6 roentgens than for the unirradiated specimens. The compressive strength does not show an increase with dose as observed in Fig. 8. However, the compressive strength is the least for the 5×10^8 roentgen exposure. The yield strength and apparent elastic limit have their lowest value at an exposure of 10^6 roentgens and are practically constant for the higher exposures.

(4) Irradiated Dome Salt.-- The stress-strain relationship was determined for specimens of dome salt after exposure to 10^6 , 10^7 , 10^8 , and 5×10^8 roentgens. The resulting curves are shown in Fig. 10, and the values of physical properties determined from these curves are given in Table 2.

The stress-strain curves for dome salt exhibit little variation up to a stress of 2500 psi. Although the modulus of elasticity is higher for exposures of 10^7 and 5×10^8 roentgens than for unirradiated salt, it is less for an exposure of 10^8 roentgens. The compressive strength decreases continuously with increasing dose. The compressive strength for the highest exposure is almost 2000 psi less than for the unirradiated specimen. The yield strength and apparent elastic limit are essentially constant for exposures of zero, 10^6 , and 10^7 roentgens, while exposures of 10^8 and 5×10^8 roentgens give values which are lower than those for the unirradiated specimens.

2. Dome and Bedded Salt - 200° C

The rise in temperature of the salt adjacent to the storage cavities of radioactive wastes in salt formations prompted an investigation of the

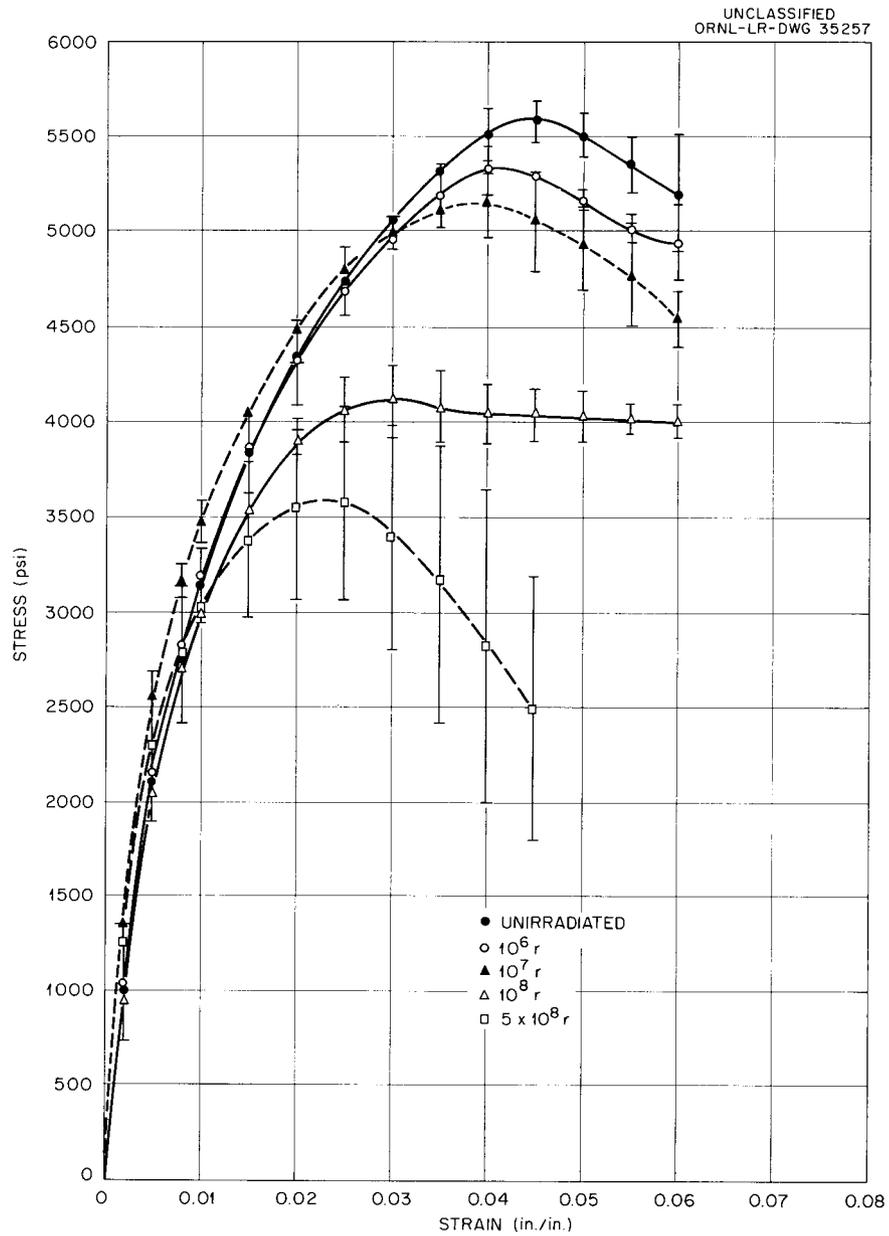


Figure 10. Compression Test of Dome Salt at Room Temperature.

physical properties of both unirradiated and irradiated salt at an elevated temperature. Because of the time required to test specimens at an elevated temperature, only two doses were studied: zero and 5×10^8 roentgens.

Specimens of dome and bedded salt were tested at a temperature of 200° C. Bedded specimens were tested parallel and perpendicular to the planes of stratification. These results are given in Figs. 11, 12, and 13, and in Table 2. (Note that the strain scale has been changed in Figs. 11, 12, and 13.)

Since the stress-strain relationships for the three types of salt respond to temperature and radiation in essentially the same manner, the results for all three will be treated together. As expected, the plasticity of salt increases quite rapidly with temperature, with a maximum deformation of 25 per cent. The deformation of specimens tested at room temperature and at 200° C is shown in Fig. 14.

The modulus of elasticity, yield strength, and apparent elastic limit at 200° C are much lower than at room temperature. The compressive strength appears to be lower than at room temperature. However, the specimens deformed to such an extent that force was exerted by the specimens on the sides of the oven. This is obviously not a true axial force, and when the sides of the specimens began to exert a force on the oven, the test was halted. Therefore, some of the specimens did not fail. This is shown by the fact that some of the stress-strain curves do not reach a peak, but are still rising at the maximum force applied.

The values given for the compressive strength are, therefore, a measure of the maximum force applied, rather than a true compressive strength.

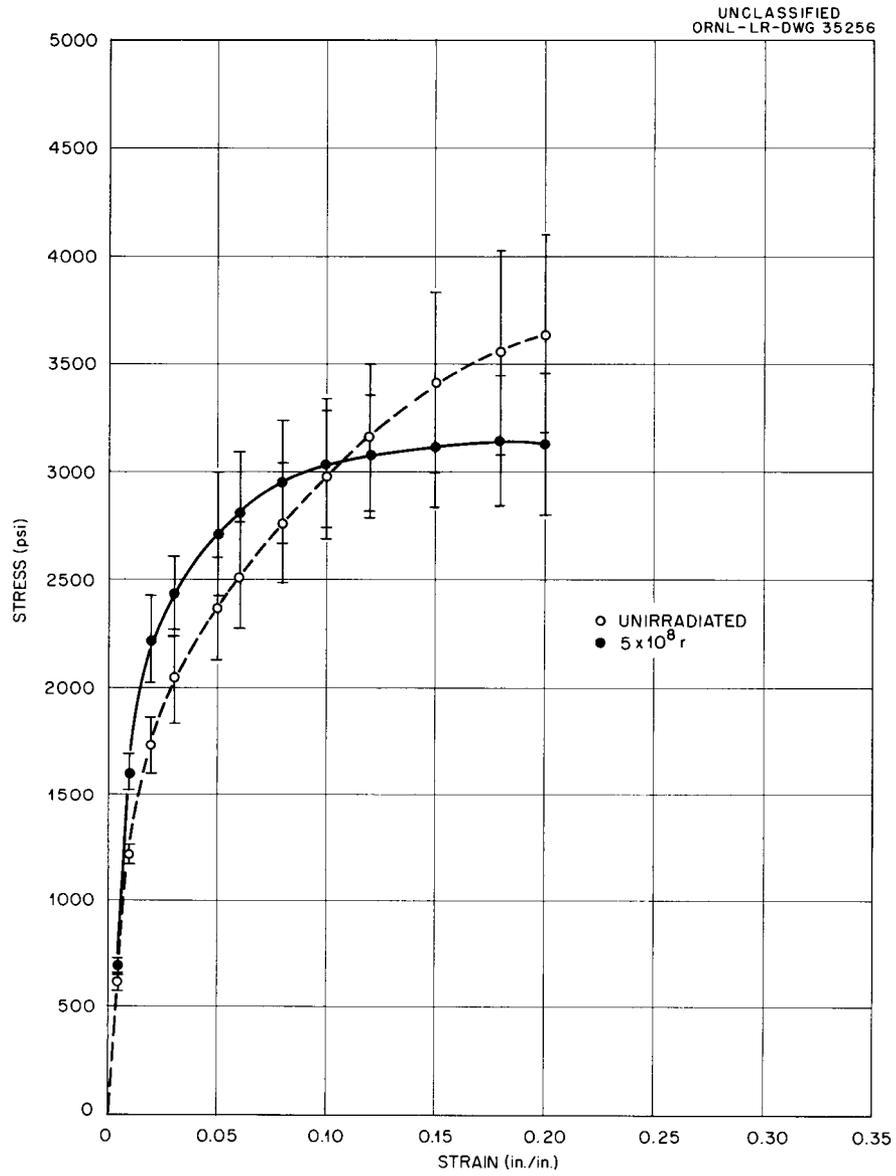


Figure 11. Compression Test of Dome Salt at 200°C.

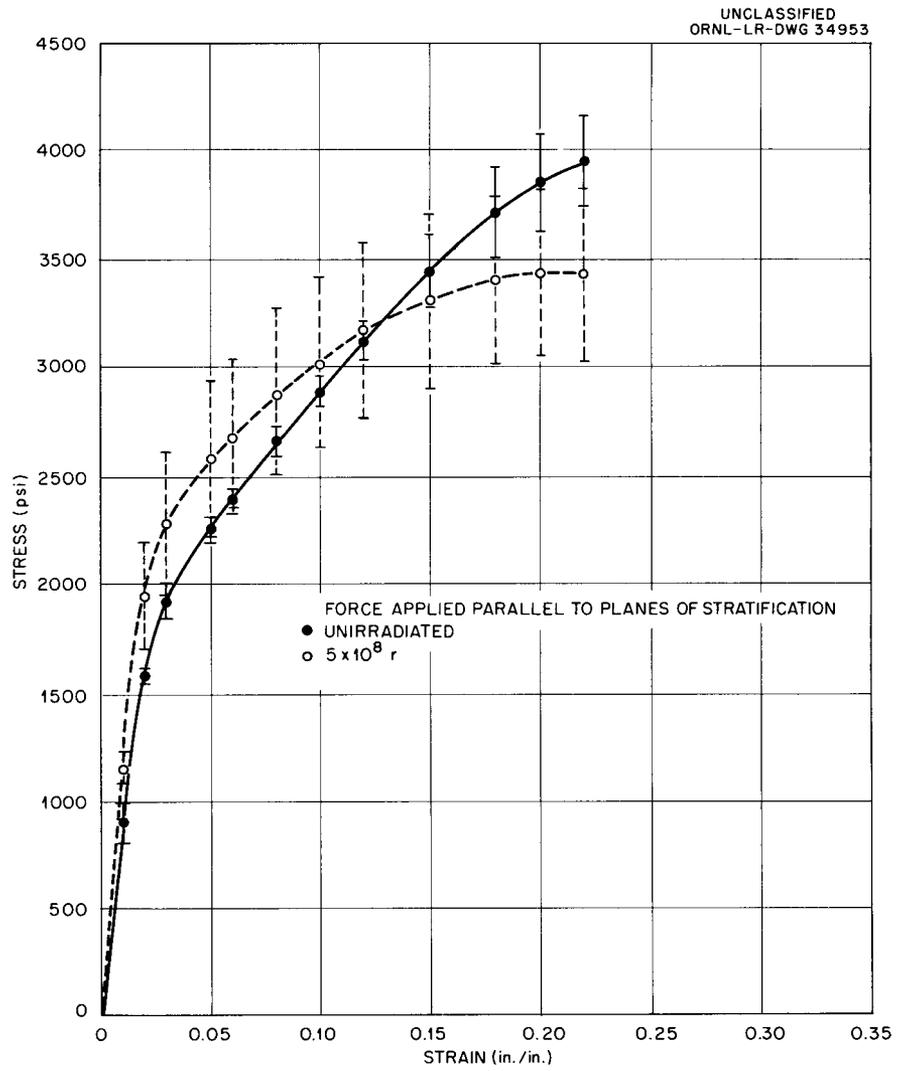


Figure 12. Compression Test of Bedded Salt at 200°C.

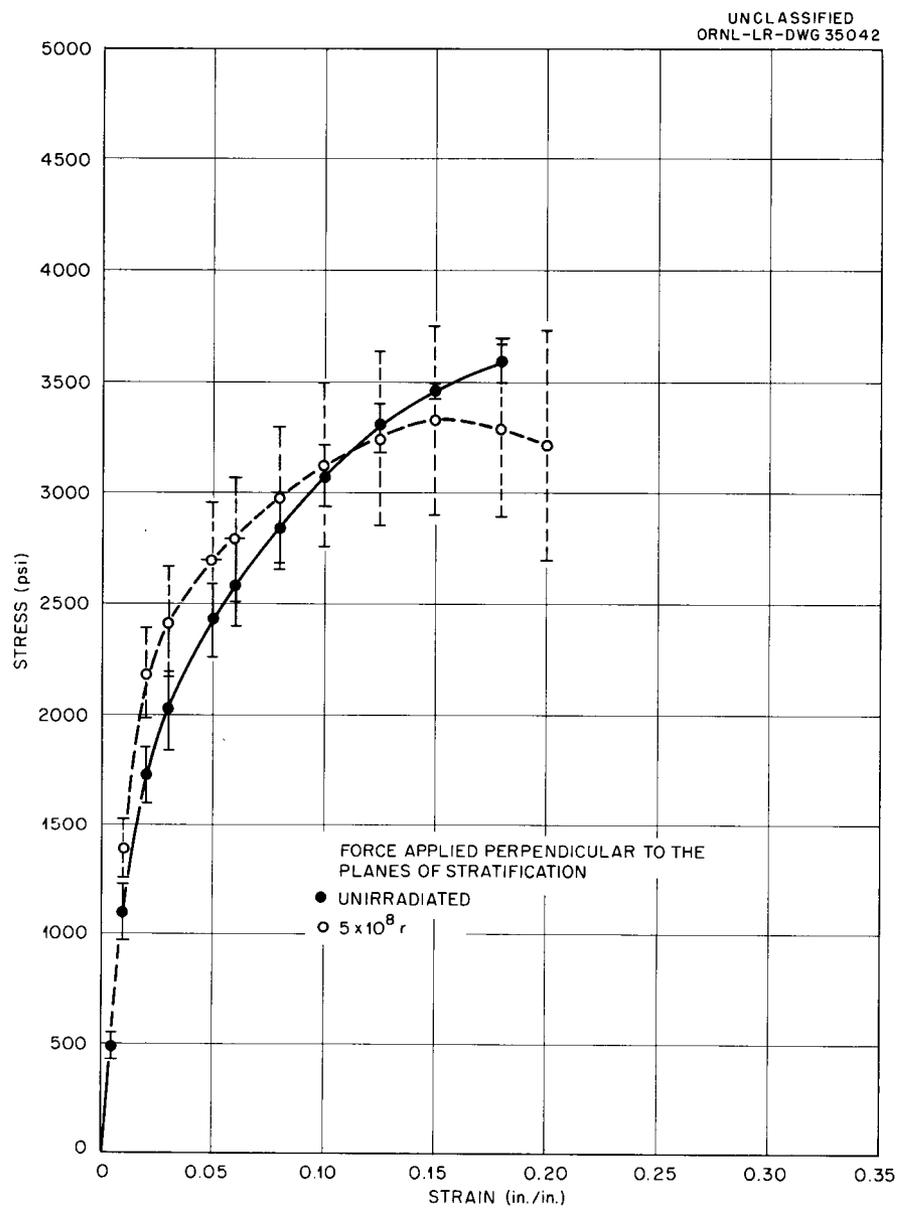


Figure 13. Compression Test of Bedded Salt at 200°C.

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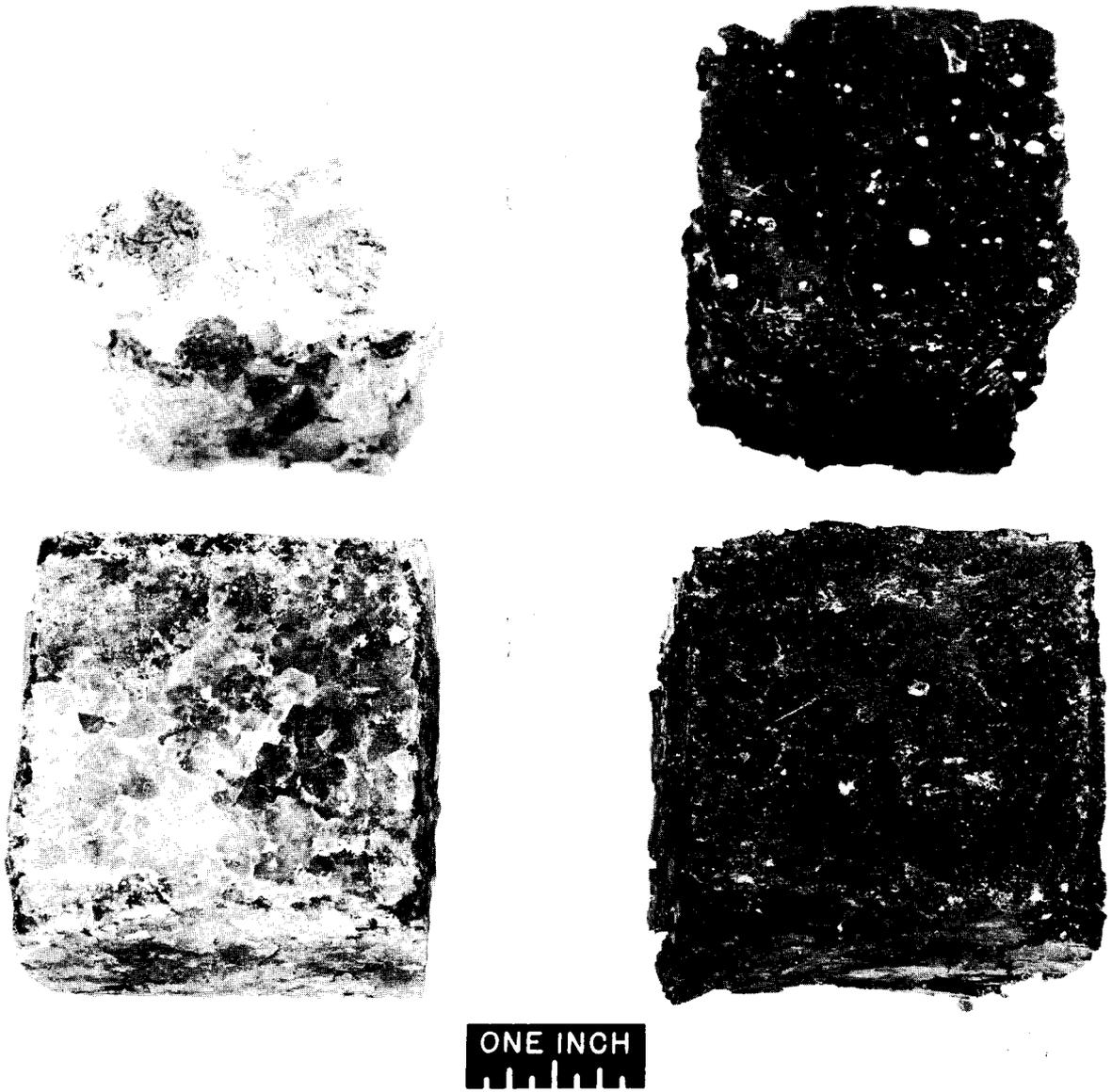


Figure 14. Deformation of Unirradiated and Irradiated Bedded Salt at Room Temperature (top) and at 200°C (bottom).

All irradiated specimens did fail, however, and the values of the compressive strength of 200° C and an exposure of 5×10^8 roentgens is comparable to those of salt tested similarly at room temperature.

For all three types of salt the stress-strain response for an exposure of 5×10^8 roentgens rises much faster initially and falls off more rapidly than the response of unirradiated specimens. Therefore, the modulus of elasticity, yield strength, and apparent elastic limit are increased.

C. Creep Tests

In addition to the static tests, the creep rate resulting from the application of a constant force of 2500 pounds per square inch for 100 minutes was measured.

1. Unirradiated Bedded and Dome Salt

The creep rates of unirradiated dome and bedded salt are shown in Fig. 15. After an initial rise, due mostly to elastic compression, the strain increases very slowly with time. As in the stress-strain tests the dome salt is strongest (least creep under the same load conditions) and exhibits the least variation in results. The bedded salt, loaded parallel to the planes of stratification, is again stronger than when loaded perpendicular to the planes of stratification.

2. Creep of Irradiated Salt

The effect of radiation on the rate of creep was studied by testing specimens exposed to 5×10^8 roentgens and comparing the results with the creep rate of unirradiated salt.

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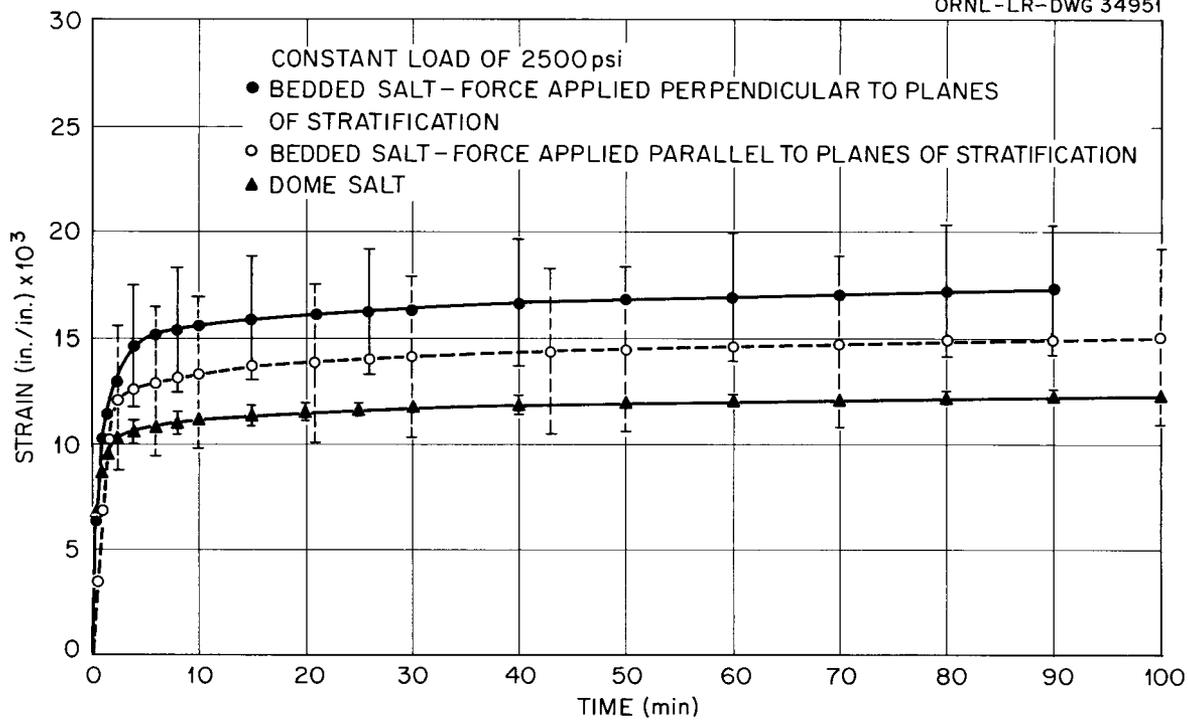


Figure 15. Creep Test of Unirradiator Salt at Room Temperature.

(1) Bedded Salt Loaded Parallel to the Planes of Stratification.--

The creep rate of bedded salt exposed to 5×10^8 roentgens and loaded parallel to the planes of stratification is compared with the creep rate of unirradiated salt in Fig. 16. Very little difference can be seen between the two creep rates. Only little over a thousandth of an inch/inch strain separates the curves. The unirradiated salt actually shows less strain than the irradiated. If the modulus of elasticity were increased, the irradiated salt should strain less. However, two of the irradiated specimens developed cracks during the test, resulting in a wide variation in results and probably causing the greater strain.

(2) Bedded Salt Loaded Perpendicular to the Planes of Stratification.-- The creep rates of unirradiated and irradiated bedded salt loaded perpendicular to the planes of stratification are compared in Fig. 17. In this case, the creep rate of the irradiated salt is less than that for the unirradiated specimens, indicating an increase in the modulus of elasticity.

(3) Dome Salt.-- Figure 18 shows the creep rate of dome salt exposed to 5×10^8 roentgens compared with the creep rate of unirradiated salt. Again the creep rate of the irradiated salt is less than for the unirradiated salt, which is another indication of a radiation induced increase in the modulus of elasticity.

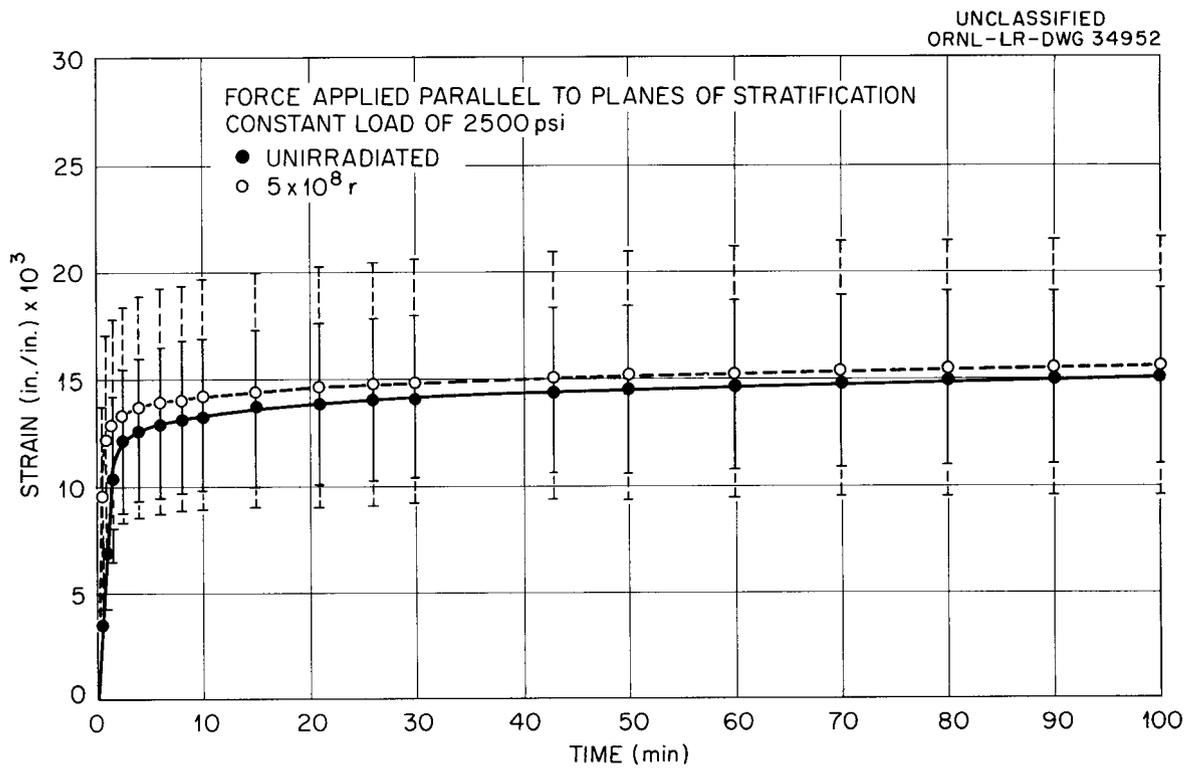


Figure 16. Creep Test of Bedded Salt at Room Temperature.

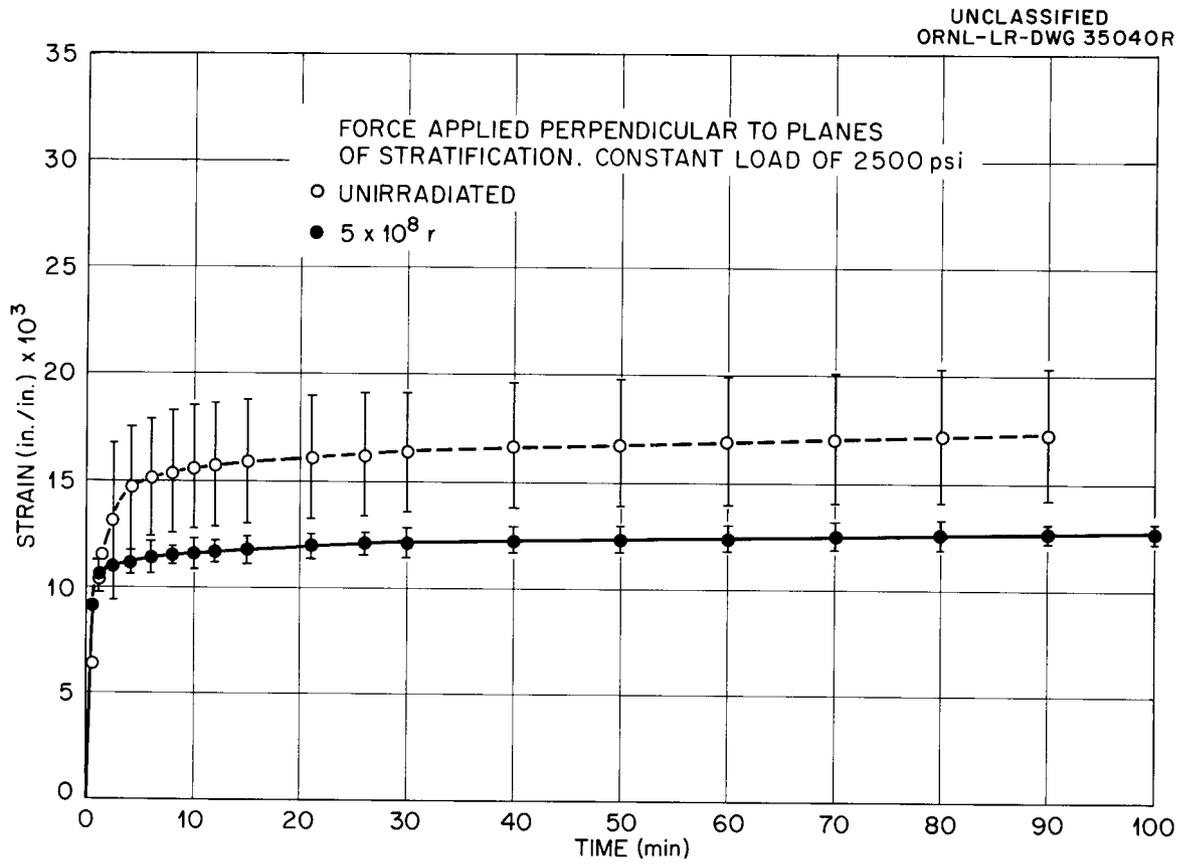


Figure 17. Creep Test of Bedded Salt at Room Temperature.

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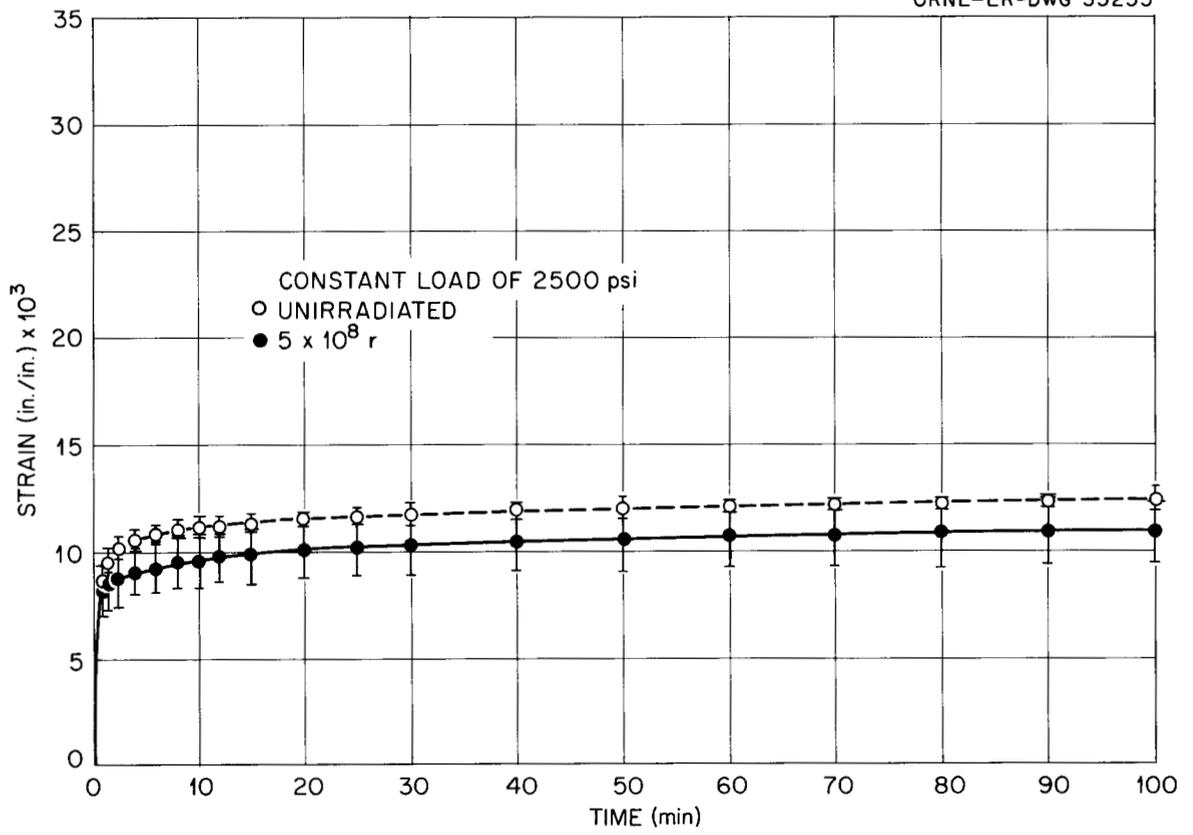


Figure 18. Creep Test of Dome Salt at Room Temperature.

IX. ANALYSIS OF RESULTS

The response of aggregates of rock salt crystals to radiation is difficult to evaluate. Although trends are observed where there appears to be a significant change in a particular physical property after irradiation, subsequent results often not only fail to substantiate the change but, in fact, often contradict such a change. However, geological formations, such as rock salt, are neither isotropic nor homogeneous, and specimens taken from geological formations vary considerably. Since the variation between specimens is large, radiation induced changes in the physical properties would necessarily have to be rather large to be easily detected.

It becomes important, therefore, to determine if the observed changes are real. A simple statistical calculation may be made which, although not conclusive, indicates the probability of a real difference existing between the two means.⁵¹ The most apparent changes have been analyzed in this manner, and the results are given below:

A. Compressive Strength

The compressive strength of rock salt exposed to 5×10^8 roentgens is, without exception, less than the compressive strength of unirradiated

⁵¹P. G. Hoel, Introduction to Mathematical Statistics (John Wiley and Sons, Inc., New York, 1947), p. 71.

rock salt. Calculations show that in every case the observed differences in the mean are probably real.

Although a continual decrease in compressive strength with increasing dose is observed for dome salt, no such change is evident for bedded salt. Possibly there is a real change at all doses, but the change is small for the lower doses and becomes apparent only at the highest dose. Furthermore, since dome salt behaves more uniformly than bedded salt, more confidence may be placed in results obtained for the dome salt. In fact, analysis of the difference between the mean compressive strength of the unirradiated dome salt and the mean compressive strength of the irradiated dome salt indicates that all the differences are probably real.

B. Modulus of Elasticity

Without exception, the modulus of elasticity is greater for exposures of 5×10^8 roentgens than for unirradiated specimens. Furthermore, the fact that the creep rate is less for irradiated salt than for unirradiated salt indicates the modulus of elasticity is increased by radiation.

Analysis of the data shows, however, that only four of the six cases indicate a probability of a real change. The results for lower exposures are even more perplexing. Not once is there a continual increase in the modulus of elasticity with dose.

C. Apparent Elastic Limit and Yield Strength

Contrasted with the compressive strength and modulus of elasticity where the more probable changes were all in the same direction, analysis

of the yield strength and apparent elastic limits show that there is a probability of an increase with dose in some cases (all tests at 200° C), a decrease in some cases (bedded perpendicular at 10^6 r and dome at 5×10^8 r), and no change in some cases (dome at 10^6 and bedded parallel at 10^6).

X. CONCLUSIONS

The response of dome and bedded rock salt aggregates to radiation and temperature was studied by determining the stress-strain relationship and the creep rate. The stress-strain relationships were used to determine the compressive strength, modulus of elasticity, yield strength (0.2% offset), and apparent elastic limit.

Unirradiated dome salt is stronger than unirradiated bedded salt. The greater strength of the dome salt is probably due to a more uniform crystalline structure. Furthermore, the dome salt exhibits the least variation in results, which is also attributed to a lack of uniformity in the bedded salt.

Under both static and creep loading conditions, the unirradiated bedded salt appears to be stronger when loaded parallel to the planes of stratification than when loaded perpendicular to the planes of stratification. However, statistical analysis shows there is little probability of a real difference.

As expected, the plasticity of rock salt increases quite rapidly with temperature. The compressive strength, modulus of elasticity, yield strength, and apparent elastic limit are less at 200° C than at room temperature.

Within the statistical variation of the experiment, radiation causes only minor changes in the physical properties of rock salt. Apparently,

any effect radiation may have on the physical properties of rock salt is small and becomes apparent only at the higher doses. Therefore, radiation effects on the physical properties of rock salt will not prohibit the disposal of radioactive wastes in salt cavities.

APPENDIX I

ADVANTAGES OF SALT CAVITIES FOR DISPOSAL OF RADIOACTIVE WASTES

The proposed use of cavities in salt formations as disposal sites for radioactive wastes is based upon the following advantages:

1. Widespread Distribution of Rock Salt

Rock salt is widely distributed. For example, the Salina formation underlies 100,000 square miles of New York, Pennsylvania, West Virginia, Ohio, and Michigan; the Permian formation, 120,000 square miles of Kansas, Colorado, Oklahoma, Texas, and New Mexico; and the Jurassic formation, 180,000 square miles along the Gulf Coast. This widespread distribution of rock salt will permit construction of disposal sites near nuclear power plants, thereby eliminating the cost of transporting wastes long distances.

2. Volume of Rock Salt

In 1943 the total volume of rock salt in the United States was estimated to be 6.0×10^{13} tons, and new deposits have been located much faster than the rate of consumption. Obviously, there is no shortage of salt and little possibility that contamination will render a valuable natural resource useless.

3. Location of Rock Salt Deposits

Rock salt deposits are located in areas of low seismic activity. Therefore, we may expect few seismic disturbances to the structure.

4. Structural Integrity of Rock Salt

Rock salt is structurally strong, and at depths of 700 feet, cavities as large as 100 feet high, 100 feet wide, and 3000 feet long need no support.

5. Thermal Conductivity of Rock Salt

The thermal conductivity of rock salt is high compared to other geological formations, thereby allowing a more rapid dissipation of fission product heat than other rock formations.

6. Impermeability of Rock Salt

Rock salt is impervious to the passage of water. This statement is supported by the absence of holes and caves in salt formations. If water were able to penetrate salt formations, one would expect to find caves and caverns similar to those formed in limestone formations by the passage of water through cracks and faults. Salt flows plastically to close any cracks or faults which might have been present, and only the surface of a salt deposit comes in contact with water.

The impermeability of salt to the passage of water should prevent the contamination of surface and ground water and assure the containment of wastes.

7. Economy of Developing Cavities in Salt

Solution cavities of 1- to 2-million-gallon capacity have been developed by the petroleum industry for as little as 1 to 5 cents per gallon. Excavated cavities cost from 2 to 10 cents per gallon. Larger cavities are cheaper.

APPENDIX II

PROBLEMS ENCOUNTERED IN THE DISPOSAL OF RADIOACTIVE WASTES IN SALT FORMATIONS

1. Migration of Radionuclides

Although salt is apparently impermeable to the passage of water, there is evidence that water molecules penetrate the crystal lattice of salt.⁵² There exists, therefore, the possibility of radionuclides migrating through the salt.

2. Heat Generation

The heat generated by fission-product decay will cause a rise in the temperature of the salt surrounding the waste-filled cavity. Since the plasticity of rock salt increases quite rapidly with temperature,⁵³ it becomes important to determine the maximum permissible temperature rise in the salt. Heat calculations have been made to determine the temperature rise in salt due to the storage of radioactive wastes in salt cavities. These calculations indicate that 6-year-old wastes may be stored in a spherical cavity of 10-foot radius without boiling.⁵⁴

⁵²R. B. Barnes, op. cit., p. 898.

⁵³W. Theile, op. cit., p. 700.

⁵⁴F. L. Parker et al., Status Report on Waste Disposal in Natural Salt Formations II, ORNL 2700 - Excerpt, p. 7.

3. Chemical Compatibility

The solubility of rock salt and associated impurities in synthetic wastes has been investigated, and the results indicate that wastes will have to be saturated with NaCl before disposal.

When wastes and rock salt are mixed, neutralized wastes have a lower gas production rate than acid wastes. The effect of radiation has been to hasten the rate of gas production.

4. Cavity Migration

The possibility of the entire cavity migrating through the salt is a major problem which could occur if the wastes were to repeatedly evaporate; condense on the salt cavity roof; dissolve the salt; and run back into the cavity.

BIBLIOGRAPHY

- Anonymous, Summary Report: AEC Reference Fuel-Processing Plant, Division of Civilian Application, Washington, D. C , WASH-743, 1957, p. 11.
- Barnes, R. B., "Plasticity of Rock Salt and its Dependence upon Water," Phys. Rev. 44, 898 (1933).
- Committee on Waste Disposal - Division of Earth Sciences, "Disposal of Radioactive Wastes on Land," April 1957, National Academy of Sciences - National Research Council Publication 519, p. 6.
- Cowdrey, I. H. and Adams, R. G , Materials Testing (McGraw Hill Book Co., Inc., New York, 1945).
- Cottrell, A. H., Dislocations and Plastic Flow in Crystals (Oxford Press, London, 1953).
- Davis, H. E., Troxell, G. E., and Wiskocil, C. T., The Testing and Inspection of Engineering Materials (McGraw Hill Book Co., Inc., New York, 1941).
- Eastermann, I., Levio, W. J., and Stern, O., "Change in Density of Potassium Chloride Crystals upon Irradiation with X-Rays," Phys. Rev. 75, 627 (1949).
- Frankl, D. R., and Read, T. A., "Effect of F-centers on the Internal Friction of Rock Salt Crystals," Phys. Rev. 89, 663 (1953).
- Gordon, R. B., and Nowick, A. S., "Elastic Modulus of X-Irradiated Salt," Phys. Rev. 98, 1540 (1955).
- Gordon, R. B., and Nowich, A. S., "Structure Sensitivity of the X-Ray Coloration of NaCl Crystals," Phys. Rev. 101, 977 (1956).
- Gordon, R. B., and Nowich, A. S., "The Pinning of Dislocations by X-Irradiation of Alkaline Halide Crystals," ACTA Metallurgia 4, 514-527 (1956).
- Heal, H. G., "Chemical Effects of Ionizing Radiation on Solids," Atomics, July 1955, p. 205.

- Heal, H. G., "Chemical Effects of Ionizing Radiation on Solids, II," *Atomics*, August 1955, p. 241.
- Hoel, P. G., Introduction to Mathematical Statistics (John Wiley and Sons, Inc., New York, 1949).
- Houwink, R., Elasticity, Plasticity, and the Structure of Water (Harren Press, Washington, D. C., 1953).
- Kuznetsov, W. D., and Sementsov, W. A., "Mechanische Eigenschaften von Steinsalzkristallen," *Zeit. für Krist.* 78, 443 (1931).
- Lane, J. A., "Nuclear Fuel Requirements for Large-Scale Industrial Power," *Nucleonics* 21(10), 65 (1954).
- Metag, W., "Einfluss von Fremdzusätzen auf die Kohäsionsgrenzen und die Ultramikroskopische Solbildung Synthetischer Steinsalzkristalle," *Zeit. für Physik* 78, 363 (1932).
- Parker, F. L., Hemphill, L., and Crowell, F., Status Report on Waste Disposal in Natural Salt Cavities, ORNL-2560, August 1958.
- "Salt," Encyclopedia of Chemical Technology (The Interscience Encyclopedia, Inc., New York, 1954), Vol. 12, p. 68.
- Schneider, E. E., "Optical and Thermal Activation Processes in X-Ray Coloured Crystals," *Symposium on Photographic Sensitivity*, Bristol, 1951, p. 13.
- Schulmann, J. H., "Effect of Impurities on the Coloration of Solids by Ionizing Radiation," *J. Phys. Chem* 57, 749 (1953).
- Seitz, R., "Color Centers in Alkali Halide Crystals, I," *Revs. Mod. Phys.* 18, 408 (1946).
- Seitz, R., "Color Centers in Alkali Halide Crystals, II," *Revs. Mod. Phys.* 26, 93 (1954).
- Serata, S., and Gloyna, E., "Reactor Fuel Waste Disposal Project," *Technical Report to the Atomic Energy Commission, AEC Contract AT(11-1) - 490*, University of Texas, January 1, 1959.
- Stamatiu, M., "Quelques Proprietes Physico-Mechanical Du Sel Gemme De Slanic," *Anuarul Institutului Geologic Al Romaniel* 17, 501 (1932).
- Shanley, F. R., Strength of Materials (McGraw Hill Book Company, Inc., New York, 1957).

Theile, W., "Temperaturabhängigkeit der Plastizität und Zugfestigkeit von Steinsalzkristallen," Zeit. für Physik 75, 770 (1932).

Weiss J., "Chemical Dosimetry Using Ferrous and Ceric Solutions," Nucleonics 10(7), 28 (1952).

Westervelt, D. R., "Mechanical Effects of Ionizing Radiation in the Alkali Halides," NAA-SR-288, February 3, 1954.

Zeitlin, H. R., Arnold, E., and Ullmann, J. W., "Economics of Waste Disposal," Nucleonics 15(1), 58 (1957).

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