TIME DEFORMATION
OF
POTASH ROCK

By

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A Thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

Time-deformation characteristics of potash under constant stress are necessary for design of potash mines under great depths of overburden. Studies of this type, made at the Colorado School of Mines, are the subject of this thesis.

Cylindrical potash specimens, 2-1/8-in. diameter, were loaded to constant stresses of 600; 750; 1,000; and 1,200 psi. The lever-type loading apparatus exhibited undesirable characteristics, but was suitable for the study. Resistance-type strain gages used for deformation measurements may have caused the excessive scatter of the data, which condition precluded fitting empirical curves to the data. Temperature fluctuations caused fluctuation of the time-deformation curves for the potash; initial strains of the potash specimens were more dependent on the degree of fracturing along intergranular boundaries than upon the applied stress.

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ACKNOWLEDGMENTS

The author wishes to take this opportunity to thank Professor Niles Grosvenor, Mining Department, Colorado School of Mines, and John Shaw, Research Director, and Robert Merrill, Physicist, of the Denver Mining Research Center, U. S. Bureau of Mines, Denver Federal Center, for advice and suggestions made during this study. Acknowledgment is also made to the Colorado School of Mines Research Foundation for use of the load frame, to the Denver Mining Research Center, U. S. Bureau of Mines for furnishing specimens and a strain indicator, and to International Minerals and Chemical Corporation for furnishing the sample blocks of potash.

INTRODUCTION

Time-deformation characteristics of potash have become increasingly important in recent years with the discovery and development of deep potash mines such as those at Moab, Utah, and Esterhazy, Saskatchewan, Canada. Lack of knowledge of the creep characteristics of potash and inability to determine these characteristics quickly in the laboratory have led to the present study, part of a Federal Bureau of Mines project.

The laboratory study of the time-deformation characteristics of potash described in this report was made to determine the general time-strain relationships for potash at low stresses, the suitability of the mechanical loading device, and the applicability of the strain-measuring method.

THEORETICAL BACKGROUND

Total strain of any material under load may generally be considered as the sum of three different types of strain: elastic strain, plastic strain, and anelastic strain (Lubahn, 1961, p. 49-52). (All compressive strains and stresses are shown as positive in this thesis.)

Elastic Strain

Elastic strain is apparent immediately after the load is applied and is recovered immediately after the load is removed. The relationship between axial stress and axial strain for perfectly elastic materials is given by Hooke's Law,

$$\sigma = E\epsilon \ , \tag{1}$$

where σ is stress in psi, ϵ is strain in μin./in., and E is the modulus of elasticity for the material in psi. The constant E, called Young's modulus, is theoretically a constant for any material which has not been stressed beyond the elastic limit. The elastic stress-strain relationship of (1) is plotted for several materials in figure 1. The slope of each straight line in figure 1 is E for the material.

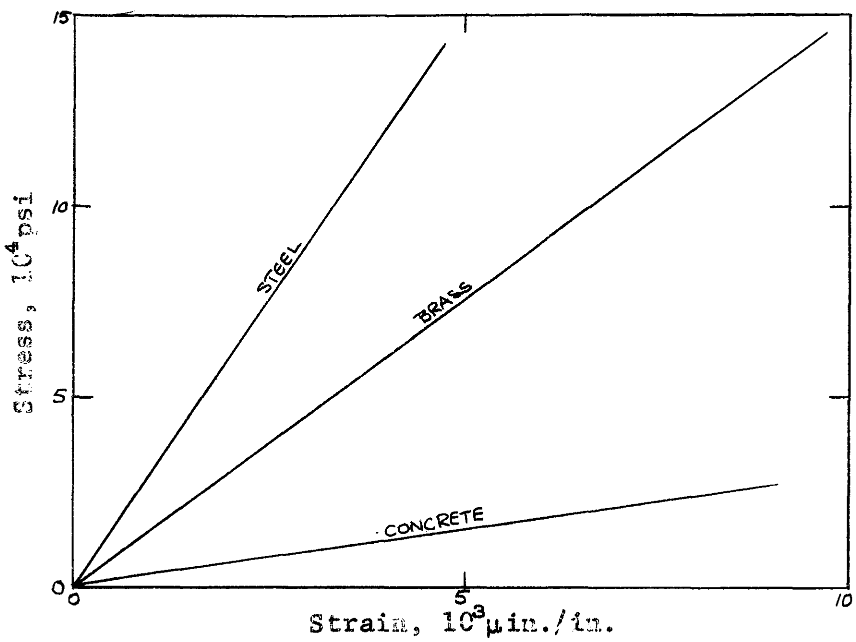


Figure 1. - Elastic stress-strain curves.

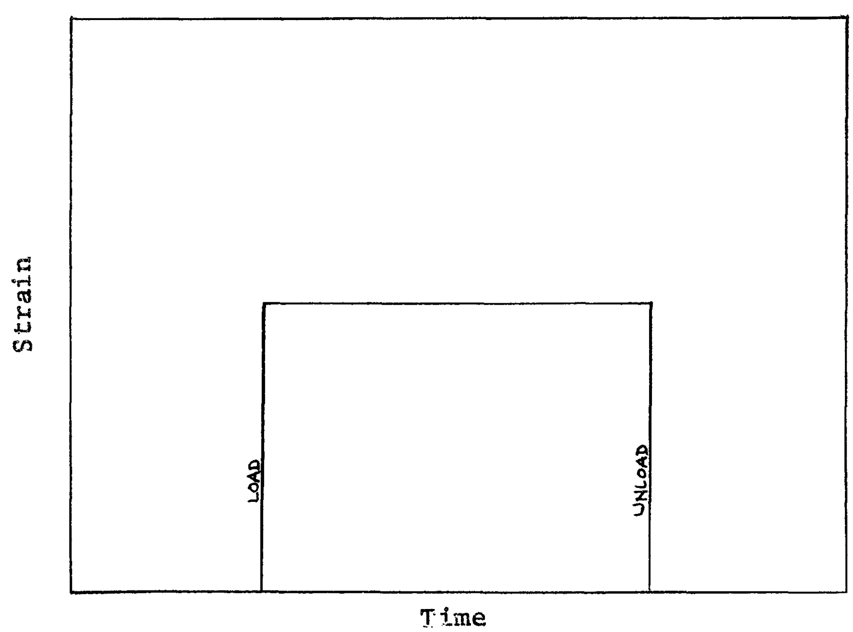


Figure 2. - Time-strain curve for ideally elastic material.

If an ideally elastic material is stressed to a constant stress level that is below the elastic limit, and later unloaded, the time-strain relationship would resemble the one shown in figure 2.

The elastic strain component is always present in any strain. The elastic component may be 100 percent of the total strain if the elastic limit is not exceeded, or may be only a small percentage of the total strain if non-elastic strains are large.

Plastic Strain

Plastic strain is not recoverable and may or may not be time dependent. Plastic strain may be apparent immediately after application of a load or may gradually increase with time. This possibility of instantaneous plastic strain makes it impossible to distinguish between elastic and plastic strain if strain measurements are made only during the loading and constant-stress portions of time-deformation tests; however, plastic and elastic strains may be differentiated if measurements are made during and after the unloading portion of the test. Figure 3 illustrates instantaneous plastic strain, and figure 4 illustrates a combination of instantaneous and time-dependent plastic strain. The elastic portion of the total strain is always recovered immediately after unloading. Plastic strain is permanent and is not recovered with time.

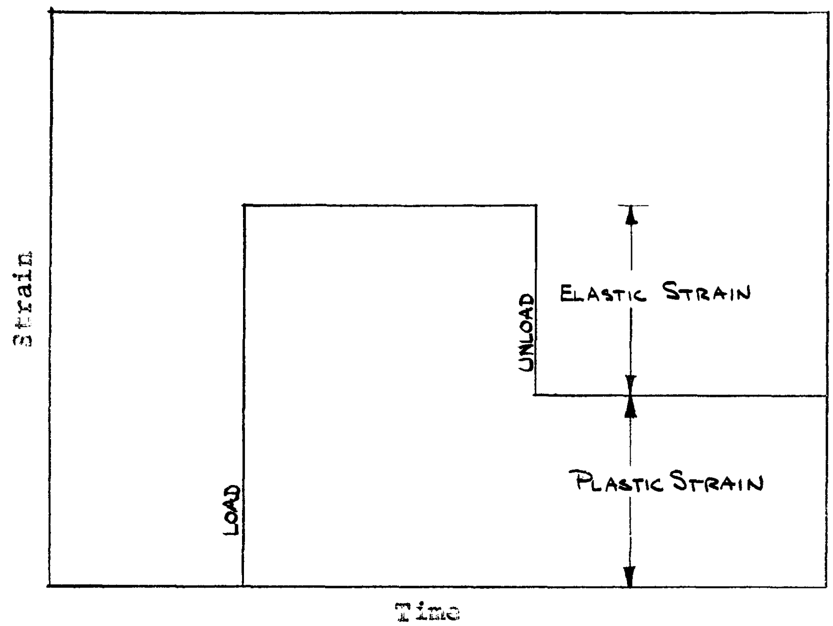


Figure 3. - Time-strain curve for elastic and instantaneous plastic strain.

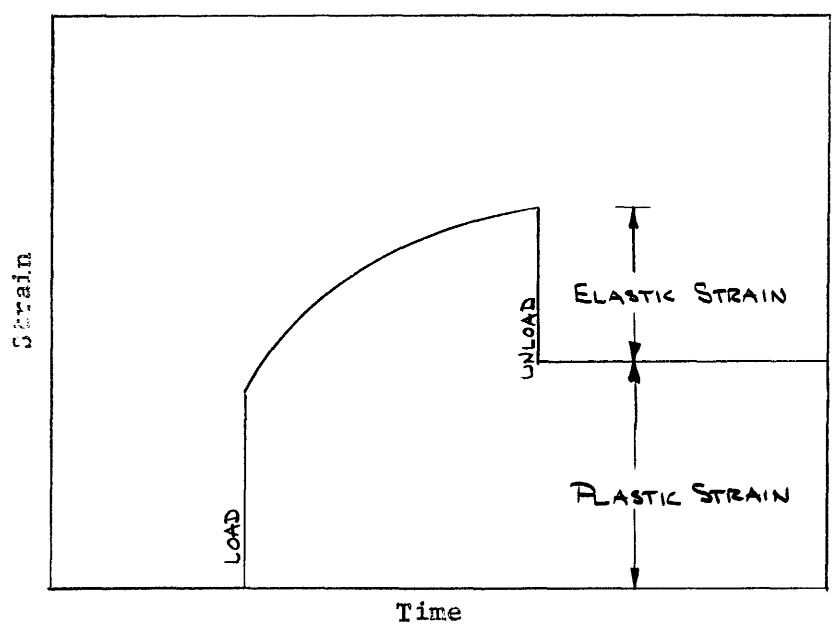


Figure 4. - Time-strain curve for elastic and time-dependent plastic strain.

Anelastic Strain

Anelastic strain is time dependent and recoverable. These two properties separate anelastic strain from elastic and plastic strains. Plastic strain is not recoverable, and elastic strain is not (theoretically) time dependent. The time dependence and recoverability of this strain are illustrated in figures 5 and 6. Figure 5 shows only elastic and anelastic strain; figure 6 illustrates elastic, plastic, and anelastic strains.

General Relationships

Actual: Long-term creep tests (fig. 7) and creep tests under various pressures (fig. 8) generally exhibit three types or stages of creep. These stages, shown in figures 7 and 8, are designated as primary (I), secondary (II), and tertiary (III) creep.

The three stages of creep are designated by Hardy (1959, p. 12-13) as follows:

(I) - primary (transient) creep. Observed in early stages of long-term tests and at low stresses.

(II) - secondary (steady-state) creep. Observed as second stage of long-term creep tests and at intermediate stresses.

(III) - tertiary (accelerating) creep. Observed as third stage of long-term creep tests or under high stresses. In both cases, it results in rapid failure of the specimen.

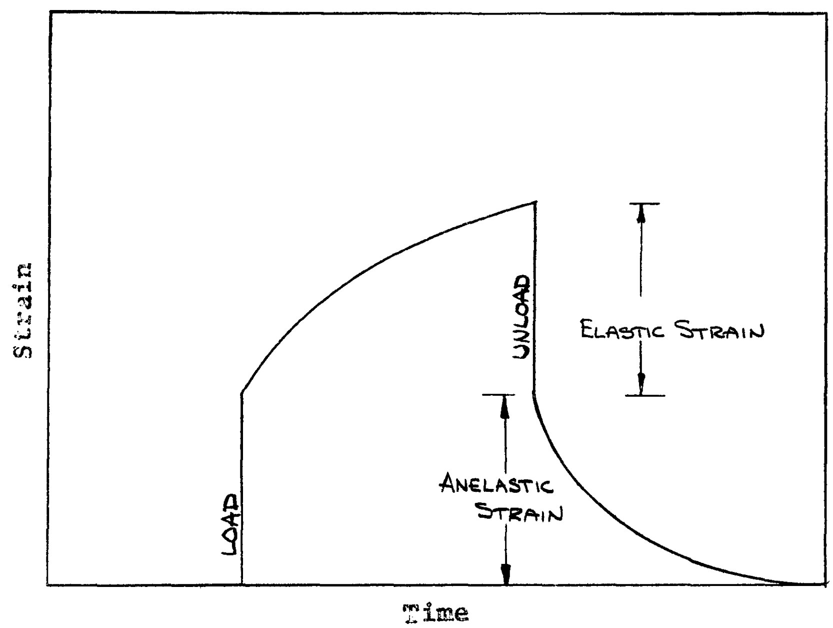


Figure 5. - Time-strain curve for elastic and anelastic strain.

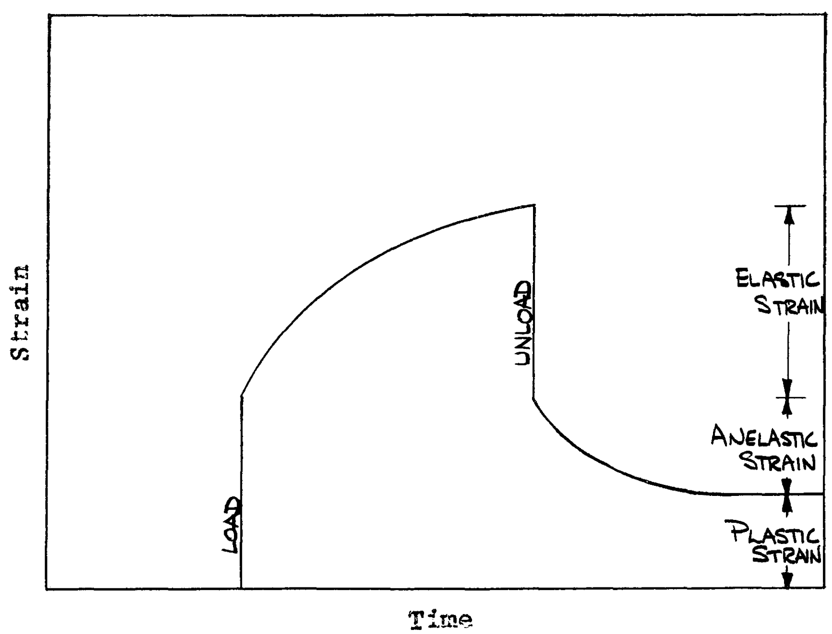


Figure 6. - Time-strain curve for plastic, anelastic, and plastic strain.

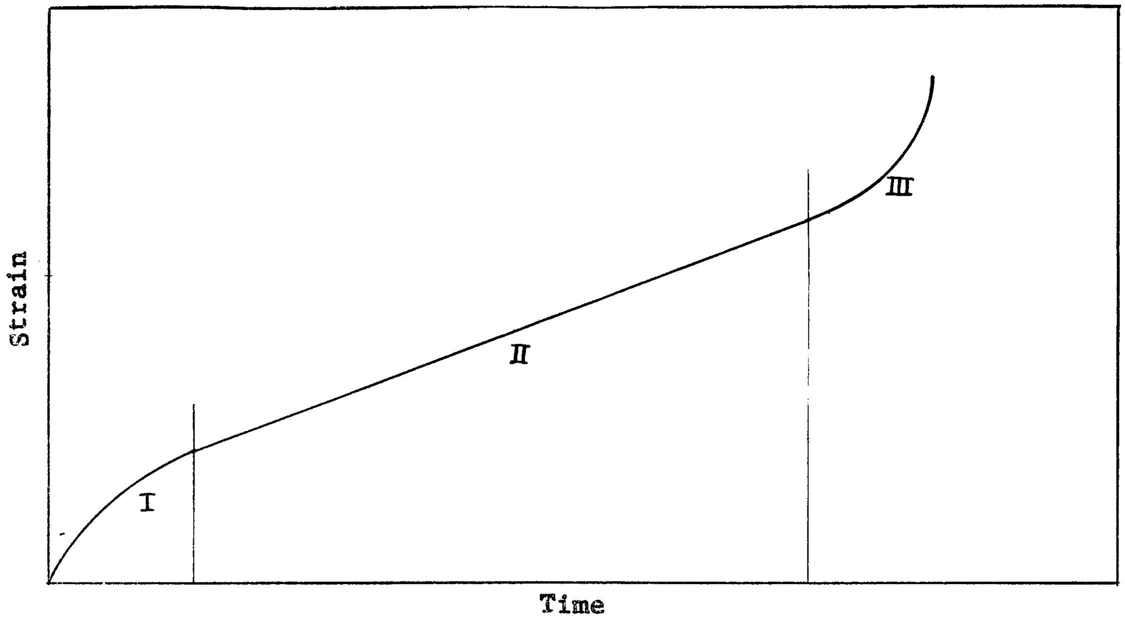


Figure 7. - Time-strain relationship for long-term creep test (constant stress).

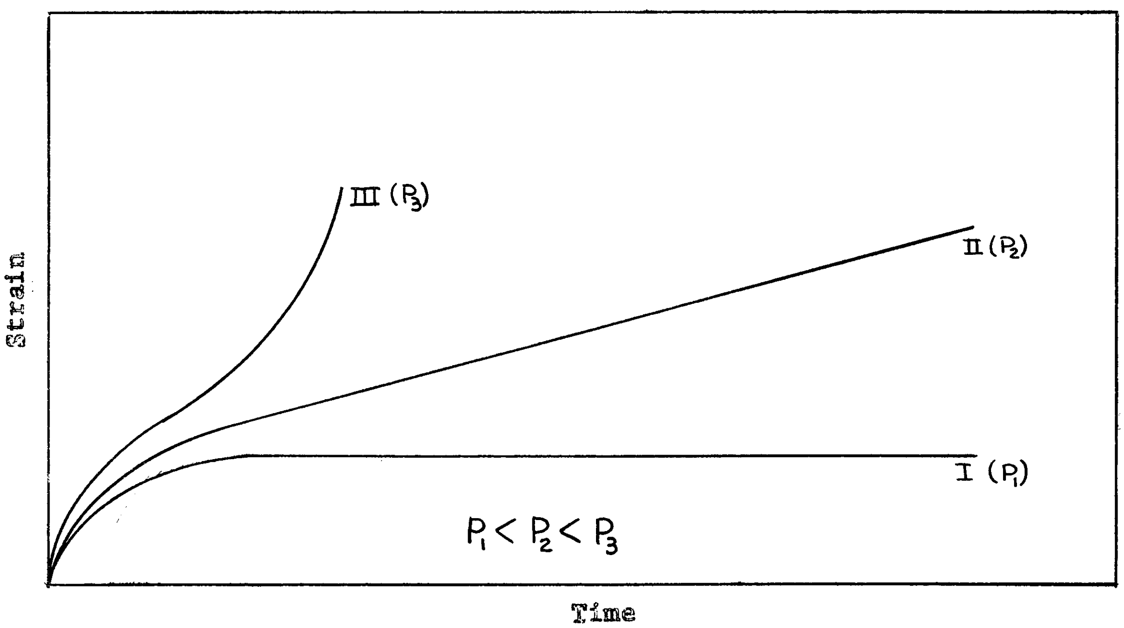


Figure 8. - Time-strain relationship for various pressures.

Rheological: Because of the difficulty encountered in theoretical approaches to the stress-strain-time relationships of time-dependent materials, most studies have involved empirical or phenomenological approaches. Empirical equations may be fitted to experimental data to obtain desired relationships for any given material. Phenomenological approaches are attempts to describe the behavior of actual materials in terms of combinations of one or more simple physical models. These physical models are shown and described in figure 9.

Several combinations of these basic Rheological models are described in figure 10.

Various time-strain studies (Hardy, 1959, p. 21) indicate that several geologic and man-made materials may obey the equations derived from the Burgers model.

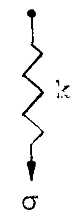
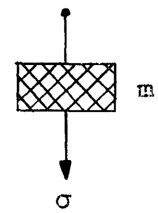
Name	Elastic	Viscous	Inertial
Representation			
Equation	$\epsilon = \frac{\sigma}{k}$	$\frac{d\epsilon}{dt} = \frac{\sigma}{\eta}$	$\frac{d^2\epsilon}{dt^2} = \frac{\sigma}{m}$

Figure 9. - Basic rheological models.

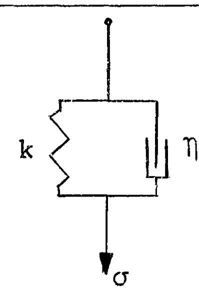
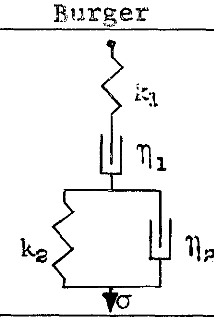
Model Name	Maxwell	Kelvin	Burger
Representation			
Equation	$\epsilon = \sigma \left(\frac{1}{k} + \frac{t}{\eta}\right)$	$\epsilon = \frac{\sigma}{k}\left(1-e^{t/\tau}\right)$ where $\tau = \frac{\eta}{k}$	$\epsilon = \sigma\left[\frac{1}{k_1} + \frac{t}{\eta_1} + \frac{1}{k_2}\left(1-e^{t/\tau}\right)\right]$ where $\tau = \frac{\eta_2}{k_2}$

Figure 10. - Common combinations of basic rheological models.

SPECIMENS

Collection

The potash specimens used for this study were taken from the 850- and the 900-foot levels of the potash mine of International Minerals & Chemical Corp., near Carlsbad, New Mexico, by personnel of the Federal Bureau of Mines (Beckman, 1963).

Blocks of potash, about 18 by 30 by 30 inches, were cut from the potash beds with a universal undercutting machine. To preclude taking material that might have been altered in some way by blasting or by the relatively high stress concentrations at the face, the blocks were obtained by cutting prisms about 1-1/2 feet by 2-1/2 feet by 10 feet, with the long dimension perpendicular to the face. The prism was cut about 2-1/2 feet from the end furthest from the face and this smaller section was used as the sample block.

For later identification and orientation, the blocks were marked with "north" and "up" arrows, and with letter designations used in the specimen identification to describe the specimen source. The block from the 850-foot level was labeled I; the block from the 900-foot level was labeled I_2.

Preparation

Cylindrical specimens were cored from the blocks with a conventional air-powered diamond drill; because the potash is soluble in water, compressed air was used to cool the NX bit and to remove the cuttings. So that the laboratory load would be similar to the assumed vertical load on the underground pillars, the specimens were cored in the vertical direction. The 2-1/8-inch-diameter cores were cut to length with a diamond saw, and the ends were finished with a surface grinder; the sawing and the finishing operations were done dry with dust-collection apparatus. The specimens were cut and finished to lengths of approximately 4-1/4 inches to give a length-diameter ratio of approximately 2 to 1. The ends of the specimen were parallel within ± 0.001 inch to prevent eccentric loading.

Table 1 describes the specimens used for the time-deformation tests.

Table 1. Description of Specimens Used in Time-Deformation Tests

Specimen	Length, in.	Description
I- 1-B	4.51	Halite, $\frac{1}{8}$ - $\frac{1}{4}$ in. grains, somewhat fractured along grain or crystal boundaries.
I- 4-A	4.28	Halite with some sylvite and keiserite $\frac{1}{16}$ - $\frac{1}{4}$ in. grains, several $\frac{1}{2}$ in. halite crystals, little or no fracturing.
I-12-E	4.29	Same as I-1-B.
I_2-19-A	4.12	Same as I-1-B, but with some $\frac{3}{4}$ - 1-in. halite crystals.
I- 7-E	4.09	Halite with some sylvite, $\frac{1}{4}$ - $\frac{1}{2}$ -in. halite grains, some fracturing near ends of specimen.
I- 2-H	4.13	Same as I-4-A, but no large halite crystals.
I- 9-E	4.09	Same as I-1-B.
I-11-E	4.35	Same as I-2-H.

LABORATORY APPARATUS

Load Frame

The load frame, figure 11, used to apply constant loads to the specimens was designed and built by the Colorado School of Mines Research Foundation. The apparatus was borrowed from the Research Foundation for this study.

This load frame was disassembled, cleaned, lubricated, and reassembled prior to use for these experiments. The major drawbacks of this apparatus are the limited load that can be placed on the specimens and the frictional contacts that are present. Because of the presence of the frictional contacts, each lever arm was calibrated at the desired load with a 3-inch-diameter aluminum load cell.

Instrumentation

The strains of the potash specimens were measured with A-6 resistance-type strain gages. The strain-gage circuit (fig. 12) is a standard external-bridge circuit, designed to eliminate temperature

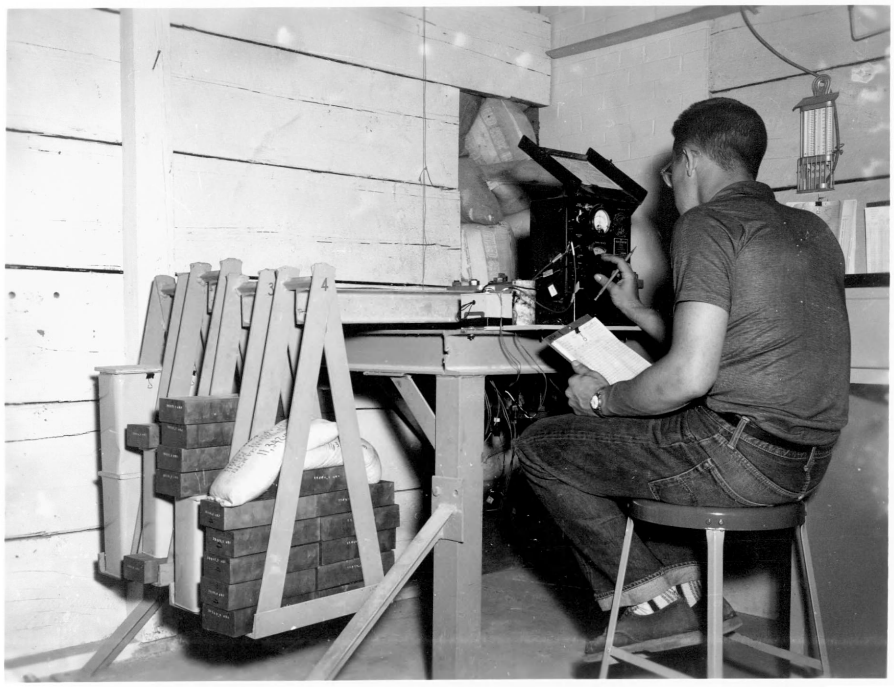


Figure 11. - Load frame.

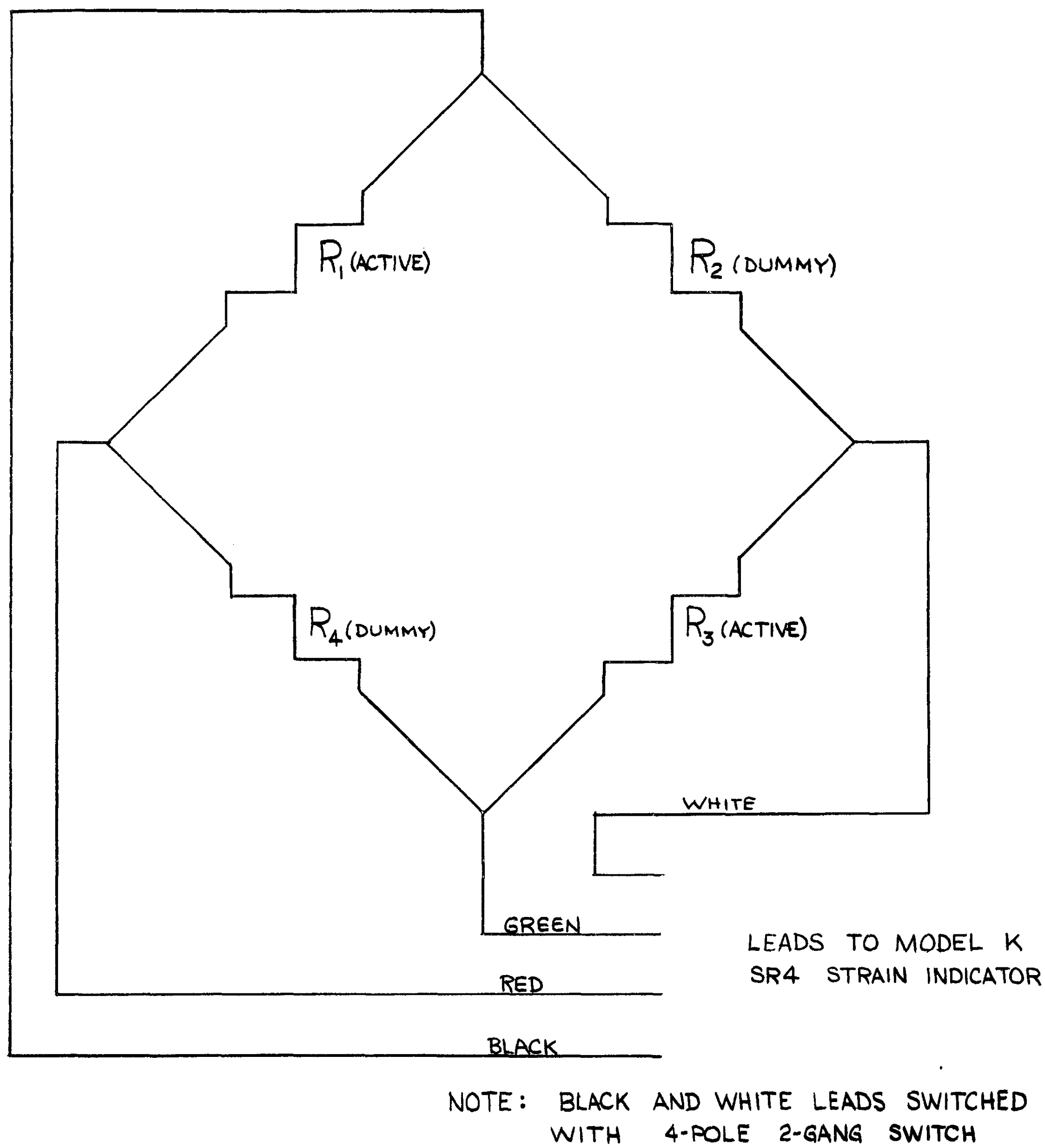


Figure 12. - Strain-gage circuit.

effects and any bending strains. The gage circuits were switched with a 4-pole, 2-gang switch. Indicated strain for the circuit is twice the actual strain; compressive strains are indicated as positive strains.

The gages were bonded to the specimens with Armstrong A-2 epoxy resin, activated with A-1 activator.

TESTING METHODS

Preliminary Tests

Preliminary tests were run on several specimens to determine the elastic limit of the material and a cement suitable for bonding strain gages to the potash.

Standard compression tests were made on three prismatic specimens to which A-5 strain gages were attached. The stress-strain curves obtained from the compression tests are shown in figure 13. The elastic limit of the tested specimens was between 1,000 and 1,200 psi. Because these specimens were taken from the same block as those to be tested for time deformation, the elastic limit of the time-deformation specimens was assumed to be 1,000 psi.

Previous creep studies, by other authors, of bonding materials indicated that SR-4 cement might be quite time dependent. Because of this possibility of time effects on the bonding material, preliminary tests were run with gages attached to a specimen with SR-4 cement and A-2 epoxy resin. The specimen was loaded to a

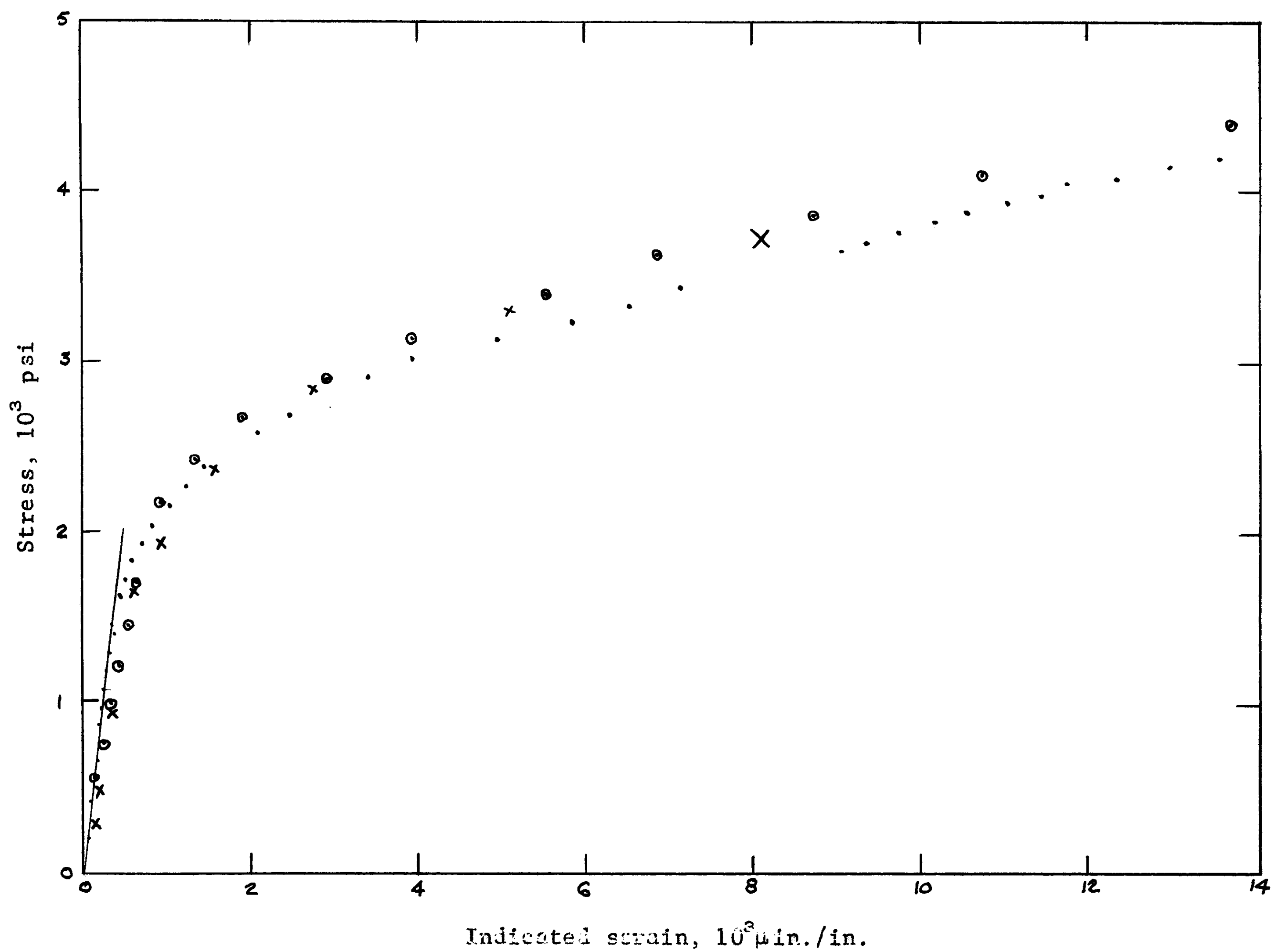


Figure 13. - Preliminary stress-strain curves.

constant stress of approximately 600 psi for 25 days. The results (fig. 14) show very little difference between the gages bonded with SR-4 cement and those bonded with A-2 epoxy resin; however, fluctuations between the data points were quite great. The A-2 epoxy resin was chosen for the gage bonding because the results of other studies have indicated that the resin exhibits minimum creep characteristics (personal communication with personnel of the Denver Mining Research Center, U. S. Bureau of Mines).

Time-Deformation Tests

The time-deformation specimens, with A-6 gages attached, were placed in the load frame. The lower platen was adjusted so that the ends of the specimen were parallel to both platens. This procedure assured uniform pressure on the specimen. The gage leads were then soldered to the wires of the external bridge circuit.

The zero of the gage was read, and weights were placed in the load-frame hangers to load the specimen as quickly as possible. The loading was generally accomplished within 1 to 2 minutes. After the load was applied to the specimen, the gages were again read to determine the initial strain. Temperature and humidity were recorded but not controlled.

Strain and temperature readings were taken at intervals to determine the strain at various times. These values were later punched on

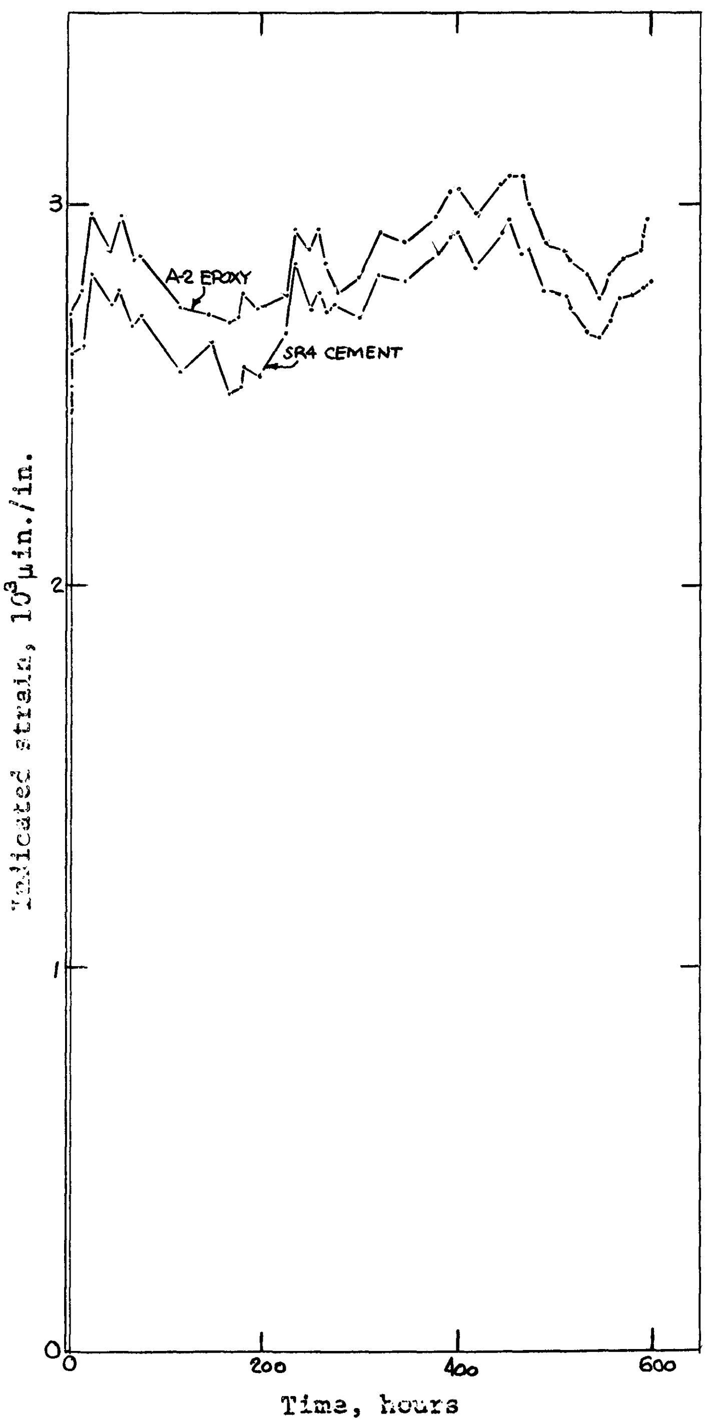


Figure 14. - Preliminary time-strain curves for two bonding agents.

IBM cards for reduction and processing with the General Electric 225 computer at the Bureau of Mines. [1/]

1/ Reference to specific makes or models of equipment is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

The specimens, respective stress levels, and length of tests are listed in table 2.

Table 2. Time-deformation tests

Specimen	Stress psi	Duration of load, days	Total duration of test, days
I-11-E	600	111	165
I-12-E	750	111	165
I- 2-H	1,000	111	165
I- 9-E	1,200	111	165
I_2-19-A	600	80	95
I- 4-A	750	80	95
I- 1-B	950	80	95
I- 7-E	1,150	80	95

RESULTS

Numerical results of the creep tests are given in tables 3 and 4. These tables are direct listings from the computer, and the time is listed in floating-point form. The values of these numbers are obtained by multiplying by 10 to the power shown by the last three characters (sign and two digits). Numbers without decimal digits are shown as whole numbers. These results are also plotted in figures 15 and 16.

The results shown in figures 15 and 16 are generally as were expected with two major exceptions: the temperature has a marked effect on the time-deformation curves, and the initial strain of the specimens is not dependent on the stress. No humidity effects could be discerned.

Because of the temperature effects, the data cards were sorted to group equal-temperature readings and again computed, yielding tables 5 and 6. These results are partially plotted in figures 17 and 18, which illustrate much smoother curves than figures 15 and 16. Readings taken at higher temperatures consistently indicate more strain than comparable readings taken at lower temperatures. This tendency implies that

TABLE 3.- TIME-STRAIN DATA , 165-DAY TESTS

TIME, DAYS	INDICATED STRAIN, MICROIN./IN. I-11-E	I-12-E	I-2-H	I-9-E	TEMP	RDG NO
0	0	0	0	0	78	2
4.1666667-02	1020	3958	1251	3015	78	3
7.2916667-02	995	3950	1225	3110	78	4
9.7083332-02	977	3939	1213	3119	77	5
7.5000000-01	903	3959	1200	3150	74	6
1.0762500+00	1057	4122	1291	3310	80	7
1.8541667+00	1055	4175	1320	3350	80	8
1.9583333+00	1141	4250	1370	3420	81	9
2.3991667+00	970	4144	1240	3301	75	10
2.9200000+00	1195	4347	1420	3500	85	11
3.8958333+00	1100	4320	1357	3450	81	12
4.0729167+00	1190	4385	1400	3514	83	13
4.7708333+00	1007	4265	1290	3393	77	14
5.8125000+00	1090	4372	1362	3490	81	15
6.1387500+00	1220	4492	1422	3598	85	16
6.7220833+00	1030	4370	1308	3460	76	17
7.1354167+00	1278	4560	1461	3670	86	18
7.7708333+00	1068	4413	1340	3503	78	19
8.1595833+00	1251	4478	1438	3635	85	20
8.7741667+00	1084	4440	1358	3530	80	21
8.9237500+00	1230	4550	1466	3642	85	22
1.0208333+01	1156	4483	1382	3575	81	23
1.0965417+01	1158	4508	1412	3583	80	24
1.1111250+01	1187	4530	1430	3610	82	25
1.1722083+01	980	4378	1304	3450	76	26
1.2041667+01	1245	4587	1483	3669	83	27
1.2694583+01	940	4386	1307	3441	72	28
1.3722083+01	975	4430	1329	3488	74	29
1.4111250+01	1109	4522	1392	3580	77	30
1.4833333+01	1110	4560	1420	3614	76	31
1.5187500+01	1161	4601	1431	3663	79	32
1.5777917+01	1080	4568	1401	3609	76	33
1.5965417+01	1319	4761	1572	3811	80	34
1.6951250+01	1178	4665	1468	3700	80	35
1.7055417+01	1166	4651	1449	3692	79	36
1.7725833+01	1012	4548	1350	3580	74	37
1.8117917+01	1019	4561	1348	3590	72	38
1.8722083+01	952	4536	1327	3548	71	39
1.9104167+01	1120	4651	1417	3680	76	40
1.9989583+01	1210	4735	1500	3752	79	41
2.0312500+01	1030	4588	1340	3598	73	42
2.0725833+01	1003	4600	1355	3599	72	43
2.1097083+01	1221	4767	1480	3769	79	44
2.2104167+01	1080	4710	1404	3705	76	45

2.2802083+01	1085	4785	1427	3764	76	46
2.3090417+01	1220	4912	1499	3890	81	47
2.3722083+01	1016	4811	1350	3746	73	48
2.5107500+01	1088	4930	1411	3841	75	49
2.5697917+01	970	4858	1342	3756	72	50
2.6083333+01	1181	5028	1470	3932	79	51
2.6763750+01	960	4951	1408	3840	71	52
2.7708333+01	960	4872	1314	3768	75	53
2.8104167+01	1030	4928	1362	3815	73	54
2.9041667+01	1010	4956	1370	3838	73	55
2.9833333+01	815	4849	1250	3712	69	56
3.0854167+01	992	5060	1409	3908	64	57
3.1614583+01	1132	5225	1455	4060	76	58
3.3116667+01	915	5098	1300	3890	67	59
3.5187500+01	1052	5278	1402	4052	72	60
3.5930417+01	1208	5430	1543	4214	78	61
3.7125000+01	1155	5370	1460	4141	76	62
3.8104167+01	1129	5370	1460	4140	76	63
3.9104167+01	1302	5508	1545	4270	82	64
4.2979167+01	1112	5391	1442	4140	74	65
4.3291667+01	1078	5348	1389	4098	73	66
4.3684167+01	916	5241	1292	3988	68	67
4.4125000+01	1279	5510	1541	4270	81	68
4.4694583+01	980	5279	1332	4038	70	69
4.5750000+01	1162	5418	1448	4172	77	71
4.5187500+01	1308	5518	1546	4288	82	70
4.6694583+01	1000	5292	1342	4050	71	72
4.7187500+01	1203	5452	1478	4210	79	73
4.9031250+01	1244	5496	1512	4248	80	74
5.1694583+01	960	5300	1329	4051	70	75
5.3694583+01	1080	5393	1390	4135	76	76
5.5909583+01	1270	5595	1566	4329	82	77
5.9069583+01	1412	5769	1626	4486	87	78
6.2958333+01	1470	5851	1689	4580	90	79
6.5687500+01	1110	5560	1410	4262	76	80
6.7687500+01	1135	5597	1430	4300	77	81
6.8729167+01	1142	5620	1453	4310	77	82
6.9895833+01	1325	5798	1615	4485	83	83
7.1562500+01	1310	5770	1578	4448	82	84
7.2687500+01	1050	5565	1385	4240	72	85
7.4687500+01	1099	5608	1417	4283	75	86
7.9687500+01	1050	5560	1384	4234	72	87
8.1687500+01	1070	5593	1409	4270	74	88
8.2770833+01	1118	5648	1464	4318	75	89
8.3854167+01	1211	5733	1540	4410	78	90
8.4854167+01	1230	5750	1540	4410	79	91
8.5854167+01	1120	5647	1438	4310	75	92
8.6750000+01	1030	5575	1380	4250	71	93

8.7770833+01	1083	5650	1444	4309	74	94
8.8770833+01	1118	5670	1444	4330	75	95
8.9687500+01	1100	5645	1417	4298	74	96
9.0979167+01	1360	5880	1630	4532	85	97
9.2677083+01	1030	5600	1360	4240	73	98
9.3958333+01	1423	5910	1650	4576	87	99
9.4687500+01	1092	5640	1385	4310	76	100
9.5729167+01	1158	5700	1435	4360	73	101
9.6875000+01	1334	5843	1600	4520	84	102
9.9854167+01	1290	5800	1585	4450	84	103
1.0189583+02	1358	5840	1618	4510	85	104
1.0277083+02	1150	5668	1460	4352	76	105
1.0379167+02	1262	5768	1546	4442	82	106
1.0768750+02	1212	5710	1495	4395	80	107
1.0910417+02	1292	5792	1568	4462	81	108
1.1010417+02	1210	5744	1519	4400	77	109
1.0958333+01	1278	5820	1600	4470	80	110
1.1097917+02	650	4670	860	3386	80	111
1.1187500+02	580	4450	785	3220	79	112
1.1304167+02	685	4490	845	3320	87	113
1.1468750+02	315	4170	550	2975	70	114
1.1568750+02	278	4110	534	2906	67	115
1.1804167+02	450	4210	680	3040	76	116
1.2189583+02	268	4034	535	2854	69	117
1.2379167+02	350	4060	607	2890	74	118
1.2506250+02	502	4130	693	3004	82	119
1.3402083+02	528	4135	720	3045	84	120
135	570	4160	740	3060	84	121
1.3822917+02	320	3950	550	2840	74	122
1.4085417+02	360	3930	610	2820	75	123
1.4568750+02	270	3845	530	2755	72	124
1.5410417+02	388	3960	635	2850	80	125
1.6468750+02	250	3800	505	2700	70	126

TABLE 4.- TIME-STRAIN DATA, 95-DAY TESTS

TIME, DAYS	INDICATED STRAIN, MICROIN./IN. I2-19-A	I-4-A	I-1-B	I-7-E	TEMP	RDG NO
3.7499989-03	1945	415	2310	1715	75	1002
1.4166666-02	2355	355	2170	1725	75	1003
4.1666667-01	3115	480	2375	1965	82	1004
1.4133333+00	3335	405	2310	1950	74	1005
2.8508333+00	3505	455	2410	2045	76	1006
4.4237500+00	3565	435	2380	2015	74	1007
5.4133333+00	3605	445	2410	2055	74	1008
6.4133333+00	3665	485	2440	2065	75	1009
6.9237500+00	3605	425	2380	2015	71	1010
7.7570833+00	3655	455	2410	2045	70	1011
8.6945833+00	3725	485	2470	2095	74	1012
1.4413333+01	3815	525	2530	2145	74	1013
1.5413333+01	3775	495	2520	2125	73	1014
1.6736250+01	3855	555	2570	2185	76	1015
1.8402917+01	3775	505	2530	2135	73	1016
2.0402917+01	3825	525	2560	2145	74	1017
2.3736250+01	3855	565	2610	2195	75	1018
2.6402917+01	3855	555	2610	2185	78	1019
2.7944583+01	3765	495	2540	2115	71	1020
3.0819583+01	3835	545	2620	2165	72	1021
3.5413333+01	3895	625	2750	2255	78	1022
3.6694583+01	3865	595	2700	2215	75	1023
6.4680833+01	3846	571	2732	2243	72	1024
6.5757083+01	3917	643	2802	2275	74	1025
7.1590417+01	3901	641	2811	2285	74	1026
7.7444583+01	3910	603	2812	2248	76	1027
7.9673750+01	3947	704	2890	2331	78	1028
7.9684167+01	3514	377	2304	1876	78	1029
8.2819583+01	3340	265	2175	1774	73	1030
8.3465417+01	3306	223	2130	1695	71	1031
8.7840417+01	3347	283	2205	1804	78	1032
9.1069583+01	3365	277	2179	1774	75	1033
9.2673750+01	3375	310	2220	1822	77	1034
9.4819583+01	3362	275	2190	1788	76	1035

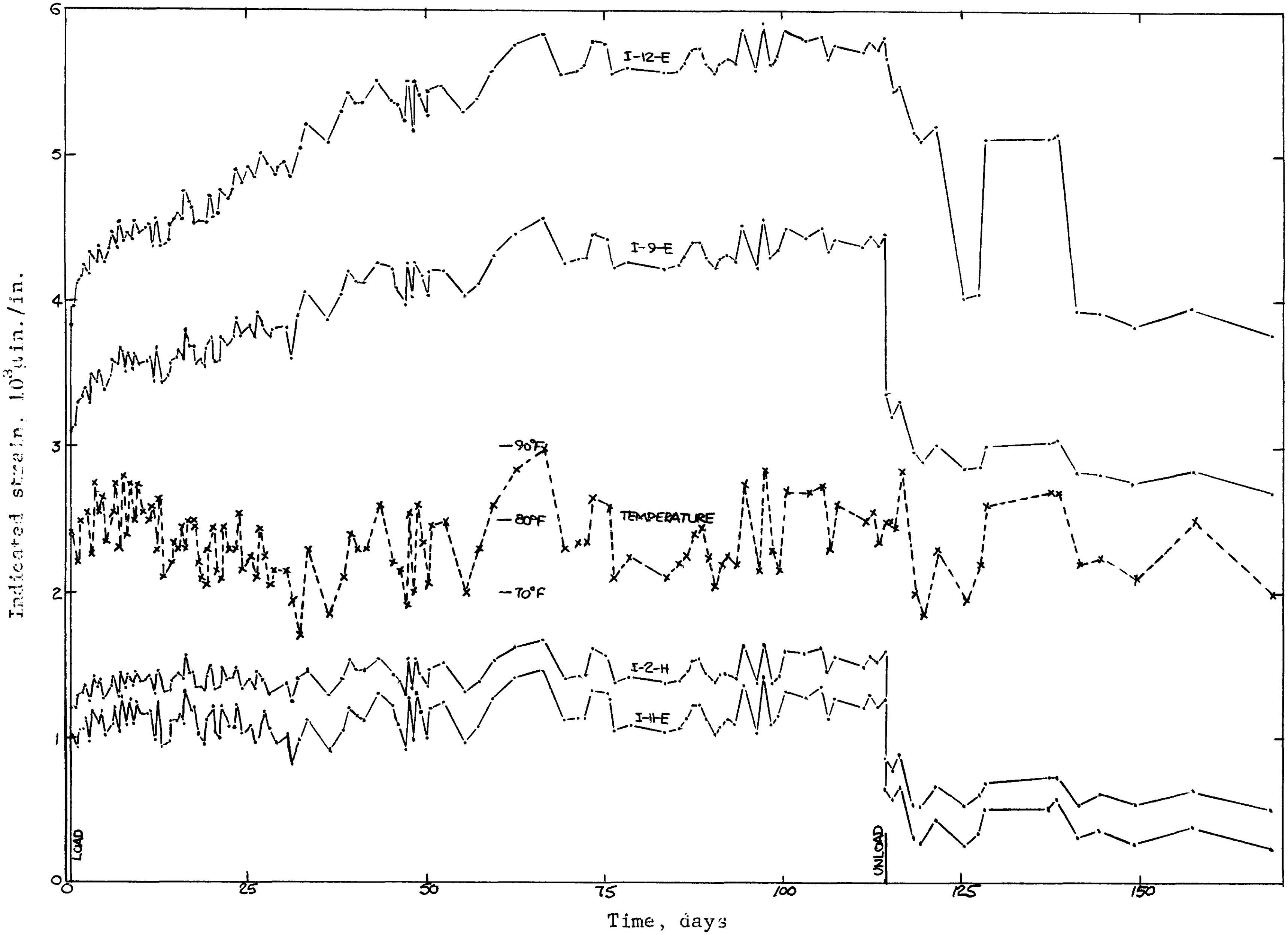


Figure 15. - Time-strain curves for 165-day tests.

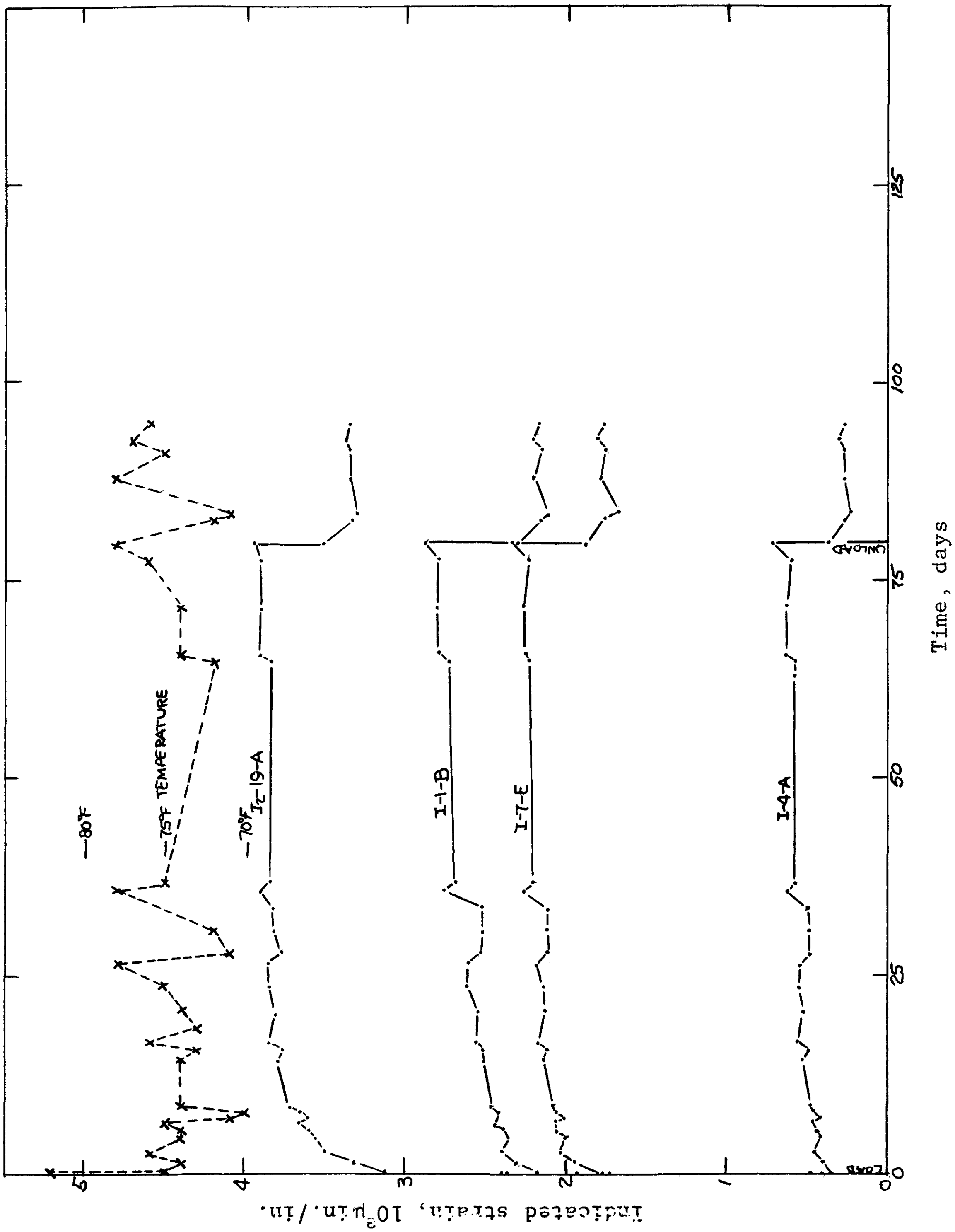


Figure 16. - Time-strain curves for 95-day tests.

TABLE 5.- TIME-STRAIN DATA, 165-DAY TESTS, GROUPED BY TEMPERATURE

TIME, DAYS	INDICATED STRAIN, MICROIN./IN. I-11-E	I-12-E	I-2-H	I-9-E	TEMP	RDG NO
3.0854167+01	992	5060	1409	3908	64	57
3.3116667+01	915	5098	1300	3890	67	59
1.1568750+02	278	4110	534	2906	67	115
4.3684167+01	916	5241	1292	3988	68	67
2.9833333+01	815	4849	1250	3712	69	56
1.2189583+02	268	4034	535	2854	69	117
4.4694583+01	980	5279	1332	4038	70	69
5.1694583+01	960	5300	1329	4051	70	75
1.1468750+02	315	4170	550	2975	70	114
1.6468750+02	250	3800	505	2700	70	126
1.8722083+01	952	4536	1327	3548	71	39
2.6763750+01	960	4951	1408	3840	71	52
4.6694583+01	1000	5292	1342	4050	71	72
8.6750000+01	1030	5575	1380	4250	71	93
1.2694583+01	940	4386	1307	3441	72	28
1.8117917+01	1019	4561	1348	3590	72	38
2.0725833+01	1003	4600	1355	3599	72	43
2.5697917+01	970	4858	1342	3756	72	50
3.5187500+01	1052	5278	1402	4052	72	60
7.2687500+01	1050	5565	1385	4240	72	85
7.9687500+01	1050	5560	1384	4234	72	87
1.4568750+02	270	3845	530	2755	72	124
2.0312500+01	1030	4588	1340	3598	73	42
2.3722083+01	1016	4811	1350	3746	73	48
2.8104167+01	1030	4928	1362	3815	73	54
2.9041667+01	1010	4956	1370	3838	73	55
4.3291667+01	1078	5348	1389	4098	73	66
9.2677083+01	1030	5600	1360	4240	73	98
9.5729167+01	1158	5700	1435	4360	73	101
7.5000000-01	903	3959	1200	3150	74	6
1.3722083+01	975	4430	1329	3488	74	29
1.7725833+01	1012	4548	1350	3580	74	37
4.2979167+01	1112	5391	1442	4140	74	65
8.1687500+01	1070	5593	1409	4270	74	88
8.7770833+01	1083	5650	1444	4309	74	94

8.9687500+01	1100	5645	1417	4298	74	96
1.2379167+02	350	4060	607	2890	74	118
1.3822917+02	320	3950	550	2840	74	122
2.3991667+00	970	4144	1240	3301	75	10
2.5107500+01	1088	4930	1411	3841	75	49
2.7708333+01	960	4872	1314	3768	75	53
7.4687500+01	1099	5608	1417	4283	75	86
8.2770833+01	1118	5648	1464	4318	75	89
8.5854167+01	1120	5647	1438	4310	75	92
8.8770833+01	1118	5670	1444	4330	75	95
1.4085417+02	360	3930	610	2820	75	123
6.7220833+00	1030	4370	1308	3460	76	17
1.1722083+01	980	4378	1304	3450	76	26
1.4833333+01	1110	4560	1420	3614	76	31
1.5777917+01	1080	4568	1401	3609	76	33
1.9104167+01	1120	4651	1417	3680	76	40
2.2104167+01	1080	4710	1404	3705	76	45
2.2802083+01	1085	4785	1427	3764	76	46
3.1614583+01	1132	5225	1455	4060	76	58
3.7125000+01	1155	5370	1460	4141	76	62
3.8104167+01	1129	5370	1460	4140	76	63
5.3694583+01	1080	5393	1390	4135	76	76
6.5687500+01	1110	5560	1410	4262	76	80
9.4687500+01	1092	5640	1385	4310	76	100
1.0277083+02	1150	5668	1460	4352	76	105
1.1804167+02	450	4210	680	3040	76	116
9.7083332-02	977	3939	1213	3119	77	5
4.7708333+00	1007	4265	1290	3393	77	14
1.4111250+01	1109	4522	1392	3580	77	30
4.5750000+01	1162	5418	1448	4172	77	71
6.7687500+01	1135	5597	1430	4300	77	81
6.8729167+01	1142	5620	1453	4310	77	82
1.1010417+02	1210	5744	1519	4400	77	109
4.1666667-02	1020	3958	1251	3015	78	3
7.2916667-02	995	3950	1225	3110	78	4
7.7708333+00	1068	4413	1340	3503	78	19
3.5930417+01	1208	5430	1543	4214	78	61
8.3854167+01	1211	5733	1540	4410	78	90
1.5187500+01	1161	4601	1431	3663	79	32
1.7055417+01	1166	4651	1449	3692	79	36
1.9989583+01	1210	4735	1500	3752	79	41
2.1097083+01	1221	4767	1480	3769	79	44
2.6083333+01	1181	5028	1470	3932	79	51
4.7187500+01	1203	5452	1478	4210	79	73

8.4854167+01	1230	5750	1540	4410	79	91
1.1187500+02	580	4450	785	3220	79	112
1.0762500+00	1057	4122	1291	3310	80	7
1.8541667+00	1055	4175	1320	3350	80	8
8.7741667+00	1084	4440	1358	3530	80	21
1.0965417+01	1158	4508	1412	3583	80	24
1.5965417+01	1319	4761	1572	3811	80	34
1.6951250+01	1178	4665	1468	3700	80	35
4.9031250+01	1244	5496	1512	4248	80	74
1.0768750+02	1212	5710	1495	4395	80	107
1.0958333+01	1278	5820	1600	4470	80	110
1.1097917+02	650	4670	860	3386	80	111
1.5410417+02	388	3960	635	2850	80	125
1.9583333+00	1141	4250	1370	3420	81	9
3.8958333+00	1100	4320	1357	3450	81	12
5.8125000+00	1090	4372	1362	3490	81	15
1.0208333+01	1156	4483	1382	3575	81	23
2.3090417+01	1220	4912	1499	3890	81	47
4.4125000+01	1279	5510	1541	4270	81	68
1.0910417+02	1292	5792	1568	4462	81	108
1.1111250+01	1187	4530	1430	3610	82	25
3.9104167+01	1302	5508	1545	4270	82	64
4.5187500+01	1308	5518	1546	4288	82	70
5.5909583+01	1270	5595	1566	4329	82	77
7.1562500+01	1310	5770	1578	4448	82	84
1.0379167+02	1262	5768	1546	4442	82	106
1.2506250+02	502	4130	693	3004	82	119
4.0729167+00	1190	4385	1400	3514	83	13
1.2041667+01	1245	4587	1483	3669	83	27
6.9895833+01	1325	5798	1615	4485	83	83
9.6875000+01	1334	5843	1600	4520	84	102
9.9854167+01	1290	5800	1585	4450	84	103
1.3402083+02	528	4135	720	3045	84	120
135	570	4160	740	3060	84	121
2.9200000+00	1195	4347	1420	3500	85	11
6.1387500+00	1220	4492	1422	3598	85	16
8.1595833+00	1251	4478	1438	3635	85	20
8.9237500+00	1230	4550	1466	3642	85	22
9.0979167+01	1360	5880	1630	4532	85	97
1.0189583+02	1358	5840	1618	4510	85	104
7.1354167+00	1278	4560	1461	3670	86	18

5.9069583+01	1412	5769	1626	4486	87	78
9.3958333+01	1423	5910	1650	4576	87	99
1.1304167+02	685	4490	845	3320	87	113
6.2958333+01	1470	5851	1689	4580	90	79

TABLE 6.- TIME-STRAIN DATA, 95-DAY TESTS, GROUPED BY TEMPERATURE

TIME, DAYS	INDICATED STRAIN, MICROIN./IN. I2-19-A	I-4-A	I-1-B	I-7-E	TEMP	RDG NO
7.7570833+00	3655	455	2410	2045	70	1011
6.9237500+00	3605	425	2380	2015	71	1010
2.7944583+01	3765	495	2540	2115	71	1020
8.3465417+01	3306	223	2130	1695	71	1031
3.0819583+01	3835	545	2620	2165	72	1021
6.4680833+01	3846	571	2732	2243	72	1024
1.5413333+01	3775	495	2520	2125	73	1014
1.8402917+01	3775	505	2530	2135	73	1016
8.2819583+01	3340	265	2175	1774	73	1030
1.4133333+00	3335	405	2310	1950	74	1005
4.4237500+00	3565	435	2380	2015	74	1007
5.4133333+00	3605	445	2410	2055	74	1008
8.6945833+00	3725	485	2470	2095	74	1012
1.4413333+01	3815	525	2530	2145	74	1013
2.0402917+01	3825	525	2560	2145	74	1017
6.5757083+01	3917	643	2802	2275	74	1025
7.1590417+01	3901	641	2811	2285	74	1026
3.7499989-03	1945	415	2310	1715	75	1002
1.4166666-02	2355	355	2170	1725	75	1003
6.4133333+00	3665	485	2440	2065	75	1009
2.3736250+01	3855	565	2610	2195	75	1018
3.6694583+01	3865	595	2700	2215	75	1023
9.1069583+01	3365	277	2179	1774	75	1033
2.8508333+00	3505	455	2410	2045	76	1006
1.6736250+01	3855	555	2570	2185	76	1015
7.7444583+01	3910	603	2812	2248	76	1027
9.4819583+01	3362	275	2190	1788	76	1035
9.2673750+01	3375	310	2220	1822	77	1034
2.6402917+01	3855	555	2610	2185	78	1019
3.5413333+01	3895	625	2750	2255	78	1022
7.9673750+01	3947	704	2890	2331	78	1028
7.9684167+01	3514	377	2304	1876	78	1029
8.7840417+01	3347	283	2205	1804	78	1032
4.1666667-01	3115	480	2375	1965	82	1004

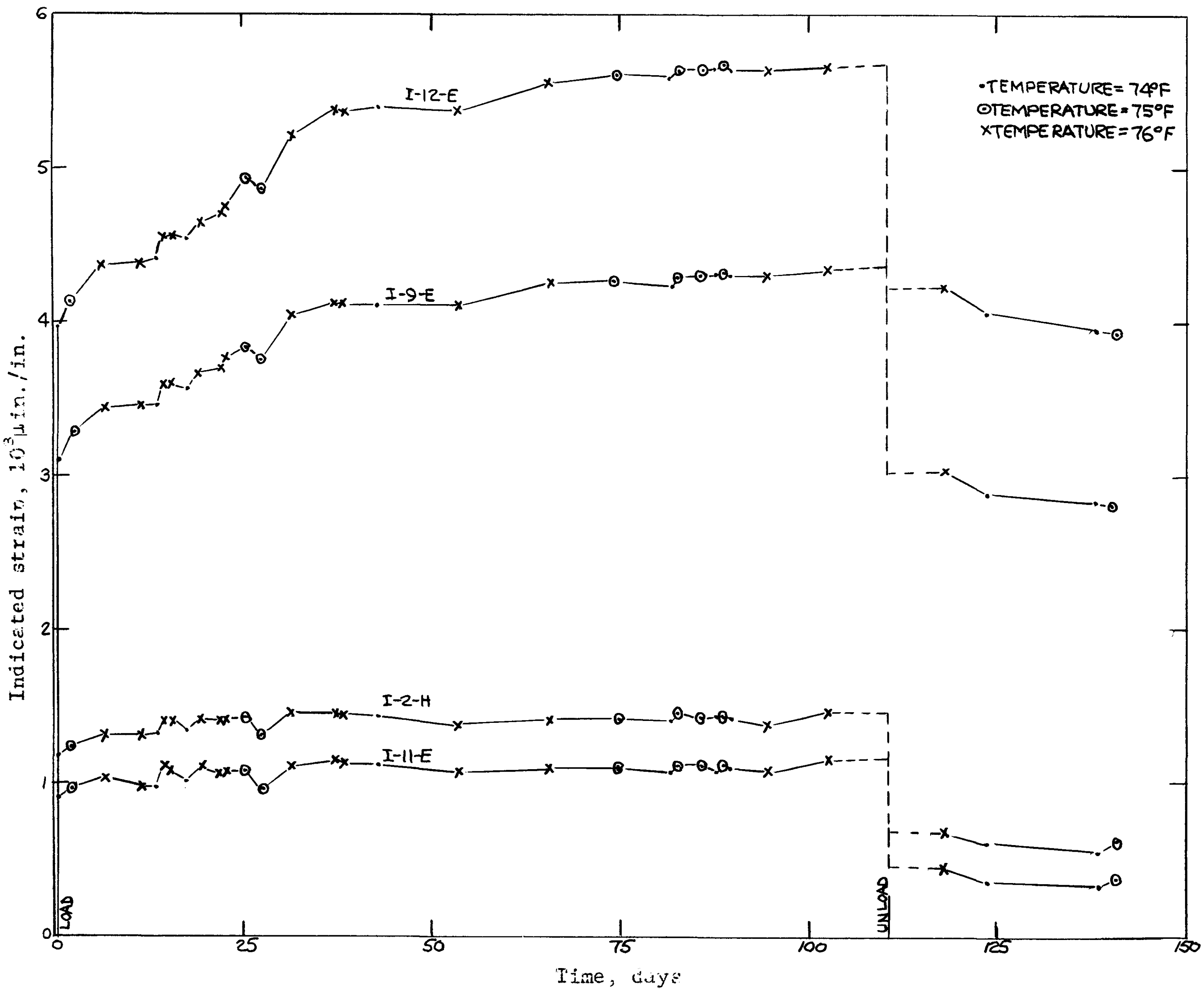


Figure 17. - Time-strain curves for 165-day tests, temperatures of 74, 75. 76°F.

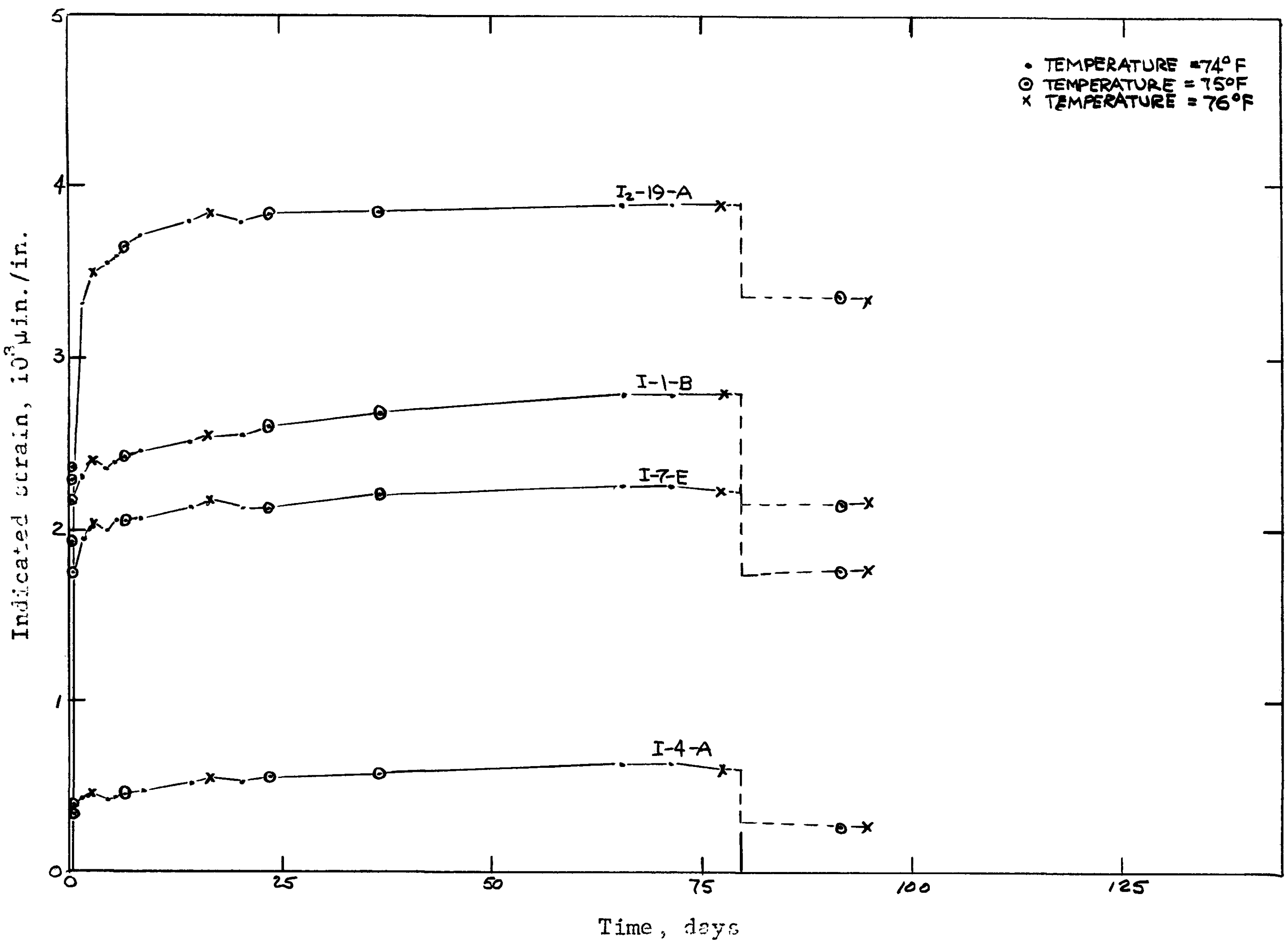


Figure 18. - Time-strain curves for 95-day tests, temperatures of 74, 74, 76°F.

the strain measurements may not have been temperature compensated, or that the potash may be affected by temperature.

The major departure of the data from theory is the relative placement of the curves (fig. 15 and 16). These curves do not illustrate a consistent relationship between stress and strain. Because of this apparent deviation from theory, a standard compression test was run on each specimen. The loading rate was 500 psi per minute and the strain-gage circuit was the same as that shown in figure 12, except that a Model 20 strain indicator was used. The results of this test, shown in figure 19, indicate that the specimens react differently to stress. The stress-strain curves of figure 19 illustrate quite pronounced hysteresis.

Comparisons of the stress-strain characteristics for creep and compression tests are made in tables 7 and 8 for various similar loading and unloading cycles. One interesting fact is that the strains measured during loading or unloading in the creep tests were larger (with one exception) than the strains for similar stress increments in the compression tests. This relationship is, possibly, an indication of work hardening, shown by the steeper curves (less strain per unit stress) for the compression tests. An indication of work hardening of potash has been found by the author in recent unpublished work done at the Bureau of Mines laboratory. Strain hardening, however, cannot explain the relative placement of the curves in figures 15 and 16.

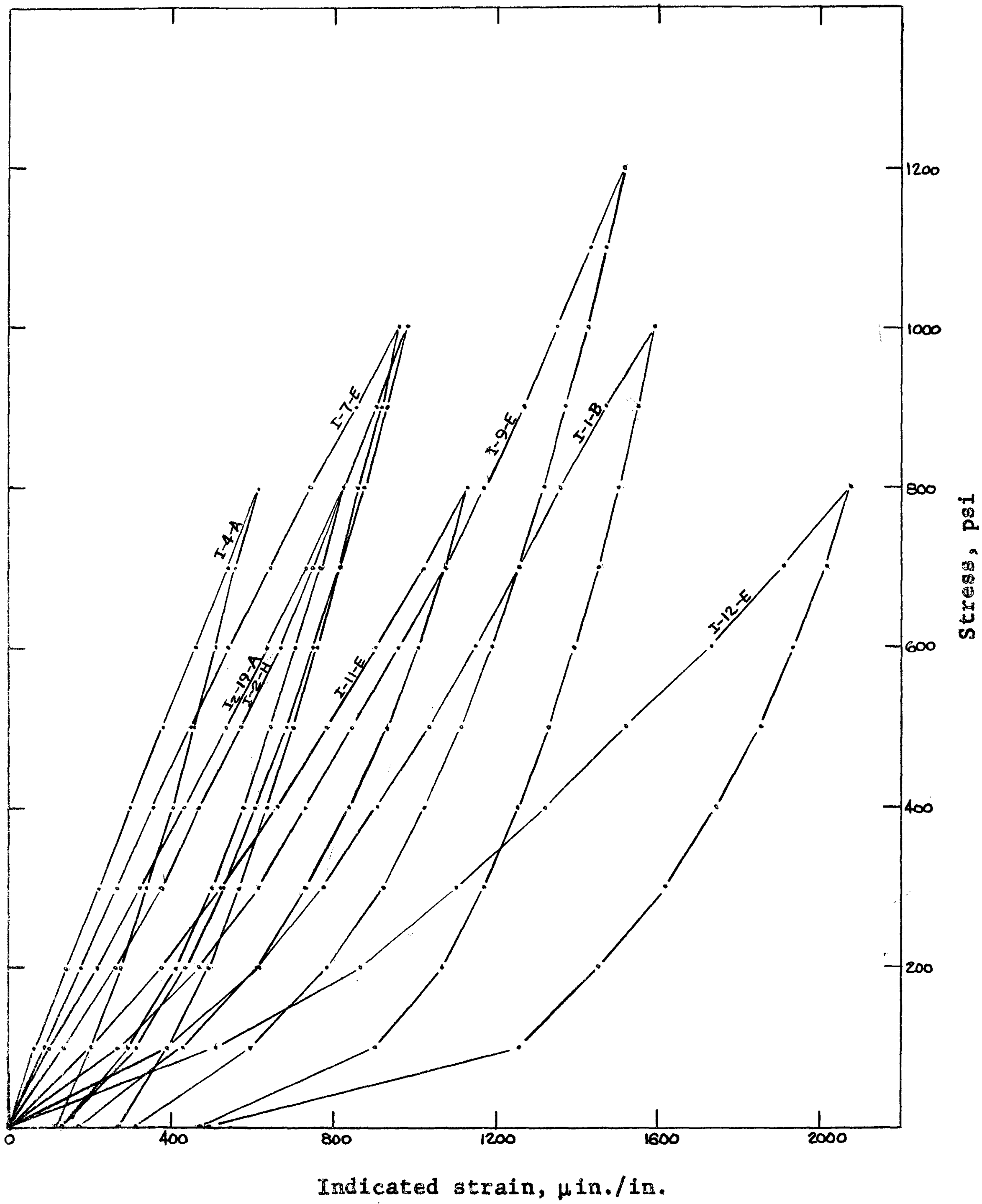


Figure 19. - Stress-strain curves for time-deformation specimens.

Table 7. Comparison of Results
Time-Deformation Tests and Compression Tests, Load Cycles

Specimen	Stress psi	Indicated initial strain μin./in. (Compression Test) ϵ_c	(Creep Test) ϵ_t	Difference $(\epsilon_t - \epsilon_c)$
I-11-E	600	900	1,010	110
I-12-E	750	1,995	3,801	1,806
I- 2-H	1,000	975	1,151	176
I- 9-E	1,200	1,515	3,015	1,500
I_2-19-A	600	635	1,945	1,310
I- 4-A	750	570	415	-155
I- 1-B	950	1,530	2,310	780
I- 7-E	1,150	1,125*	1,715	590

*Extrapolated

Table 8. Comparison of Results
Time-Deformation Tests and Compression Tests, Unload Cycles

Specimen	Stress psi	Indicated relief strain, μin./in. ϵ_t	ϵ_c	Difference $\epsilon_c - \epsilon_t$
I-11-E	600	628	833	205
I-12-E	750	1,150	1,550	400
I- 2-H	1,000	740	805	65
I- 9-E	1,200	1,094	1,207	113
I_2-19-A	600	433	575	142
I- 4-A	750	94	463	369
I- 1-B	950	586	1,101	515
I- 7-E	1,150	455*	855	400

*Extrapolated

Further comparisons were made to determine a possible cause for the high initial strains exhibited by some of the specimens.

A comparison of table 1 with figures 15 and 16 divulged that the specimens exhibiting higher initial strains were fractured along crystal or grain boundaries. Movement along these boundaries would explain the high initial strains. However, even after fractured specimens have been eliminated, the initial strains are not consistent with theory. Table 9 lists the nonfractured specimens, stress, and initial strain.

Table 9. Indicated Strains of Nonfractured Specimens, Time-Deformation Tests

Specimen	Stress psi	Indicated strains, μin./in. Initial	Recovery
I-11-E	600	1,010	628
I- 4-A	750	415	94
I- 2-H	1,000	1,151	740

Specimen I-4-A, under a stress of 750 psi, indicates much less initial and recovery strain than specimen I-11-E, under a 600-psi stress. Specimen I-4-A was also the exception in the results listed in table 7: the initial strain of the creep test was less than the strain of the specimen at a load of 750 psi in the compression test. These factors indicate that the specimen may not have been under a stress of 750 psi, but rather under a lower stress. Excessive friction or restraint is possible in the loading frame, even though precautions were taken to prevent friction and restraint.

Because of the variability of the initial strains, no attempt was made to analyze the data with respect to phenomenological models; however, attempts were made to fit curves to the portion of the curves following the initial strain (for three temperatures). The data cards for these specimens were again computed, using the first reading after application of the load as the zero data. The computer printout is shown in tables 10 and 11. These data suggested that a semi-log or log-log plot of the data might be a straight line, but the excessive scatter of the points on the semi-log and log-log plots precluded any attempt at curve fitting.

This scatter of the data possibly was caused by the method of strain measurement.

TABLE 10.- TIME-STRAIN DATA, 165-DAY TESTS, NEW ZERO POINTS

TIME, DAYS	INDICATED STRAIN, MICROIN./IN. I-11-E	I-12-E	I-2-H	I-9-E	TEMP	RDG NO
3.0812500+01	-28	1102	158	893	64	57
3.3075000+01	-105	1140	49	875	67	59
1.1564583+02	-742	152	-717	-109	67	115
4.3642500+01	-104	1283	41	973	68	67
2.9791667+01	-205	891	-1	697	69	56
1.2185417+02	-752	76	-716	-161	69	117
4.4652917+01	-40	1321	81	1023	70	69
5.1652917+01	-60	1342	78	1036	70	75
1.1464583+02	-705	212	-701	-40	70	114
1.6464583+02	-770	-158	-746	-315	70	126
1.8680417+01	-68	578	76	533	71	39
2.6722083+01	-60	993	157	825	71	52
4.6652917+01	-20	1334	91	1035	71	72
8.6708333+01	10	1617	129	1235	71	93
1.2652917+01	-80	428	56	426	72	28
1.8076250+01	-1	603	97	575	72	38
2.0684167+01	-17	642	104	584	72	43
2.5656250+01	-50	900	91	741	72	50
3.5145833+01	32	1320	151	1037	72	60
7.2645833+01	30	1607	134	1225	72	85
7.9645833+01	30	1602	133	1219	72	87
1.4564583+02	-750	-113	-721	-260	72	124
2.0270833+01	10	630	89	583	73	42
2.3680417+01	-4	853	99	731	73	48
2.8062500+01	10	970	111	800	73	54
29	-10	998	119	823	73	55
4.3250000+01	58	1390	138	1083	73	66
9.2635417+01	10	1642	109	1225	73	98
9.5687500+01	138	1742	184	1345	73	101
7.0833333-01	-117	1	-51	135	74	6
1.3680417+01	-45	472	78	473	74	29
1.7684167+01	-8	590	99	565	74	37
4.2937500+01	92	1433	191	1125	74	65
8.1645833+01	50	1635	158	1255	74	88
8.7729167+01	63	1692	193	1294	74	94

8.9645833+01	80	1687	166	1283	74	96
1.2375000+02	-670	102	-644	-125	74	118
1.3818750+02	-700	-8	-701	-175	74	122
2.3575000+00	-50	186	-11	286	75	10
2.5065833+01	68	972	160	826	75	49
2.7666667+01	-60	914	63	753	75	53
7.4645833+01	79	1650	166	1268	75	86
8.2729167+01	98	1690	213	1303	75	89
8.5812500+01	100	1689	187	1295	75	92
8.8729167+01	98	1712	193	1315	75	95
1.4081250+02	-660	-28	-641	-195	75	123
6.6804167+00	10	412	57	445	76	17
1.1680417+01	-40	420	53	435	76	26
1.4791667+01	90	602	169	599	76	31
1.5736250+01	60	610	150	594	76	33
1.9062500+01	100	693	166	665	76	40
2.2062500+01	60	752	153	690	76	45
2.2760417+01	65	827	176	749	76	46
3.1572917+01	112	1267	204	1045	76	58
3.7083333+01	135	1412	209	1126	76	62
3.8062500+01	109	1412	209	1125	76	63
5.3652917+01	60	1435	139	1120	76	76
6.5645833+01	90	1602	159	1247	76	80
9.4645833+01	72	1682	134	1295	76	100
1.0272917+02	130	1710	209	1337	76	105
118	-570	252	-571	25	76	116
5.5416666-02	-43	-19	-38	104	77	5
4.7291667+00	-13	307	39	378	77	14
1.4069583+01	89	564	141	565	77	30
4.5708333+01	142	1460	197	1157	77	71
6.7645833+01	115	1639	179	1285	77	81
6.8687500+01	122	1662	202	1295	77	82
1.1006250+02	190	1786	268	1385	77	109
3.1250000-02	-25	-8	-26	95	78	4
7.7291667+00	48	455	89	488	78	19
3.5888750+01	188	1472	292	1199	78	61
8.3812500+01	191	1775	289	1395	78	90
1.5145833+01	141	643	180	648	79	32
1.7013750+01	146	693	198	677	79	36
1.9947917+01	190	777	249	737	79	41
2.1055417+01	201	809	229	754	79	44
2.6041667+01	161	1070	219	917	79	51

4.7145833+01	183	1494	227	1195	79	73
8.4812500+01	210	1792	289	1395	79	91
1.1183333+02	-440	492	-466	205	79	112
1.0345833+00	37	164	40	295	80	7
1.8125000+00	35	217	69	335	80	8
8.7325000+00	64	482	107	515	80	21
1.0923750+01	138	550	161	568	80	24
1.5923750+01	299	803	321	796	80	34
1.6909583+01	158	707	217	685	80	35
4.8989583+01	224	1538	261	1233	80	74
1.0764583+02	192	1752	244	1380	80	107
1.1091667+02	258	1862	349	1455	80	110
1.1093750+02	-370	712	-391	371	80	111
1.5406250+02	-632	2	-616	-165	80	125
1.9166667+00	121	292	119	405	81	9
3.8541667+00	80	362	106	435	81	12
5.7708333+00	70	414	111	475	81	15
1.0166667+01	136	525	131	560	81	23
2.3048750+01	200	954	248	875	81	47
4.4083333+01	259	1552	290	1255	81	68
1.0906250+02	272	1834	317	1447	81	108
1.1069583+01	167	572	179	595	82	25
3.9062500+01	282	1550	294	1255	82	64
4.5145833+01	288	1560	295	1273	82	70
5.5867917+01	250	1637	315	1314	82	77
7.1520833+01	290	1812	327	1433	82	84
1.0375000+02	242	1810	295	1427	82	106
1.2502083+02	-518	172	-558	-11	82	119
4.0312500+00	170	427	149	499	83	13
12	225	629	232	654	83	27
6.9854167+01	305	1840	364	1470	83	83
9.6833333+01	314	1885	349	1505	84	102
9.9812500+01	270	1842	334	1435	84	103
1.3397917+02	-492	177	-531	30	84	120
1.3495833+02	-450	202	-511	45	84	121
2.8783333+00	175	389	169	485	85	11
6.0970833+00	200	534	171	583	85	16
8.1179167+00	231	520	187	620	85	20
8.8820833+00	210	592	215	627	85	22
9.0937500+01	340	1922	379	1517	85	97
1.0185417+02	338	1882	367	1495	85	104
7.0937500+00	258	602	210	655	86	18

5.9027917+01	392	1811	375	1471	87	78
9.3916667+01	403	1952	399	1561	87	99
113	-335	532	-406	305	87	113
6.2916667+01	450	1893	438	1565	90	79

TABLE 11.- TIME-STRAIN DATA, 95-DAY TESTS, NEW ZERO POINTS

TIME, DAYS	INDICATED STRAIN, MICROIN./IN. I2-19-A	I-4-A	I-1-B	I-7-E	TEMP	RDG NO
7.7533333+00	1710	40	100	330	70	1011
6.9200000+00	1660	10	70	300	71	1010
2.7940833+01	1820	80	230	400	71	1020
8.3461667+01	1361	-192	-180	-20	71	1031
3.0815833+01	1890	130	310	450	72	1021
6.4677083+01	1901	156	422	528	72	1024
1.5409583+01	1830	80	210	410	73	1014
1.8399167+01	1830	90	220	420	73	1016
8.2815833+01	1395	-150	-135	59	73	1030
1.4095833+00	1390	-10	0	235	74	1005
4.4200000+00	1620	20	70	300	74	1007
5.4095833+00	1660	30	100	340	74	1008
8.6908333+00	1780	70	160	380	74	1012
1.4409583+01	1870	110	220	430	74	1013
2.0399167+01	1880	110	250	430	74	1017
6.5753333+01	1972	228	492	560	74	1025
7.1586667+01	1956	226	501	570	74	1026
1.0416667-02	410	-60	-140	10	75	1003
6.4095833+00	1720	70	130	350	75	1009
2.3732500+01	1910	150	300	480	75	1018
3.6690833+01	1920	180	390	500	75	1023
9.1065833+01	1420	-138	-131	59	75	1033
2.8470833+00	1560	40	100	330	76	1006
1.6732500+01	1910	140	260	470	76	1015
7.7440833+01	1965	188	502	533	76	1027
9.4815833+01	1417	-140	-120	73	76	1035
9.2670000+01	1430	-105	-90	107	77	1034
2.6399167+01	1910	140	300	470	78	1019
3.5409583+01	1950	210	440	540	78	1022
7.9670000+01	2002	289	580	616	78	1028
7.9680417+01	1569	-38	-6	161	78	1029
8.7836667+01	1402	-132	-105	89	78	1032
4.1291667-01	1170	65	65	250	82	1004

SUMMARY AND CONCLUSIONS

A study of potash specimens under constant load indicates that these specimens deform plastically, even at stresses below the elastic limit. The initial deformations (immediately after application of loads) of the specimens tested were more dependent on the degree of fracturing within the specimen than on the applied stress. Compression tests of the specimens used in the time-deformation tests indicate that the potash may have work hardened during the creep tests. An empirical time-strain relationship (after initial strain) of the potash under constant stress could not be found because of excessive scatter of the data.

The lever-type load frame used for the tests allowed only low stresses to be applied to specimens and incorporated several frictional contacts. These factors were undesirable, but the apparatus was suitable for this study. The deformation measurements, made with A-6 resistance-type strain gages, may have caused the scatter of the data. Temperature effects on the data may have been caused by temperature effects on the potash or the strain-measuring circuit.

Recommendations concerning further studies of this type are as follows:

1. Use of loading devices capable of applying higher stresses to specimens.
2. Use of loading devices incorporating fewer frictional contacts -- possibly a hydraulic-type loading device.
3. Possible use of linear differential transformers for strain measurement.
4. Use of two or more strain-measuring methods with comparable accuracies.
5. Use of more uniform specimens.
6. Use of temperature-controlled environment.

REFERENCES

1. Beckman, Robert T., 1963, Compressive Strength Versus Length-Diameter Ratios of Potash Specimens: U. S. Bur. of Mines Rept. of Inv. (In progress).

2. Hardy, H. R., Jr., 1959, Time-Dependent Deformation and Failure of Geologic Materials: Canada Dept. of Mines and Tech. Surveys, Mines Branch, Fuels Div., Tech. Memo. 25/29-MIN, 57 pp.

3. Lubahn, J. D., and R. P. Felgar, 1961, Plasticity and Creep of Metals: John Wiley and Sons, Inc., New York, 608 pp.