RATCHETTING DEFORMATION AS AFFECTED BY RELATIVE
VARIATIONS OF THE LOADING SEQUENCE*

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ABSTRACT

As part of a program undertaken to obtain experimental verification of the magnitude and effect of creep ratchetting in high-temperature, sodium-cooled reactor design, tests have been performed to extend the range of the ratchetting test parameters from that of a previous study and to examine the effect of relative variations in the loading sequence. Test results over the extended range of parameters tend to verify the analytical predictions of the magnitude of plastic ratchetting strain per cycle made by Bree and by Burgreen. The sensitivity of the amount of ratchetting strain per cycle to the phase relation between the bend cycle (thermal transient) and the axial stress (internal pressure) indicates that care should be taken in preparing design specifications to properly show the variations in system pressure relative to the thermal transients and hold times.

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INTRODUCTION

In a previous paper by Anderson (1)* it was shown that the magnitude of creep ratchetting deformation induced in a simple test could be reasonably well predicted by a simple analytical model (1,2). The results of the tests and subsequent analysis of components indicate that predicted ratchetting deformation can be the most restrictive factor in analytical assurance of component performance. This is especially true in large components of the heat transfer systems of high-temperature nuclear reactors.

Additional tests have since been performed to extend the range of the ratchetting test parameters from that presented in the previous study and to study the effect of relative variations in the loading sequence. The primary purpose of extending the range of parameters was to experimentally confirm, if possible, the predicted magnitude of time-independent ratchetting. The primary purpose of the experimental study of the effect of relative variations in the loading sequence on ratchetting deformation was to determine if the effect was of sufficient magnitude that design of the plant control system and operating procedures could be considered as a source for potential alleviation of the severity of the ratchetting problem.

TEST EQUIPMENT

It was necessary to modify the test equipment described previously (1) to facilitate performance of tests which require variation with time of the axial stress.

An air-operated cylinder with 2-1/2-in. bore and a 1.0-in. stroke was attached to the machine by an adapter plate in place of the axial loading spring. Air pressure was supplied from pressurized bottles. The maximum air pressure specified for the cylinder was 250 psi. A more detailed description of the equipment for this type of testing is presented separately (3).

*Numbers in parentheses refer to list of references at end of paper.

TEST RESULTS

EFFECT OF THE MAGNITUDE OF AXIAL STRESS

Two different experimental studies of the effect of the magnitude of axial stress were undertaken. One study examined the effect of the magnitude of axial stress in ratchetting tests with essentially zero hold time in an effort to achieve plastic ratchetting tests. The objective of the second study was to demonstrate that significant reductions in the magnitude of creep ratchetting strain result from reduction of the magnitude of axial stress.

All tests were performed at 1200° F using specimens of Type 304 stainless steel from the same batch as that used in tests reported earlier (1).

Plastic Ratchetting Tests

Twelve tests were performed at 1200° F in the regime where plastic ratchetting is expected. Ten different test conditions were involved with duplicate specimens for two tests. The tests were performed as rapidly as possible to minimize the amount of creep deformation involved. The maximum axial load was applied for a total period of 40 min or less. In spite of this, it is estimated that approximately 0.1% creep ratchet deformation occurred in the gage length of each specimen. This amount of deformation would be anticipated because of the high primary creep rate induced by residual stresses near the value of the yield strength.

The test conditions and results of the tests are given in Table 1. Also presented in Table 1 are the predicted values of strain per cycle after the first cycle. Predictions were made using Bree's charts (4) and checked by results from Burgreen (5). It can be observed from the results that the trends are as predicted and that duplicate tests yield approximately the same results. Table 2 shows the ratio of strain per cycle for each of these tests with the strain accumulated in the second cycle of each test taken as unity.

Figure 1 shows the location of the tests on the Bree charts.

The Effect of the Magnitude of the Axial Stress in Creep Ratchetting

A group of four tests with a relatively few number of cycles were performed specifically to obtain data on the effect of the reduction in magnitude of the axial stress on the resulting magnitude of creep ratchetting strain. Another group of four specimens were tested with a very large number of cycles in an attempt to

obtain rupture of the specimens as a result of the creep-fatigue interaction induced under ratchetting conditions. These latter four tests were all performed with the same cycle type, bending strain, and hold time. Three different magnitudes of axial stress were used in the tests, so the results also provide some information on the effect of the magnitude of the axial stress on the hold time.

The results of these eight tests are presented in Table 3 along with the results of Tests 1 and 5 for comparative purposes.

TIME EFFECTS IN RATCHETTING

Two experimental studies of the effect of the time parameter on test results were undertaken. The first investigated the effect of varying the hold time for different tests at a constant axial stress. The other studied the effect of varying the axial force in time at different phase relations with the cyclic bending. Variations of phase relation of axial and bending stress variations which are considered as cycle types for this program are shown in Figure 2.

Cycle Type A is intended to simulate a service condition where the major mechanical stress (axial stress) is not reduced following a thermal transient (bending strain). This could be the situation when the major mechanical stress is induced by deadweight forces.

Cycle Type B is intended to simulate a service condition where the major mechanical stress is made inactive briefly following a thermal transient.

Cycle Type C is intended to simulate a service condition where the advent of a transient is sensed with sufficient time that the major mechanical stress can be removed before the maximum stress induced by the transient is achieved.

Cycle Type D is intended to simulate a service condition where the thermal stress (bending strain) is induced by steady-state heat conduction and varies cyclically as the thermal load is varied, while the major mechanical stress remains relatively constant. This condition can exist in fuel element cladding and heat exchanger parts.

Cycle Type E is intended to simulate a service condition similar to Cycle Type B, except that the major mechanical load is kept inactive while the system is brought to operating temperature and maintained at temperature for some period of time before being made active. This cycle type was considered as possibly offering a procedure for reducing the ratchetting strain per cycle by removing

some of the damaging residual stresses before the major mechanical stress could interact with them to cause appreciable ratchetting strain.

The Effect of Variations in Hold Time

A group of ten tests were performed to provide data for study of the effect of hold time. In Test 11, 15, 20, 21, 23, 24, 31, 34, 40, and 46, the axial force was held constant and all of the hold time was expended with the specimen held against the hold mandrel as in Cycle Type A. The results of these tests are shown in Table 4 with results from previously reported (1) Tests 1, 5, and 6 for comparative purposes. These tests utilize only two loading conditions with the hold time varying from 5 min to 168 hr.

The Effect of Time-Dependent Variations in Axial Stress

A group of twelve tests were conducted to provide data for study of the effect of variations of phase relation of axial and bending stress variations. Tests 25, 26, and 27 were performed in the plastic ratchetting range. Tests 26 and 27 were performed with Cycle Types C and B, respectively, and the results are shown in Table 5 with results from Test 25 (Cycle Type A) for comparative purposes.

The other group of nine tests were all performed with a 24-hr hold time and with the same magnitudes of bending strain and axial stress. Only the phase relation between bending strain and axial stress was varied. All five of the cycle types shown in Figure 2 were included. The results of these tests are also given in Table 5. The tests were performed using the air cylinder to provide the axial stress. To provide a more consistent basis for comparison than would be provided by the results from Tests 1 and 5, Tests 32 and 39 were performed using the air cylinder.

DISCUSSION OF RESULTS

EXPERIMENTAL ERROR DUE TO FRICTION

The friction drag in the air cylinder is an added source of potential error in the determination of the axial stress in the specimen. This error tends to increase the axial stress and thereby the ratchetting strain per cycle. It is, therefore, anticipated that seemingly identical tests might result in more ratchetting strain from the air cylinder-loaded specimen than from the spring-loaded

specimen. This is confirmed by comparison of results of Tests 1 and 5 with results from Tests 32 and 39 in Table 5.

An experimental investigation was performed to determine the effect of friction on the axially distributed force in the specimen as the specimen is subjected to a bending and loading cycle. The results of the investigation showed that with no attempt to control the friction, the actual magnitude of the axial stress at both ends could increase by as much as 17% at the peak of bending during an operating cycle. However, also with no attempt to control the friction, the axial stresses at the two ends of the specimen vary from each other by no more than a few percent during the course of an operating cycle. It was also determined that the friction could be controlled by lubrication to maintain this increase in stress within 5%. It must be understood that the friction force discussed here is developed in the axial loading train between the spring or air cylinder and the specimen where modifications to the equipment can be most effective; it is not between the specimen and mandrel where the basic nature of the tests would be subject to question.

RESULTS OF PLASTIC RATCHETTING TESTS

The data of Table 1 indicate that reasonably accurate predictions of plastic ratchetting strain may be made by the use of Bree's charts (4) for plastic ratchetting. Similar analytical results were also obtained using the charts developed by Burgreen (5). Agreement is not achieved for those cases where no plastic ratchetting strain is predicted. Some of this may be due to the primary creep strain occurring during the very short period of the test, as mentioned previously. It may be observed, however, that the largest deviation from prediction for these cases occurs with the largest bending strain or smallest mandrel radius. Under the condition of largest bending strain the largest transverse movements and forces in the test equipment also are induced. Seemingly, these would result in the largest axial friction forces being induced and the largest error effected by this source.

Table 2 indicates the approximate amount of strain per cycle relative to the amount of strain induced in the second cycle. The first cycle is expected to incur a larger amount of plastic strain as the residual stress pattern is initiated, as noted previously (1). It can be seen that approximately 50% of the total strain occurs in the first cycle for those tests where the plastic ratchet strain per cycle

is predicted to be zero. It appears that a hardening mechanism results in continuing reduction in the strain per cycle where plastic ratchetting is expected to continue.

Footnote 1 of NB-3222.5 of Section III of the ASME Boiler and Pressure Vessel Code allows the use of $1.5 S_m$ when it is greater than S_y in establishing the limits for stresses to avoid ratchetting. S_m may be established at 90% of the 0.2% offset yield strength, which is the case at 800° F for Type 304 stainless steel. This limit is shown in Figure 1. If this limit were to be applied to these very short-time tests and the properties of this specific batch of material, as it does at 800° F, then the test of Specimens 9 and 22 would definitely exceed the Code limits established to prevent cyclic growth in diameter, as shown in Figure 1. Tests of Specimens 12 and 16, however, would barely exceed the Code limit and all the other tests would be within the limit. The group within the Code limit includes No. 17, which developed more than 1% strain, and No. 13, which developed more than 0.5% strain. Also, Nos. 12 and 16, which barely exceed the Code limit, attained 1.32% and 1.0% strain, respectively. The value of 1% strain is the deformation limit set by recent high-temperature design criteria as a matter of safety. When considered in the light of component operability in cases where dimensional tolerances are critical, rules allowing 1% strain could be quite optimistic.

RESULTS OF CHANGE OF MAGNITUDE OF THE AXIAL STRESS .

The data of Table 3 indicate a very substantial reduction in ratchetting strain as a result of decreasing the magnitude of axial stress. Tests 38 and 42 were performed under conditions similar to Tests 1 and 5 except that the axial stress was reduced to one-half the magnitude. The results of Test 38 indicate a reduction in strain per cycle by a factor of 3 to 4. The results of Test 42 indicate a reduction in strain per cycle by a factor of from 10 to 30. The total strain induced in Specimen No. 42 was actually below the threshold of measurement accuracy, which accounts in part for this wide variation. Tests 33 and 36 are directly comparable. Again it can be observed that reducing the axial stress by a factor of one-half reduces the induced strain by a factor of approximately 3.

Comparison of results from Tests 45, 46, and 47 indicates that after approximately 225 cycles, Specimen 45 with an axial stress of 20% of yield stress had developed 0.87% strain, Specimen 46 with 26% of yield stress had developed 2.6%

strain, and Specimen 47 with 34% of yield stress had developed 7.8% strain in the center 1 in. In this case, more reliable measurements could be made, and the results show a reduction of ratchetting strain by a factor of 3 between Tests 46 and 45 with a reduction of 23% of axial stress. Test conditions of Specimen 47 are in the regime where some plastic ratchetting is expected; therefore, the reduction of ratchetting strain by a factor of nine with a reduction of about one-half in axial stress from Test 47 to Test 45 is not unexpected.

RESULTS OF THE EFFECT OF CHANGES OF HOLD TIME

Comparison of the results of tests (Table 4) performed under the same conditions of bending strain and axial stress but with different hold times shows, with the exception of Test 6, a reasonably consistent increase in strain per cycle with hold time, as might be expected. Since the first seven tests shown in Table 4 were performed with a relatively large value of bending strain where error due to friction can be greatest, this inconsistency of Specimen No. 6 is not unexpected. Examination of Bree's graphical results (2) and the results of analysis indicate that near saturation enhanced creep is to be expected after a period of time which is an inverse function of the axial stress. This tendency is visible in the results of the tests.

Use of the simplified calculational method reported previously in Reference 2 indicates that an increase in strain of 45% is to be expected with an increase in hold time from 24 to 168 hr. An increase of 79% is observed when comparing the averages of the results of Tests 6 and 40 to those of Tests 21 and 34. An increase of 23% is observed on comparison of the average of the results of Tests 1 and 5 and those of Tests 20 and 24.

The results of Tests 46 and 47 are of special significance when one examines the ratchetting behavior over a large number of cycles as shown in Figure 3. First, it appears that the strain per cycle decreases consistently throughout the duration of the test; and second, the amount of strain achieved in both Tests 46 and 47 exceeds that achieved in a monotonic creep test. In one creep test performed at 1200° F with a stress of 85% of yield stress, rupture occurred in 160 hr with an elongation of only 2.5%. Failure (a multitude of surface cracks) has been achieved in Specimen No. 47 after 335 cycles with a strain of 10.3% after 2080 hr of testing.

TIME EFFECTS IN RATCHETTING

The results of Tests 25, 26, and 27 given in Table 5 are to be compared to each other to determine the effect of time-dependent variation in axial force relative to the time of the bend cycle on the amount of ratchet strain per cycle. Under essentially similar conditions of rapid cycle plastic ratchetting, the variation from Cycle Type A, as shown in Figure 2, to Cycle Type B resulted in approximately 25% less ratchetting strain per cycle for Test 27 relative to Test 25. The test with Cycle Type C resulted in approximately 70% less ratchetting strain per cycle for Test 26 relative to Test 25.

In changing from Cycle Type A to Cycle Type B under similar load and hold time conditions, the change from the average strain of Tests 32 and 39 to the average strain of Tests 29 and 35 does not show the anticipated significant decrease. In changing from Cycle Type A to Cycle Type C, the average strain of Tests 28 and 43 indicates a reduction in strain of 75%. The change from Cycle Type A to Cycle Type D yields an increase of 42%, while the change to Cycle Type E results in a reduction of 22%.

From the results of the tests it appears that modifying operational controls or procedures to achieve Cycle Type B rather than Cycle Type A has little to offer. However, if the transients are sufficiently slow and/or the controls sufficiently rapid, achieving Cycle Type C can result in worthwhile reductions in the ratchetting strain per cycle.

The test with Cycle Type D confirms expectations that periodic variations of steady-state thermal stress under conditions of reasonably constant mechanical stress result in a special ratchetting case which has not been well covered to date.

The tests with Cycle Type E indicate that some minor relief from ratchetting can be achieved by special treatment following a thermal transient.

CONCLUSIONS FROM TEST RESULTS

Conclusions from the test results are summarized as follows:

- 1) Test results tend to verify the analytical predictions of the magnitude of plastic ratchetting strain per cycle made by Bree and by Burgreen. The amount of strain per cycle is of such magnitude that plastic ratchetting conditions must be avoided for any normal or upset operating conditions.

- 2) The results of these ratchetting tests infer that the allowable use of $1.5 S_m$ rather than S_y in establishing ratchetting limits at temperature limits up to 800°F may result in allowing significantly more ratchetting deformation than originally anticipated. The problem merits additional testing.
- 3) It appears that hold time is an important parameter and that care should be taken in specifying the hold time both for design of equipment and development testing of equipment. This is especially noticeable in comparing the results of Specimen 15 with no hold time to the results of Specimens 20 and 24 with 1-week hold time, and noting that the latter tests exhibit six times as much strain per cycle.
- 4) The sensitivity of the amount of ratchetting strain per cycle to the phase relation between the bend cycle (thermal transient) and the axial stress (internal pressure) indicates that care should be taken in preparing design specifications to properly show the variations in system pressure relative to the thermal transients and hold times. Excessively conservative design for operational upset conditions may be imposed on facilities and test items unless such care is taken.
- 5) The control systems for an LMFBR plant may be designed and the operating procedures may be prepared for periods subsequent to the occurrence of severe transients so as to establish mechanical conditions which will minimize the ratchetting damage resulting from such a transient.
- 6) The lack of consistency in agreement between different tests and between test results and analytical predictions of the effect of changing the hold time of the most simple ratchetting tests, Cycle Type A, suggests that variation of conditions for these tests may be near the limits of reproducibility of the equipment.
- 7) The results of Test 47 indicate that the low ductility achieved for some materials in a monotonic creep test may not be an accurate indicator of the safe limit for ratchetting deformation.

- 8) As the program develops, further questions are being raised which require experimental data for evaluation of the problem. The test results which would be required to evaluate the problem posed by these questions may near the threshold of reproducibility of results on this equipment. It appears that the study of hold times can be at that threshold. Any attempt to verify Leckie's rule of a ratchetting limit based on $n/(n + 1) \cdot \sigma_y$ is also expected to be at that threshold. Improved equipment or different test methods for refined studies of ratchetting problems should be developed. The goals of this program are to be kept within limits imposed by the equipment.
- 9) It may be that tests of this type will be of as much value in obtaining data on creep-fatigue interaction with a mean stress as in obtaining data on ratchetting.
- 10) Other more fundamental programs should be undertaken which will yield basic information on the stress-strain relations and creep properties of materials (constitutive equations) which govern ratchetting behavior. Such tests should be performed under conditions which as nearly as possible simulate actual service conditions.
- 11) Increased emphasis should be placed on improved analytical predictions of the ratchetting results from these tests. Analytical methods have undergone sufficient development so that such an effort can now be efficiently undertaken.

REFERENCES

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2. J. Bree, "Incremental Growth Due to Creep and Plastic Yielding of Thin Tubes Subjected to Internal Pressure and Cyclic Thermal Stresses," J. Strain Analysis 3, No. 2 (1968), p 122

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5. D. Burgreen, "Structural Growth Induced by Thermal Cycling," J. Basic Eng., Paper No. 68-WA/Met-14 (December 1968)

FIGURES

1. Bree Chart Showing Ratchetting Test Parameters (Strain per Cycle = $\delta \cdot \sigma_y / E$)
2. Time Variation in Bending and Axial Stress
3. Ratchetting Specimen Elongation With Time at Temperature

TABLE 1
PLASTIC RATCHETTING TESTS

TEST CONDITIONS AND RESULTS	SPECIMEN NUMBER											
	9	11	12	13	14	15	16	17	18	19	22	23
TEST CONDITIONS:												
Specimen thickness (in.)	0.1155	0.1155	0.116	0.1155	0.1155	0.1155	0.116	0.114	0.114	0.116	0.1157	0.1155
Specimen width (in.)	0.483	0.493	0.495	0.498	0.495	0.493	0.495	0.498	0.494	0.492	0.486	0.490
Hold mandrel, radius (in.)	40	40	40	40	80	80	80	80	80	80	40	40
Bend mandrel, radius (in.)	20	20	20	20	40	40	20	20	20	80	20	20
Bend strain (% yield)	382	382	382	382	192	192	318	318	318	127	382	382
Axial load (lb)	855	349	702	424	846	636	850	694	416	839	832	353
Axial stress (% yield)	63	26.1	52	31.4	63	52	63	52	31.4	63	63	26.1
No. of cycles	4	6	10	15	15	7	6	15	5	7	5	6
No. of hours at temp	<24	<24	<24	2	<24	<24	<24	<24	<24	4	4	4
TEST RESULTS:												
Total strain, center inch (in./in.)	0.0098	0.00346	0.01326	0.00607	0.00408	0.0015	0.010	0.0109	0.00153	0.00175	0.0123	0.00338
Average strain/cycle (total test)(in./in.)	0.00245	0.00058	0.00133	0.00040	0.00027	0.00021	0.00167	0.00073	0.00031	0.00025	0.00246	0.00056
Average strain/cycle (first 7 cycles) (%/cycle)*	0.25	0.058	0.154	0.064	0.047	0.021	0.167	0.103	0.031	0.025	0.25	0.056
Average strain / cycle (cycles 2-7)(%/cycle)*	0.21	0.027	0.131	0.040	0.036	0.013	0.138	0.081	0.016	0.018	0.21	0.036
Predicted strain (%/cycle)	0.34	0.000	0.227	0.045	0.057	0.000	0.227	0.148	0.000	0.000	0.34	0.000

*Except where less than 7 cycles were performed.

TABLE 2
APPROXIMATE RATIOS OF STRAIN PER CYCLE FOR FIRST SEVEN CYCLES

SPECIMEN NUMBER	CYCLE NUMBER						
	1	2	3	4	5	6	7
9	1.45	1.00	0.88	0.75	—	—	—
11	4.27	1.00	0.73	0.36	0.36	0.36	—
12	1.50	1.00	0.76	0.67	0.61	0.52	0.46
13	2.67	1.00	0.67	0.46	0.38	0.25	0.33
14	1.76	1.00	0.72	0.56	0.40	0.36	0.32
15	2.64	1.00	0.55	0.45	0.27	0.45	0.18
16	1.63	1.00	0.76	0.68	0.63	0.58	—
17	1.83	1.00	0.78	0.61	0.50	0.47	0.42
18	2.88	1.00	0.38	0.38	0.25	—	—
19	2.07	1.00	0.57	0.36	0.29	0.14	0.21
22	1.56	1.00	0.82	0.79	0.74	—	—
23	1.85	1.00	0.38	0.23	0.15	0.19	—

TABLE 3

DATA ON THE EFFECT OF THE MAGNITUDE OF THE AXIAL STRESS

TEST CONDITIONS AND RESULTS	SPECIMEN NUMBER									
	1	5	38	42	33	36	44	45	46	47
TEST CONDITIONS:										
Specimen thickness (in.)	0.1155	0.1165	0.116	0.116	0.116	0.1155	0.1155	0.116	0.116	0.115
Specimen width (in.)	0.520	0.519	0.493	0.496	0.493	0.496	0.484	0.498	0.496	0.490
Hold mandrel, radius (in.)	80	80	80	80	40	40	40	40	40	40
Bend mandrel, radius (in.)	40	40	40	40	40	40	20	20	20	20
Bend strain (% yield)	192	192	192	192	254	254	382	382	382	382
Axial load (lb)	712	716	349	350	524	270	447	266	342	450
Axial stress (% yield)	50.4	50.4	26	26	39	20	34	20	26	34
No. of cycles	10	11	7	7	8	7	125	234	295	335
No. of hours at temp	265	290	168	168	192	168	780	1434	1836	2080
Hold time (hr)	24	24	24	24	24	24	6	6	6	6
TEST RESULTS:										
Total strain, center inch (in./in.)	0.0074	0.0063	0.00179	0.00020	0.00685	0.00229	0.04070	0.00869	0.03026	0.10335
Average strain/cycle (total test)(in./in.)	0.00074	0.00057	0.00026	0.00003	0.00086	0.00033	0.00033	0.00004	0.00010	0.00031
Average strain/cycle (first 7 cycles) (%/cycle)*	0.086	0.068	0.026	0.003	0.090	0.033	0.115	0.029	0.053	0.129
Average strain/cycle (cycles 2-7)(%/cycle)*	0.072	0.056	0.018	0.002	0.082	0.022	0.096	0.017	0.042	0.111

*Except where less than 7 cycles were performed.

TABLE 4
DATA ON THE EFFECT OF VARIATION OF HOLD TIME

TEST CONDITIONS AND RESULTS	SPECIMEN NUMBER												
	11	23	46	6	40	21	34	15	31	1	5	20	24
TEST CONDITIONS:													
Specimen thickness (in.)	0.1155	0.1155	0.116	0.1165	0.1135	0.1156	0.1131	0.1155	0.1155	0.1155	0.1165	0.1155	0.1135
Specimen width (in.)	0.493	0.490	0.496	0.519	0.499	0.496	0.493	0.493	0.493	0.520	0.519	0.494	0.497
Hold mandrel, radius (in.)	40	40	40	40	40	40	40	80	80	80	80	80	80
Bend mandrel, radius (in.)	20	20	20	20	20	20	20	40	40	40	40	40	40
Bend strain (% yield)	382	382	382	382	382	382	382	192	192	192	192	192	192
Axial load (lb)	349	353	342	367	345	352	342	636	682	712	716	685	687
Axial stress (% yield)	26.1	26.1	26	25.0	26	26.1	26	52	51	50.4	50.4	51	51
No. of cycles	6	6	295	16	7	7	7	7	12	10	11	7	7
No. of hours at temp	4	4	1836	400	168	1176	1176	4	144	265	290	1175	1176
Hold time (hr)	~0	~0	6	24	24	168	168	~0	12	24	24	168	168
TEST RESULTS:													
Total strain, center inch (in./in.)	0.00346	0.00338	0.03026	0.00500	0.00633	0.00837	0.00670	0.00150	0.00650	0.00740	0.00630	0.00566	0.00735
Average strain/cycle (total test)(in./in.)	0.00058	0.00056	0.00010	0.00031	0.00090	0.00120	0.00096	0.00021	0.00054	0.00074	0.00057	0.00084	0.00105
Average strain/cycle (1st 7 cycles)(%/cycle)*	0.058	0.056	0.053	0.046	0.090	0.120	0.096	0.021	0.066	0.086	0.068	0.081	0.105
Average strain/cycle (cycles 2-7)(%/cycle)*	0.027	0.036	0.042	0.036	0.070	0.105	0.085	0.013	0.055	0.072	0.056	0.070	0.087

*Except where less than 7 cycles were performed

TABLE 5
DATA ON THE EFFECT OF TIME DEPENDENT VARIATION IN AXIAL STRESS

TEST CONDITIONS AND RESULTS	SPECIMEN NUMBER											
	25	26	27	32	39	29	35	28	43	30	37	41
TEST CONDITIONS:												
Specimen thickness (in.)	0.1156	0.1155	0.1157	0.115	0.1165	0.116	0.115	0.1158	0.1155	0.116	0.114	0.116
Specimen width (in.)	0.485	0.4955	0.492	0.492	0.496	0.495	0.494	0.484	0.488	0.488	0.488	0.494
Hold mandrel, radius (in.)	40	40	40	80	80	80	80	80	80	80	80	80
Bend mandrel, radius (in.)	20	20	20	40	40	40	40	40	40	40	40	40
Bend strain (% yield)	382	382	382	192	192	192	192	192	192	192	192	192
Axial load (lb)	825	828	828	691	690	688	694	688	690	679	690	690
Axial stress (% yield)	63	63	63	52	52	51	52	52	52	51	52	52
No. of cycles	4	4	4	7	7	8	7	9	7	8	7	7
No. of hours at temp	4	4	4	>168	>168	>192	>168	>215	>168	>192	>168	>168
Hold time (hr)	~0	~0	~0	24	24	24	24	24	24	24	24	24
TEST RESULTS:												
Total strain, center inch (in./in.)	0.01162	0.00347	0.00990	0.00669	0.00756	0.00883	0.00647	0.00169	0.00194	0.01061	0.00586	0.00537
Average strain/cycle (total test)(in./in.)	0.00290	0.00087	0.00247	0.00096	0.00108	0.00110	0.00092	0.00019	0.00028	0.00133	0.00084	0.00077
Average strain/cycle (cycles 2-7)(%/cycle)*	0.260	0.048	0.207	0.080	0.099	0.100	0.082	0.019	0.025	0.128	0.073	0.066
Phase relation diagram (cycle type)	A	C	B	A	A	B	B	C	C	D	E	E

*Except where less than 7 cycles were performed.

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Figure 1. Bree Chart Showing Ratchetting Test Parameters (Strain per Cycle = $\delta \cdot \sigma_y/E$)

Figure 2.
Time Variation in Bending
and Axial Stress

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