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EX-REACTOR DEFORMATION OF EXTERNALLY PRESSURIZED SHORT LENGTHS OF FUEL ROD CLADDING

(LWBR Development Program)

cp

May 1979

CONTRACT EY-76-C-11-0014

BETTIS ATOMIC POWER LABORATORY
WEST MIFFLIN, PENNSYLVANIA

Operated for the U. S. Department of Energy by
WESTINGHOUSE ELECTRIC CORPORATION

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I.A. Selsley

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BETTIS ATOMIC POWER LABORATORY WEST MIFFLIN, PENNSYLVANIA 15122

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NOTICE

FOREWARD

The Shippingport Atomic Power Station located in Shippingport, Pennsylvania was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. This program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. It has provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

Subsequent to development and successful operation of the Pressurized Water Reactor in the DOE-owned reactor plant at the Shippingport Atomic Power Station, the Atomic Energy Commission in 1965 undertook a research and development program to design and build a Light Water Breeder Reactor core for operation in the Shippingport Station.

The objective of the Light Water Breeder Reactor (LWBR) program has been to develop a technology that would significantly improve the utilization of the nation's nuclear fuel resources employing the well-established water reactor technology. To achieve this objective, work has been directed toward analysis, design, component tests, and fabrication of a water-cooled, thorium oxide fuel cycle breeder reactor for installation and operation at the Shippingport Station. The LWBR core started operation in the Shippingport Station in the Fall of 1977 and is expected to be operated for about 3 to 4 years. At the end of this period, the core will be removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for a detailed examination to verify core performance including an evaluation of breeding characteristics.

In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration established the Advanced Water Breeder applications (AWBA) program to develop and disseminate technical information which would assist U.S. industry in evaluating the LWBR concept for commercial-scale applications. The program will explore some of the problems that would be faced by industry in adapting technology confirmed in the LWBR program. Information to be developed includes concepts for commercial-scale prebreeder cores which would produce uranium-233 for light water breeder cores while producing electric power, improvements for breeder cores based on the technology developed to fabricate and operate the Shippingport LWBR core, and other information and technology to aid in evaluating commercial-scale application of the LWBR concept.

All three development programs (Pressurized Water Reactor, Light Water Breeder Reactor, and Advanced Water Breeder Applications) have been administered by the Division of Naval Reactors with the goal of developing practical improvements in the utilization of nuclear fuel resources for generation of electrical energy using water-cooled nuclear reactors.

Technical information developed under the Shippingport, LWBR, and AWBA programs has been and will continue to be published in technical memoranda, one of which is this present report.

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EX-REACTOR DEFORMATION OF EXTERNALLY PRESSURIZED SHORT LENGTHS OF FUEL ROD CLADDING

(LWBR Development Program)

I.A. Selsley

1. INTRODUCTION

1.1 Problem Description

Cladding collapse and cladding deformation into short, unsupported axial gaps that have occurred in pellet-filled, cylindrical fuel elements have been documented for commercial reactors. (See Reference 1 for an extensive review of fuel rod failures.) Although certain design and manufacturing features, notably use of high density oxide fuel pellets, reduce the potential for formation of axial gaps, mechanisms still exist which could lead to axial gap formation. These mechanisms include: (1) in-reactor densification of fuel pellets, (2) irradiation induced growth of Zircaloy cladding, and (3) pellet-cladding interactions which can increase the cladding length and decrease the fuel pellet length.

Fuel rod axial gaps are undesirable because they disturb local neutron flux thereby causing power peaking in fuel pellets adjacent to the axial gap and in adjacent fuel rods without axial gaps. In addition, by depriving fuel rod cladding of fuel pellet support, axial gaps can permit local deformation of the cladding in fuel rods not having freestanding cladding. Undesirable potential consequences of cladding deformation over axial gaps are: (1) loss of proper grid support, resulting in increased fuel rod vibration and wear, (2) interference with adjacent fuel rods or support structures, and (3) fuel rod failure (probably by cracking) if cladding collapses into the axial gap. Axial gaps are potentially larger at higher fuel rod elevations because fuel stack and cladding strains are cumulative upward from the fuel rod bottom, with the largest possible gap forming in the top plenum region above the fuel stack. Because the fuel rod plenum is in a low neutron flux region, cladding deformation there occurs primarily by thermal creep. Thus, this portion of the cladding is amenable to direct ex-reactor testing.

This report documents testing and analysis of data in the DECAG (Deformation of Cladding into Axial Gaps) test program conducted as a part of the Light Water Breeder Reactor (LWBR) fuel element development program. The test program investigated (1) deformation (average diameter decrease and ovality increase) of unsupported cladding over short axial gaps, and (2) the potential for collapse into these gaps.

1.2 Related Work by Other Investigators

Several investigators recently reported results of their tests on Zircaloy cladding deformation resulting from external pressure. Some of these tests were used to establish Zircaloy properties such as anisotropy characteristics in tension and compression. Others, like the DECAG tests, were directly related to cladding stability questions. Most investigators used internal pressure tests which are relatively easier to conduct and which provide significant data on stress-strain relationships without the complicating factors of superposed ovality and collapse tendency associated with external pressure tubing tests. Significant tests which complement certain aspects of the DECAG test program are discussed below. The Zircaloy tubing in the cited tests, as well as in the DECAG tests, was tested in two conditions: (1) highly cold worked (70 to 80 percent) which was stress relief annealed (SRA) at 950F for four hours after final working, and (2) fully recrystallization annealed (RXA) tubing which was annealed at 1200 to 1250F for four hours.

1.2.1 Oak Ridge National Laboratory (ORNL)

Hobson and co-workers at ORNL (References 2 to 6) developed cladding creep and dynamic collapse tests with unique eddy current probe instrumentation that permitted continuous measurement of externally pressurized tubing deformations during testing at high temperatures and pressures. The ORNL thermal creep tests were conducted ex-reactor at 700F in the pressure range of 2100 to 2500 psig. Tubing tested was highly cold-worked material with a stress relief anneal (SRA). Tubing specimens had 0.430 inch diameters with 0.025-inch wall thicknesses (OD/t=17.2) which resulted in a hoop stress range of 18,000 to 21,500 psi. These conditions were similar to the DECAG-II test conditions of 674F with hoop stress of about 20,900 psi. Tubing specimens with unsupported axial lengths in the range 0.4 to 4.0 inches were tested. These axial gap lengths span the range of the DECAG-II tests (0.525 to 1.65 inches) and are of the magnitude of potential gaps in reactor fuel elements. Some data have been reported by ORNL (Reference 5) for specimens with 0.4- and 0.8-inch unsupported lengths and about 1000 hours of test time. Diameter and ovality changes reported are in substantial agreement with those experienced in the DECAG tests relative to both magnitude of the changes and the deformation mechanisms. These tests provide an important contribution to the understanding of cladding creep-down over axial gaps where there is no support for the cladding, and over fueled lengths where support is obtained as cladding creeps down onto pellets.

ORNL dynamic collapse testing is reported in Reference 6. Specimens were similar to those described above for thermal creep tests, but the test temperature was 800F and test pressures ranged from 3200 to 5000 psig to produce rapid collapse.

An empirical model for predicting collapse pressure as a function of gap length, specimen hardness, and test temperature is presented in Reference 6. The empirical equation applicable to Zircaloy tubing specimens at 800F and having a 0.008-inch initial diametral pellet-cladding gap is given as

$$P = 14{,}700 + \frac{G}{0.000217G - 0.000018} - 183H + 0.729H^2 - 0.00074H^2 - 2.09T \qquad \text{(Eq. 1.1)}$$

where: P = collapse pressure (psi)
G = pellet-to-pellet axial gap (inch)
H = room temperature midwall hardness (Diamond Point Hardness)
T = test temperature (F)

1.2.2 Hitachi Research Laboratory

Maki and Hara (Reference 7) reported results of tests on circumferential ridging of cladding at pellet-pellet interfaces that may occur due to hourglassing of ceramic fuel pellets. Both cold-worked (SRA) and annealed (RXA) Zircaloy-2 specimens were tested. Simulation of pellet hourglassing was achieved by machining cylindrical stainless steel pellets into spool-like shapes with ridges at both ends. In the original test (Reference 7) these spools were 0.83 inch long with a 0.79-inch unsupported length between ridges. Additional lengths were tested (Reference 8) to support the conclusions of the first test. Control specimens of empty tubing 5.12 inches long also were tested. All tubing had 0.564-inch outside diameter (OD) and 0.032-inch wall thickness (OD/t=17.6).

Testing was performed in an electrically heated pressure vessel using argon gas for pressurization. SRA tubes, both hollow and pellet filled, were tested in pairs in nine tests; the environmental conditions were combinations of the following temperatures and pressures:

Test temperatures - 572, 662, and 752F
Test pressures - 790, 1031, and 1273 psig

Tests on RXA material were conducted only for the combination of 662F, 1031 psig whereas SRA material was tested at all pressure-temperature combinations. All pressures are lower than those used in the DECAG test program and correspond to hoop stresses of 6950, 9070, and 11,200 psi. The exposure period for each test was 270 days, with measurements obtained after elapsed times of 30, 90, 180, and 270 days.

Little deformation was noted for the low temperature, low pressure combinations (572F at 790 and 1031 psig), but tests at higher temperature/pressure combinations produced discernible increases in diameter over pellet ridges. The authors attributed these diametral increases to bending stresses which occurred as the unsupported portions of the tubing deformed into the spool recesses on either side of the ridges.

Unlike the Oak Ridge and DECAG tests, which had pellet-to-tubing radial gaps of up to 0.004 inch at test temperature, the stainless steel pellets in these tests were designed to contact the tubes at test temperature; that is, the ridges contacted the interior surface of the tubes from the beginning of the test. Creep deformation of the pellet-filled tubes, as measured by decrease in average diameter at mid-length of the unsupported tubing sections, was greater than that of the empty control specimens exposed in the same environment. Maki and Hara conclude that a certain length of unsupported tubing in the range 0.0 to 0.8 inch maximizes external pressure creep deformation under the conditions of their tests. This conclusion was reinforced in continuing tests (Reference 8) with both shorter and longer unsupported lengths (0.43 inch and 1.46 inches. In these later tests the shorter length deformed more, and the longer length deformed less, than the 0.79-inch gap length specimens reported earlier in Reference 7. The deformations noted in the 1.46-inch unsupported length specimens were essentially the same as the deformations in the empty control specimens. This phenomenon is discussed more completely in conjunction with the DECOP tests (See Section 2.5).

1.2.3 Kraftwerk Union AG

Uniaxial and biaxial tensile burst and creep tests were performed on Zircaloy-2 tubes having 0.42-inch outside diameter and 0.028-inch wall thickness (OD/t=15) (Reference 9). The purpose of the test was to measure mechanical and anisotropy parameters of tubing. Both cold-worked, SRA and RXA tubing were tested with emphasis on SRA tubing.

Biaxial tests, using both internally and externally pressurized tubes, were conducted in a furnace using helium for pressurization. Deformation measurements were obtained by means of linear variable differential transformers connected to the specimens through a system of knife edges and quartz tubes.

Of primary interest in the present context are the results of the biaxial creep tests under both tensile and compressive stress. The ratio of tensile to compressive creep rate (that is, the rate of diameter changes for internally and externally pressurized specimens, respectively) was found to be greater than unity and to increase with generalized stress up to about 18,000 psi but then to decrease. However, because of experimental uncertainties in the tests, the authors stated that detailed conclusions were not justified. Nonetheless, a strength differential was clearly revealed in their 752F tests for both uniaxial tests and biaxial tests with closed end specimens. The creep-down of the tubes under external pressure was less than expected from the theory based on tensile or internal pressure tests alone. These results highlight the need for additional information to more completely characterize compressive properties of Zircaloy material.

2. PRIOR BETTIS WORK ON SHORT TUBE COLLAPSE

Prior to the design and implementation of the DECAG test program ex-reactor investigations of Zircaloy cladding deformation were conducted at Bettis in two areas: (1) dynamic collapse studies at high temperature and pressure in order to determine short time material operational limits on stress, and (2) creep deformation studies under lower temperature and pressure conditions more nearly similar to reactor environments in order to determine system operating margins.

2.1 Dynamic Collapse Tests

The dynamic collapse tests were short term, high pressure, elevated temperature tests designed primarily to determine material operational margins. Nine dynamic collapse specimens were fabricated by welding end plugs with a 0.5-inch long tapered section into short pieces of cold-worked (SRA) Zircaloy-4 tubing. Specimen lengths were selected so that unsupported sections of tubing ranged from 0.25 to 1.50 inches. The OD/t ratio was 17.7.

The dynamic collapse tests were conducted at 700F in a nitrogen atmosphere whose pressure was increased at 300 psi per minute. Specimen collapse was indicated by circuit interruption when an electrically instrumented ceramic ring positioned around the specimen midlength broke due to cladding collapse. Collapse pressures ranged from 5950 psig for a 1.5-inch axial gap to 9500 psig for a 0.3785-inch gap, corresponding to hoop stresses in the range 52,700 to 84,100 psi. The 0.25-inch axial gap specimen did not collapse at a test pressure of 10,000 psig.

The test results were compared to calculations using the BUSHL computer program (Reference 10) as the basis for an analytical model. In this comparison the data were bounded by the calculations. However, the BUSHL program uses equations of plasticity based on Hill's anisotropic theory of plasticity to determine stress-strain relations which are not general enough to handle the anisotropy of Zircaloy. The form of Hill theory used requires compressive and tensile yield strengths to be equal; as noted in Reference 9, Zircaloy compressive and tensile yield strengths are not equal.

2.2 Short-Time Creep Tests

The second phase of the short tube collapse tests consisted of short-time creep tests at a pressure below that found for dynamic collapse of the 1.5-inch axial gap specimens. These tests were conducted for 120 hours at 700F and an external pressure of 5500 psig. Ceramic ring instrumentation was again used to indicate specimen collapse.

Specimens with gap lengths of 0.75 and 1.0 up to 1.5 inches collapsed in 58 hours or less, while those with gaps of 0.875 and 0.63 down to 0.25 inch survived the full 120 hours. Thus, the critical gap length for collapse under these conditions was in the range 0.75 to 0.875 inch.

BUSHL analyses of these tests conservatively bounded the data and indicated that analysis using isochronous stress-strain curves correlated reasonably well with the test data, in spite of the limitations on BUSHL noted above. Tubing over the axial gap was modeled by assuming clamped end boundary conditions and allowing for property anisotropy.

2.3 Long-Tube Dynamic Collapse Tests

Empty tubes 12 inches long were tested ex-reactor to study the dynamic-instantaneous collapse pressure of Zircaloy-4 tubing at 700F. These tests were similar to the short tube dynamic collapse tests discussed above except that the unsupported length was greater and both RXA tubes and cold worked, SRA tubes were included. Instantaneous collapse pressures for RXA material tended to be 10 to 15 percent lower than for SRA tubing with similar values of OD/t. This result is consistent with the lower yield strength of fully annealed material. This result also agrees qualitatively with the findings of Hobson (discussed in Section 1.2.1) that the collapse pressure is explicitly a function of room temperature midwall hardness as formulated in Equation 1.1, although Equation 1.1 over-predicts collapse pressures experienced in the Bettis long-tube dynamic collapse tests by about 25 percent.

2.4 Axial Wrinkling Tests

Axial wrinkling tests were run to study the mechanism of axial wrinkling and subsequent shrinkage of the Zircaloy-4 cladding around solid pellets. The test specimens were eight inches long and contained solid Zircaloy-4 pellets of various diameters to provide pellet-to-cladding diametral gaps of 0.010, 0.008 and 0.006 inch. Tubing wall thickness and diameter variations gave OD/t ratios of 22.5, 20.4 and 18.7. These ratios indicate nonfreestanding cladding when tested at 2200 psig in the temperature range of 650F to 830F. Both RXA and cold-worked SRA specimens were tested. Measurements were made at cumulative times of 10, 100, 500 and 1000 hours. Comparison of results at 700F and 2200 psig on RXA and SRA specimens showed similar propensity toward axial wrinkling. However, RXA material showed less tendency toward diameter creep shrinkage for similar OD/t. Wrinkles which formed early-in-test on specimens tested at 830F were ironed out by end-of-test as diameter decrease completely closed the pellet-to-cladding radial gap.

The GAPL-3 computer program, (Reference 11), was used to analyze long tube creep collapse and axial wrinkling. Calculations were not in good agreement with test data. A major weakness of the GAPL-3 analysis was the use of isochronous stress-strain curves in a state point analysis of creep deformation. This method is incapable of predicting the actual history of the tube deformation.

2.5 The DECOP Tests

Another Bettis test program related to the DECAG program was the DECOP (DEformation of Cladding Over Pellets) test. This test experimentally evaluated local cladding deformation into a variety of unsupported regions including fuel pellet end tapers and chamfers, fuel surface voids caused by chipping and cracking, and interpellet axial gaps. The interpellet axial gaps are of primary concern in the present context. In the axial gap portion of the test, cladding diameter decrease and progressive ovalization over a 0.6-inch long axial gap were monitored.

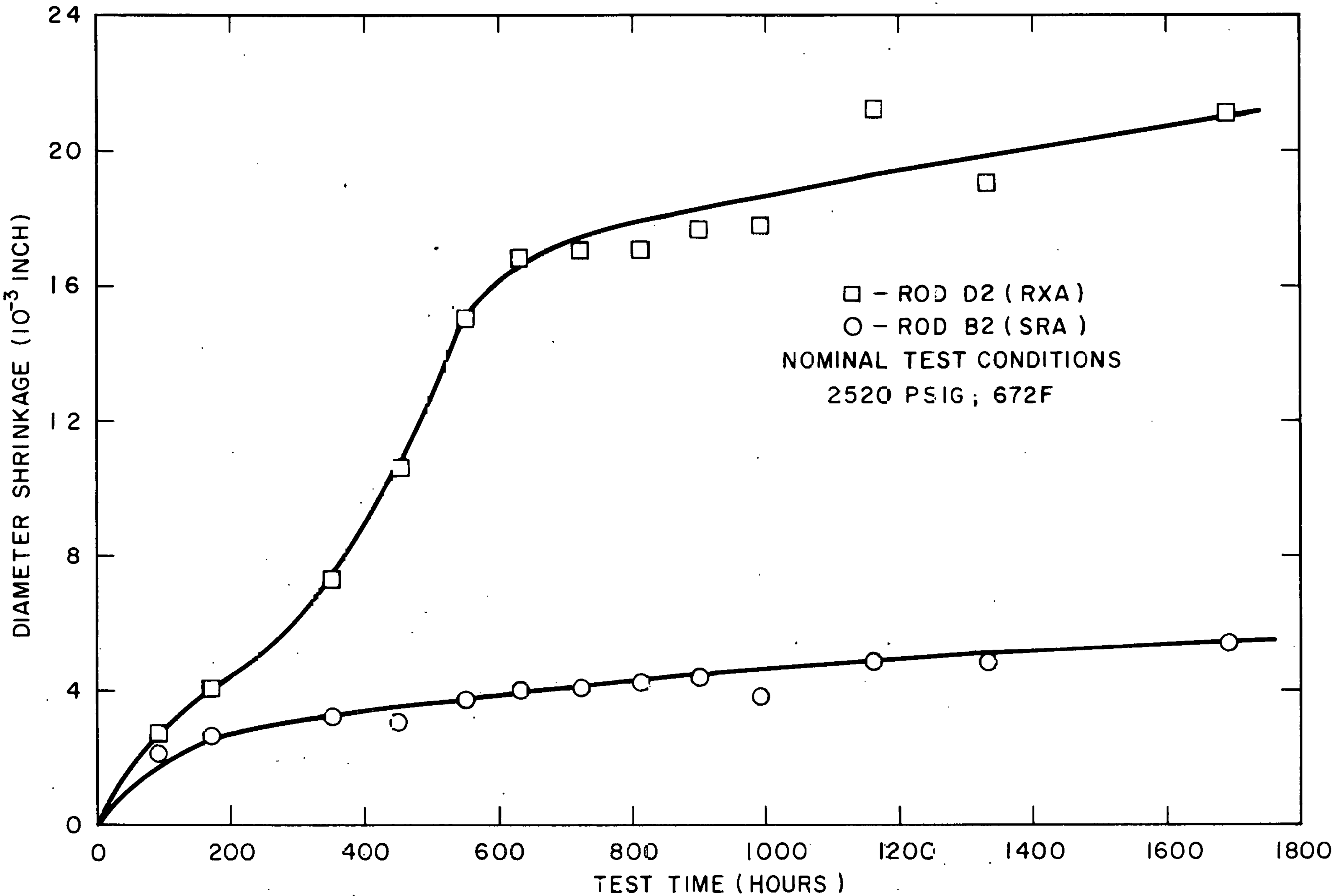
There were four test rods, each about two feet long by 0.506 inch OD. Each test specimen was filled with stainless steel pellets containing simulations of various potential defects machined into the pellets. Axial gaps 0.6 inch long were formed in two of the rods (one RXA and one SRA tubing material) by reducing pellet diameter in the center of a 1.0-inch long pellet to 0.25 inch, thus forming a spool-shaped insert.

Testing was conducted in an autoclave at 2520 psig and 672F. Periodically the specimens were removed from the autoclave to obtain measurements consisting of contour axial traces on four orthogonal tracks and circumferential profiles at key axial positions.

Figure 2.1 shows progressive diameter shrinkage measured over the 0.6-inch axial gaps of both the RXA and SRA rods. After 1700 hours test time the measured diameter shrinkages were relatively large, 0.0054 inch for SRA material and 0.021 inch for RXA, compared with later DECAG tests in which maximum diameter changes were less than 0.004 inch for longer test periods. Maki and Hara (Reference 7) reported similar results showing greater creep deformation for RXA Zircaloy-2 tubing than for SRA tubing under similar conditions. Comparison of these results with the DECAG-I and DECAG-II tests (See Figures 4.6 and 4.8) reveals an apparent anomaly in that the DECAG tests clearly show that SRA material creeps faster under a given set of environmental conditions than does RXA material. The apparent anomaly can be explained by comparing the behavior of the stainless steel spool pieces used in both the DECOP and Hitachi tests with the uniform Zircaloy inserts of the DECAG tests.

In the DECOP and Hitachi tests the stainless steel spool pieces contacted the internal surface of the cladding, possibly with a small amount of interference, thus introducing uncertainties concerning axial and transverse (hoop) stress distribution in the tubing over the unsupported region. In the supported region near the spool ridge, bending stress in the cladding resulting from combined thermal and hydrostatic forces can exceed the yield strength of RXA material but not SRA material. Under these circumstances, RXA material is expected to deform faster. On the other hand the Zircaloy inserts used in the DECAG tests do

FIGURE 2.1
AVERAGE CLADDING DEFORMATION
0.6 INCH AXIAL GAPS IN DECOP RODS



not contact the internal surface of the cladding as do the stainless steel spools; thus the driving forces for deformation in the DECAG specimens are hydrostatic only. Without a mechanism for inducing bending stresses, the generalized stresses are much less than the material yield strength for either RXA or SRA materials. Other investigators have shown that creep rates of Zircaloy-4 for given tempeature-pressure conditions increase with increasing amounts of cold work (Reference 12). Thus, under these circumstances SRA specimens are expected to deform faster than RXA specimens for a given set of temperature-pressure conditions.

In summary, the DECAG specimens deform by thermal creep whereas the DECOP and Hitachi specimens yield plastically due to local bending stresses in the vicinity of the spool ridges. Since SRA material creeps faster than RXA, deformation rates will be greater in DECAG SRA specimens than in RXA specimens. But SRA material has a higher yield strength, so deformation rates in DECOP and Hitachi SRA specimens will be less than in the RXA specimens.

These arguments also explain why both shorter gap specimens (0.43 and 0.79 inch) deformed faster than a longer gap specimen (1.46 inches) in the Hitachi tests. For some critical gap lengths, which are dependent on pressure and temperature conditions, the influence of the bending stresses is reduced to zero at the gap axial centerline and only thermal creep remains as a driving force. In the Hitachi tests this occurs between 0.79 and 1.46 inches, which is indicated by the fact that the 1.46-inch axial gap specimen had about the same centerline deformations as the empty control specimens, which were more than five inches long.

Another effect of the stainless steel inserts which contact the inner surface throughout the test period is to prevent cladding ovalization and thus assist in maintaining stability over the short, unsupported length. Maximum ovality noted in the DECOP test was only about 0.002 inch; Maki and Hara report that no elliptical deformation (ovalization) was observed in the Hitachi tests on pellet filled specimens.

2.6 The Need for Additional Testing

Previous testing at Bettis characterized the potential for cladding collapse and provided certain details concerning operating margins for Zircaloy-4 clad fuel rods, that is, testing was primarily concerned with cladding instability. It was recognized that test conditions in almost all cases were much more severe than would be experienced in operating reactors. Accordingly, the DECAG test program was designed to more nearly simulate conditions that actual fuel rods might experience in order to confirm not only stability but progressive deformation of cladding over axial gaps. Also, a more extensive data base would be useful in improving analytical methods, both by empirical fitting of test results and by theoretical analysis using computerized numerical methods.

3. DESCRIPTION OF DECAG TESTS

3.1 General Description of All DECAG Tests

The DECAG (DEformation of Cladding into Axial Gaps) test program reported herein is composed of three sets of specimens in twelve test series. The specimen sets are designated DECAG-I, DECAG-II and DECAG-III on the basis of specimen type: DECAG-I set is composed of 0.5685-inch nominal OD recrystallization annealed tubing (RXA), DECAG-II set is composed of 0.5685-inch nominal OD 78 percent cold worked tubing with a stress-relief anneal (SRA), DECAG-III set is composed of 0.305-inch nominal OD RXA tubing. After fabrication, specimens were vapor blasted and pickled to reduce wall thicknesses to the desired testing values. Tubing for DECAG-I and DECAG-II specimens was pickled to reduce the wall thickness to a nominal 0.0255 inch and the tubing for DECAG-III specimens was reduced to a nominal 0.020-inch wall thickness.

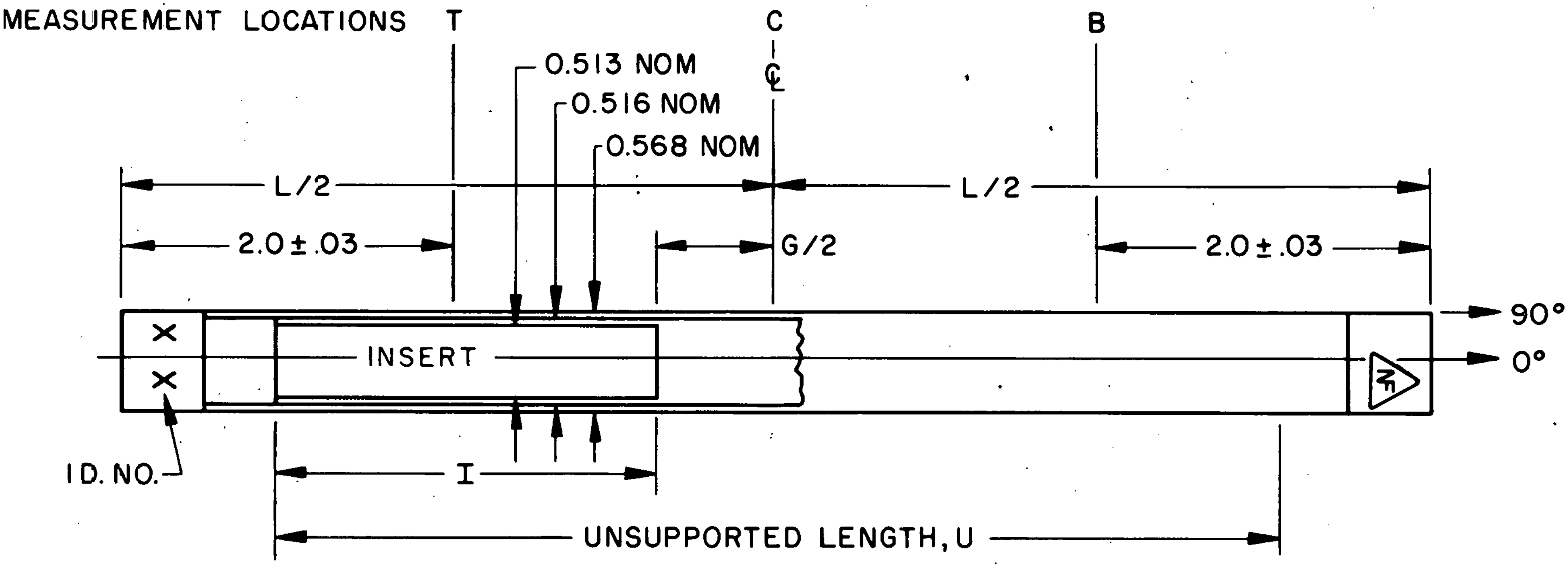
Each DECAG-I and DECAG-II specimen was fabricated by welding two end plugs with integrally machined extensions into a section of tubing. The end plug extension, referred to as an "insert" on Figure 3.1, was machined to a diameter which provided a nominal 0.0015-inch radial gap between insert and cladding. The tubing lengths were selected such that when the tubing and end plugs were assembled, the desired axial gaps were formed as lengths of empty, unsupported tubing. A major advantage of this design as opposed to the "spool" configuration used in DECOP specimens (see Section 2.5) or in the tests by Maki, et al (Reference 7) is that hydrostatic end loads are unambiguously transmitted to the gap cladding, as in a fuel rod with a gap.

Each DECAG-III specimen was fabricated by welding two end plugs without inserts into 10-inch long lengths of tubing. Three of the seven specimens were equipped with full length springs, which would normally be in a fuel rod plenum to suppress motion in fuel stacks, and the remainder were empty tubes.

Testing was performed in autoclaves in either a water or steam environment depending on temperature-pressure characteristics. Axial temperature distribution in the autoclave was maintained with $\pm$10F of nominal.

Diameter and ovality measurements were obtained with either a dial micrometer snap gage (0.0001 inch/division) or a Pratt and Whitney Bench Micrometer (0.00001 inch/division). Circumferential profile measurements were obtained with a Bendix-Cleveland Product-O-Ron profilometer. (See Appendix 2 for details of measurement systems.)

FIGURE 3.1 SCHEMATIC OF DECAG TEST SPECIMENS



DIMENSION	DECAG-I VALUE	DECAG-II VALUE
G	0.25 - 2.50	0.525 - 1.65
U	3.25 - 5.50	5.225 - 6.35
I	1.5	2.35
L	5.200 - 7.45	7.175 - 8.300

3.2 DECAG-I Tests

The DECAG-I test program was designed to study creep deformation and collapse of cladding at two pressures, 2200 psig and 2600 psig, and at two temperatures, 625F and 674F. The specimens were made with axial gap lengths ranging from 0.25 to 2.50 inches (Figure 3.1). The insert length was 1.5 inches; therefore, the overall tubing length range was from 3.25 to 5.50 inches and the tubing was initially unsupported over this length.

Table 3.1 summarizes the test histories of each of the three series of specimens in the DECAG-I program.

Table 3.1
Test History for Three DECAG-I Series

Cycle Number	Series 26674 Pressure = 2600 psig Temperature = 674F	Series 26625 Pressure = 2600 psig Temperature = 625F	Series 22674 Pressure = 2200 psig Temperature = 674F
	Total Time at End of Cycle (Hours)		
1	50	51	54
2	139	138	160
3	378	376	365
4	634	631	621
5	890	832	753
6	1098	1087	961
7	1440	1397	1218
8	2051	2028	1513
9	4276	4276	1799
10	4923	5414	2600
11			4546
12			4746

3.3 DECAG-II Test Program

The initial phase of the DECAG-II test program was designed to test the effects of periodic pressurization simulating plant hydrostatic and relief valve testing. These tests were expected to be short duration ($\leq$ 6 hours) high pressure tests (2500 - 2750 psig) at hot standby temperature ($\leq$ 534F). Each simulated hydrostatic test in the primary test group (Series 4) would be separated by accelerated normal operation for 500 hours at 2000 psig and 674F, with elevated temperature as the acceleration factor. Six specimens with nominal 0.525-inch axial gaps at beginning-of-test were to be periodically cut apart, remachined and rewelded to incrementally enlarge the axial gap to 1.65 inches. The length of inserts for use in DECAG-II specimens was increased to 2.35 inches to provide machining stock to be removed in lengthening axial gaps. (See Figure 3.1.) Thus, the overall length range of the as-fabricated specimens was 7.175 to 8.300 inches encompassing specimens initially fabricated with axial gaps of 0.525, 0.75, 1.0 and 1.65 inches. Subsequent testing revealed a critical axial gap length for stable operation to be between 1.00 and 1.65 inches; specimens were fabricated with axial gaps of 1.2 and 1.4 inches to provide data in that critical range.

Table 3.2 summarizes test histories for each of the eight series and subseries comprising the DECAG-II test program; the purposes of each series follow.

Table 3.2
Test History of Eight DECAG-II Test Series

Number	Parameter*	Series 1	2	3A	3A2	3B	3B2	4	5
1	Press.	2750	2750	2200	2200	2000	2200	2750	2200
	Temp.	534	534	674	645	636	645	534	645
	Time	8	8	162	84	954	84	24	84
2	Press.	2750	2750	2000	2000	2000	2000	2750	2750
	Temp.	534	534	674	674	636	636	534	534
	Time	24	24	386	234	2344	434	48	132
3	Press.	2750	2750	2000	2000	2000	2000	2500	
	Temp	534	534	674	674	636	636	534	
	Time	48	48	2086	484	3786	900	84	
4	Press.	2500	2500	2000	2000		2000	2000	
	Temp.	534	534	674	674		636	674	
	Time	84	84	2782	992		2604	584	
5	Press.	2750	2750	2000+	2000		2000	2750/2500	
	Temp.	450	450	674	674		636	534	
	Time	104	104	3282	1582		4572	590	
6	Press.	2500	2500	2000+	2000			2000	
	Temp.	450	450	674	674			674	
	Time	114	114	3782	2582			1096	
7	Press.		2750					2750/2500	
	Temp.		534					534	
	Time		268					1102	
8	Press.		2750					2000	
	Temp.		534					674	
	Time		373					1602	
9	Press.							2750/2500	
	Temp.							534	
	Time							1608	
10	Press.							2000	
	Temp.							674	
	Time							2108	
11	Press.							2750/2500	
	Temp							534	
	Time							2114	
12	Press.							2000+	
	Temp.							674	
	Time							2614	
13	Press.							2000+	
	Temp.							674	
	Time							3114	

See notes on following page.

Notes to Table 3.2

*Press. = Pressure, psig
Temp. = Test Temperature, °F
Time = Accumulated Time to End of Cycle, Hours

+Variable gap specimens from Series 3A2 and 4 (four total) combined and continued in test; balance of both test series discontinued.

3.3.1 DECAG-II Series 1, 2 and 5

Series 1, 2 and 5 were short term scoping tests. Series 1 and 2 were designed to determine the effects of beginning-of-life hydrostatic testing on cladding deformation in order to evaluate the proposed test program for Series 4. The two tests were identical with the exception that Series 2 specimens were plastically deformed (preovaled) by compressing the tubing portion of the fabricated specimens in a hydraulic press between flat anvils to provide approximately 0.005-inch initial ovality. After deformation, these specimens received a stress relief anneal for four hours at 950F. Initial ovality of Series 1 specimens was 0.001 inch or less, averaging 0.0007 inch.

Series 5 specimens were exposed only to a corrosion filming operation, 2200 psig at 645F for 84 hours, in order to provide a correction to Series 4 data in which this operation was not provided.

3.3.2 DECAG-II Series 3

Series 3 consisted of four subseries of tests, designated 3A, 3A2, 3B and 3B2. These tests were intended to verify applicability of the Larson-Miller Parameter (Reference 13) to determine an acceleration factor for Series 4 based on temperature. Because of the long test periods and the inclusion of specimens in which the axial gaps were enlarged periodically, these tests provided much valuable information related to cladding deformation. Series 3A and 3B each contained four specimens: three with initial 0.525-inch axial gaps (including one which was preovaled) and one with initial 1.65 inch axial gap. Subsequent testing of Series 4 demonstrated that long term stability for a gap existing from beginning-of-test could be expected for gap lengths greater than 1.0 inch, but less than 1.65 inches. To further investigate this critical gap length range Series 3A2 and 3B2 were initiated, each with eight paired specimens having axial gaps of 1.0, 1.2, 1.4 and 1.65 inches. Test conditions were essentially the same as sister tests 3A and 3B except that these specimens received pretest corrosion filming.

3.3.3 DECAG-II Series 4

Series 4 was a long term, accelerated lifetime simulation, including periodic hydrostatic and relief valve test operations. Intermittent hydrostatic and relief valve tests were performed in real time (6 hours total test time at 2500 - 2750 psig and 534F). Normal operation was accelerated by increasing temperatures, with temperature-time correspondence to real time based on Larson-Miller Parameter equivalence.

The test consisted of twelve specimens: six with 0.525-inch gaps and two each with 0.75-, 1.0- and 1.65-inch axial gaps. Half of the specimens of each size were as fabricated from LWBR quality tubing, and the other half were preovaled in the manner described for Series 2 specimens in Section 3.3.1.

3.4 DECAG-III Test

The DECAG-III test was designed as an accelerated lifetime test to confirm the freestanding characteristic of small diameter RXA cladding with a long (10 inch) unsupported length. The test consisted of seven specimens, four of which were empty tubes and three of which contained springs. The test program is presented in Table 3.3.

4. SUMMARY OF TEST RESULTS

4.1 DECAG-I Tests

Diameter change and ovality data for DECAG-I test specimens are summarized in Figures 4.1 through 4.6. Data tables from which these curves were constructed are presented in Appendix 1. Both diameter and ovality were measured at the axial gap mid-plane using a dial micrometer snap gage. The figures demonstrate that diameter changes are independent of axial gap length whereas ovality is a strong function of axial gap length. This phenomenon is discussed more fully in Section 5.

4.2 DECAG-II Tests

4.2.1 Scoping Tests - Series 1, 2 and 5

As noted in Section 3.3.1, these short scoping tests were conducted to determine the effects of simulated beginning-of-life testing on the DECAG-II specimens in order to gain assurance that the relatively high test pressure, 2750 psig, would not produce effects that would make subsequent testing of Series 4 specimens difficult to interpret. The diameter change and ovality data obtained in these tests are summarized in Tables A1-7 through A1-10. The changes noted are small and, for the most part, within the limits of measurement accuracy. The biggest effect is noted in the preovaled specimens which experienced ovality decreases (became more nearly round) of about 0.003 inch.

The Series 5 tests demonstrate that correction is not required to beginning-of-life test data for Series 4. Comparison of ovality changes of Series 5 specimens (See Table A1-9) after 84 hours of corrosion filming and an additional 48 hours of hydrostatic test simulation, with ovality changes of Series 4 specimens (See Table A1-15) after 48 hours of hydrostatic test simulation, reveals initial deformation of the same small magnitude. Similar comparison of diameter change data (See Tables A1-10 and A1-16) indicates that diameter changes for Series 4 specimens are slightly greater than for Series 5 specimens. However, measurement techniques may be responsible for most of the changes in Series 4. Initial measurements were obtained with a dial micrometer snap gage rather than the more accurate Pratt and Whitney Bench Micrometer (See Appendix 2) used for subsequent Series 4 and all Series 5 data. Series 5 data show that little diameter change is to be expected as a result of both corrosion filming and hydrostatic test simulation; hence no correction was applied to Series 4 data.

Table 3.3
Test History of DECAG-III Small Diameter RXA Cladding

Cycle Number	Pressure psig	Temperature °F	Cycle Time Hours	Accumulated Time Hour
1	2200	645	84	84
2	2750	534	24	108
3	2750	534	24	132
4	2500	534	36	168
5	2000	674	358*	526
6	2750/2500	534	4/2	532
7	2000	674	500	1032
8	2750/2500	534	4/2	1038
9	2000	674	300*	1338
10	2000	674	500	1838
11	2000	674	300	2138

*Short test cycles due to autoclave failures.

FIGURE 4.1
OVALITY OF DECAG-I SPECIMENS
TESTED AT 2600 PSIG AND 674 F

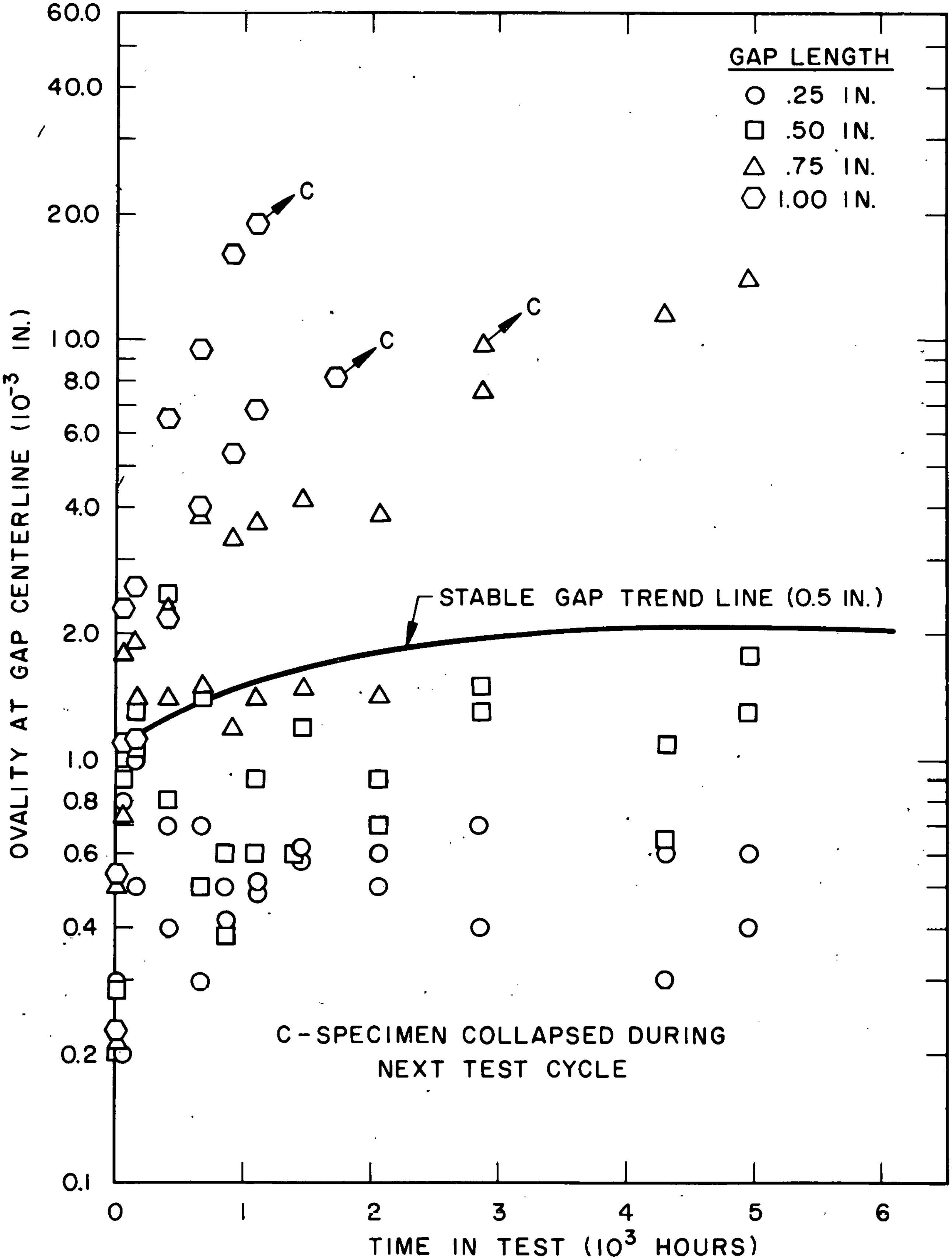


FIGURE 4.2
CHANGE OF AVERAGE DIAMETER OF DECAG-I SPECIMENS TESTED AT 2600 PSIG AND 674 F

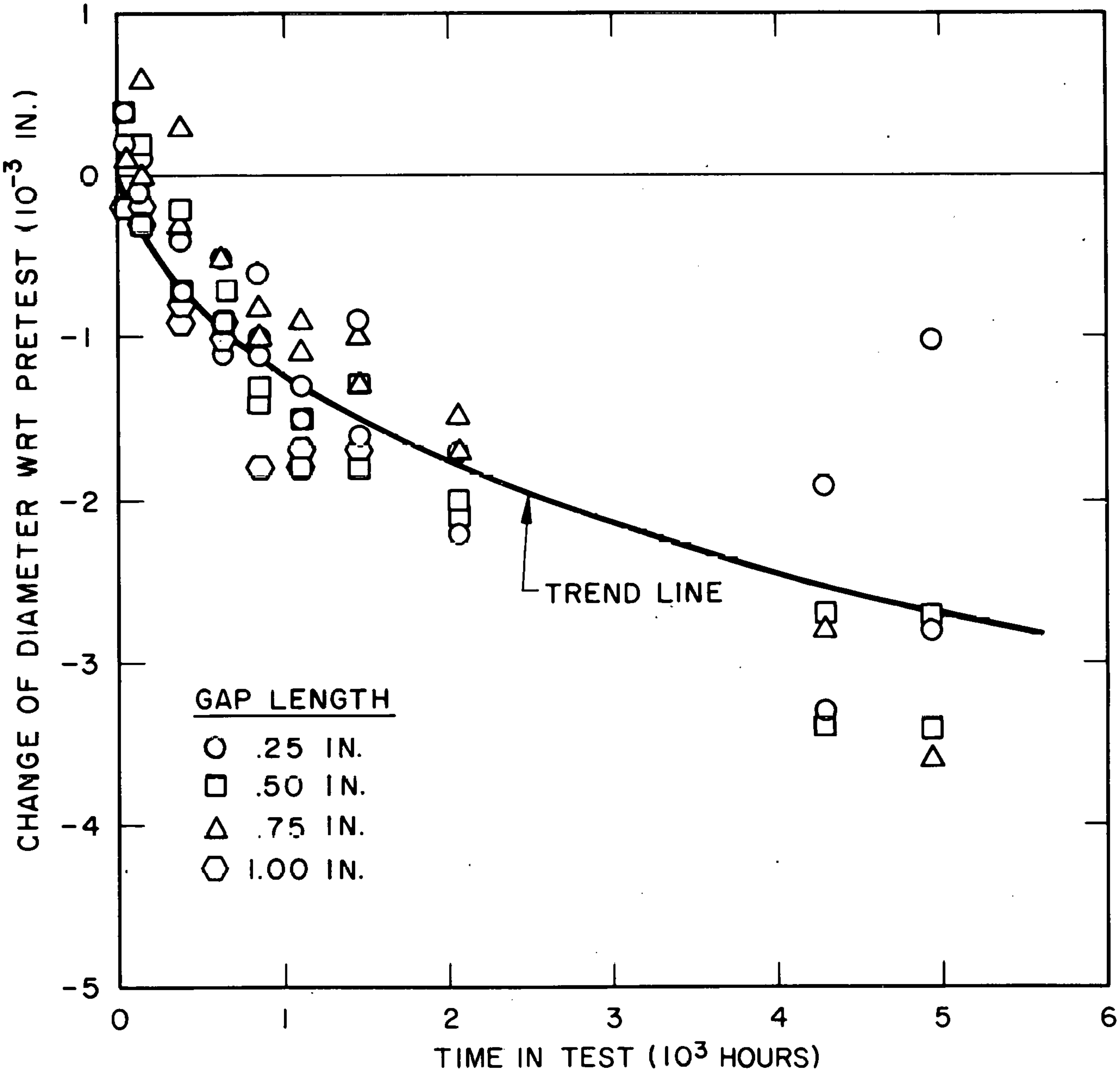


FIGURE 4.3
OVALITY OF DECAG-I SPECIMENS
TESTED AT 2600 PSIG AND 625F

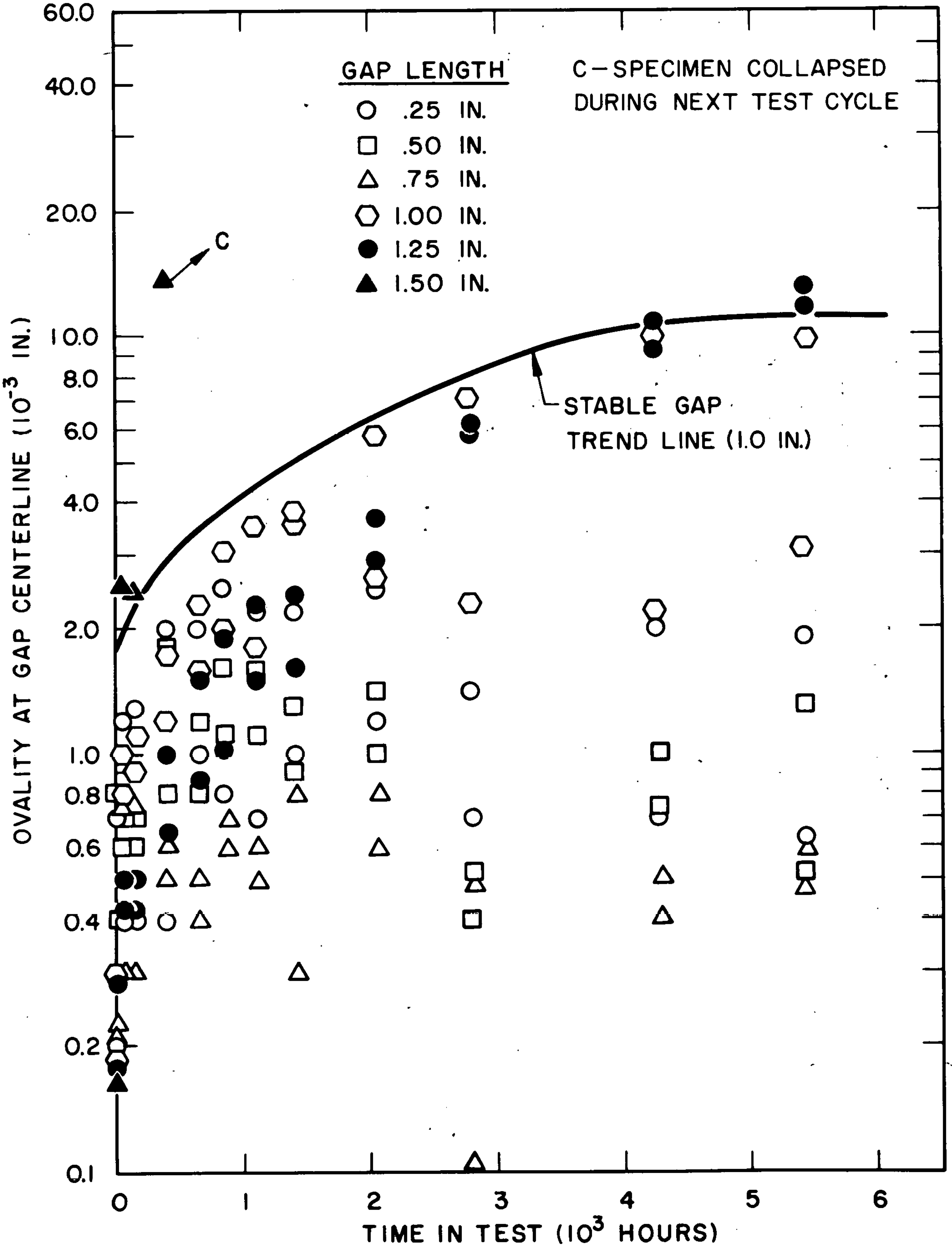


FIGURE 4.4
CHANGE OF AVERAGE DIAMETER OF DECAG-I SPECIMENS
TESTED AT 2600 PSIG AND 625 F

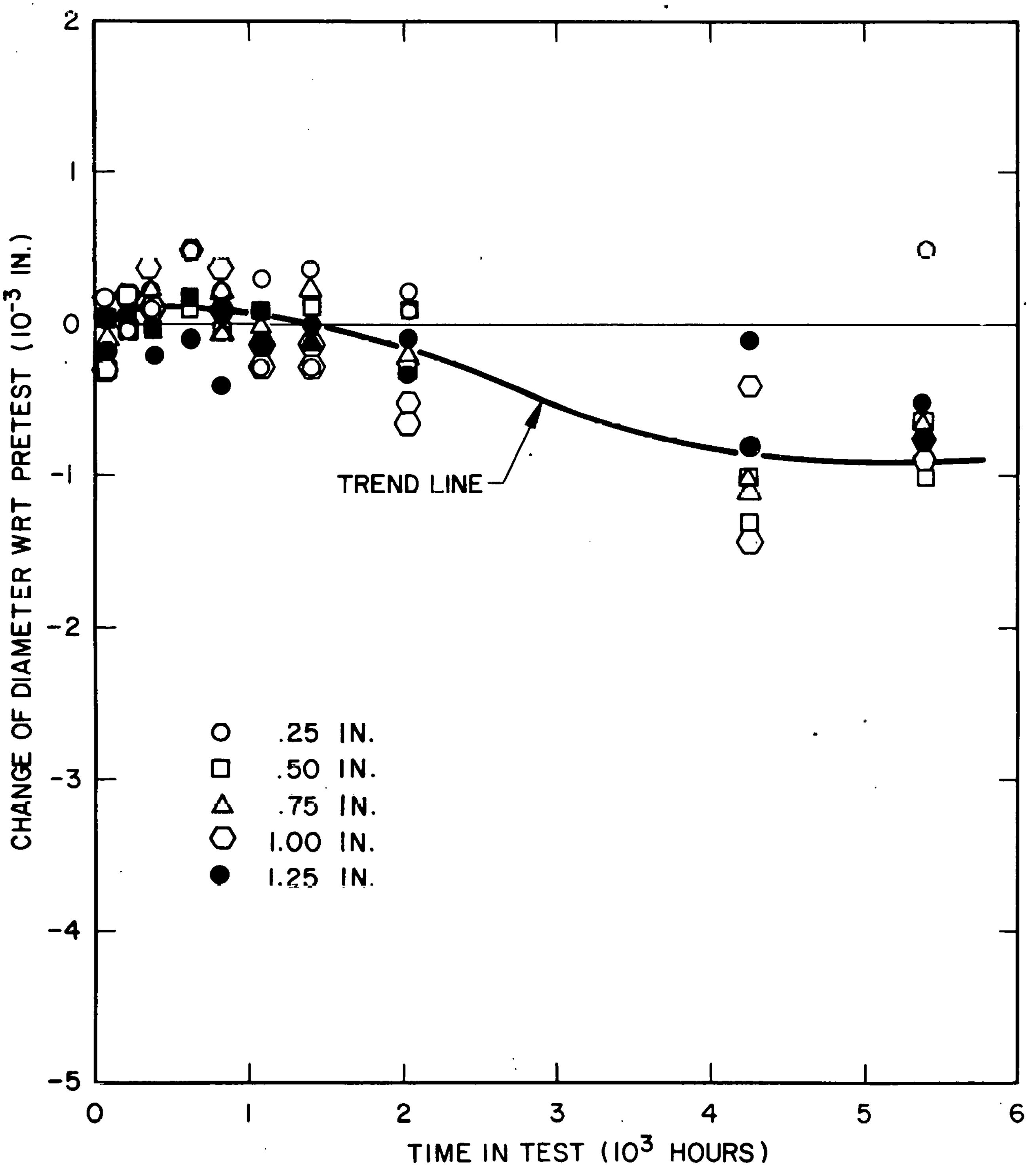


FIGURE 4.5
OVALITY OF DECAG - I SPECIMENS
TESTED AT 2200 PSIG AND 674F

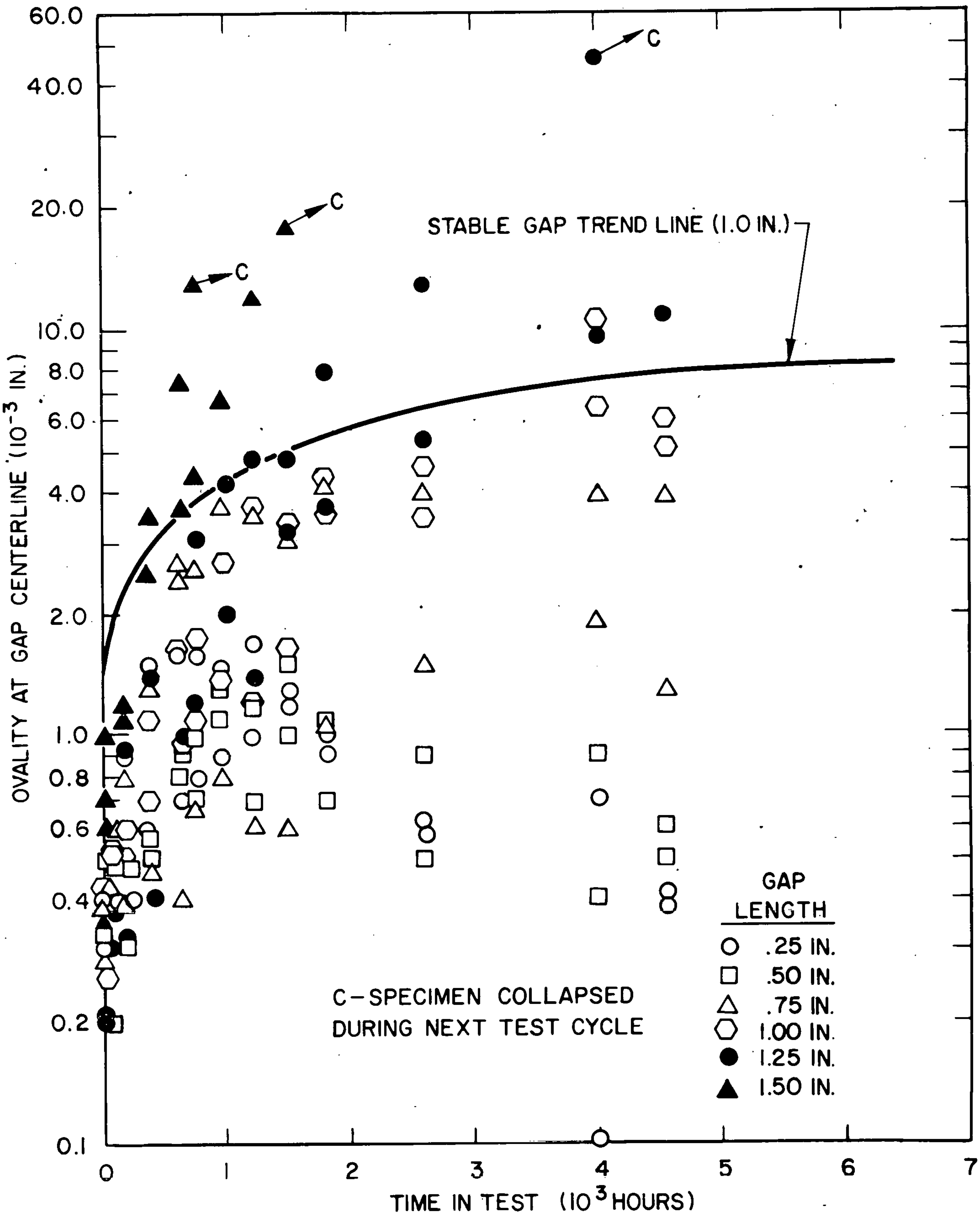
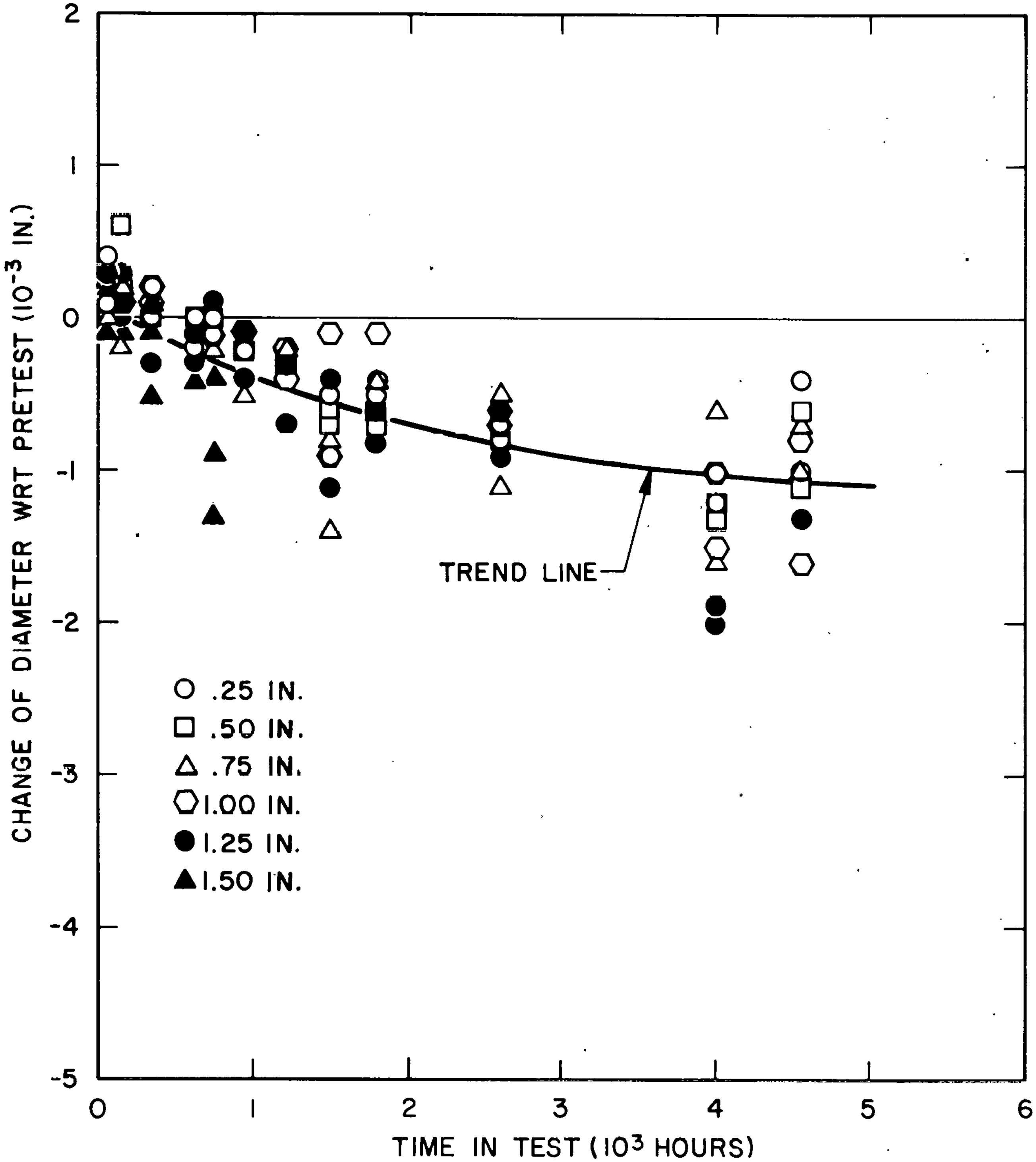


FIGURE 4.6
CHANGE OF AVERAGE DIAMETER OF DECAG-I SPECIMENS TESTED AT 2200 PSIG AND 674 F



4.2.2 Series 3 and 4

Figure 4.7 summarizes the test results related to ovality change for Series 3A, 3A2 and 4 as fabricated specimens from the three tests; Figure 4.9 provides a summary of ovality data for the eight preovaled specimens in Series 3A and 4; and Figure 4.8 summarizes diameter shrinkage data for all Series 3A, 3A2 and 4 specimens. All of these specimens were tested at 674F. Summaries of data from the 636F tests, Series 3B and 3B2, are presented in Figures 4.10 and 4.11 for both as fabricated and preovaled specimens.

Each figure contains engineering trendlines which are designed to help clarify and interpret the data. These treadlines reinforce the findings of the DECAG-I tests concerning lack of gap length dependence for diameter changes.

4.3 DECAG-III Tests

RXA cladding with a relatively small OD/t ratio of 15 was shown to be freestanding under the test conditions of 2000 psig and 674F. At the completion of testing (See Table A1-22) average diameter change and ovality of all specimens was near zero, within the limits of measurement accuracy, in contrast to a strain of 0.0033 in./in. ($\Delta d/d_0$) and several collapsed specimens for SRA DECAG-II specimens with the same exposure.

5. DISCUSSION OF TEST RESULTS

5.1 Axial Gap Stability Against Collapse

Previous work at Bettis and elsewhere has demonstrated that cladding which collapses into axial gaps initially manifests a gradual increase in ovality until an unstable condition exists and then rapidly collapses. Thus, ovality can be used to quantify cladding stability. Ovality data for DECAG-I tests are summarized in Figures 4.1, 4.3, and 4.5; data for DECAG-III are summarized in Figures 4.7 and 4.9. Trendlines have been constructed on these figures to emphasize trends manifested by the data.

The trendlines represent approximate upper bounds to data for the longest axial gap specimen for which the data show a leveling off of the ovality with time. This permits the selection of a maximum stable length for the conditions of each test.

Stable gap performance is seen in those specimens which manifest an initial small increase in ovality but then remain unchanged for long periods (such as the 1.2-inch specimens on Figure 4.7) or even show a decrease in ovality (such as the 1.0-inch specimens in the same figure). This latter action is graphically demonstrated by the preovaled specimens (See Figure 4.9) which have initial ovalities of 0.003 to 0.006 inch. All specimens with axial gaps of 1.0 inch or less manifest a decrease in ovality throughout the test period.

FIGURE 4.7

OVALITY OF AS FABRICATED DECAG — II SPECIMENS TESTED AT 2000 PSIG, 674F

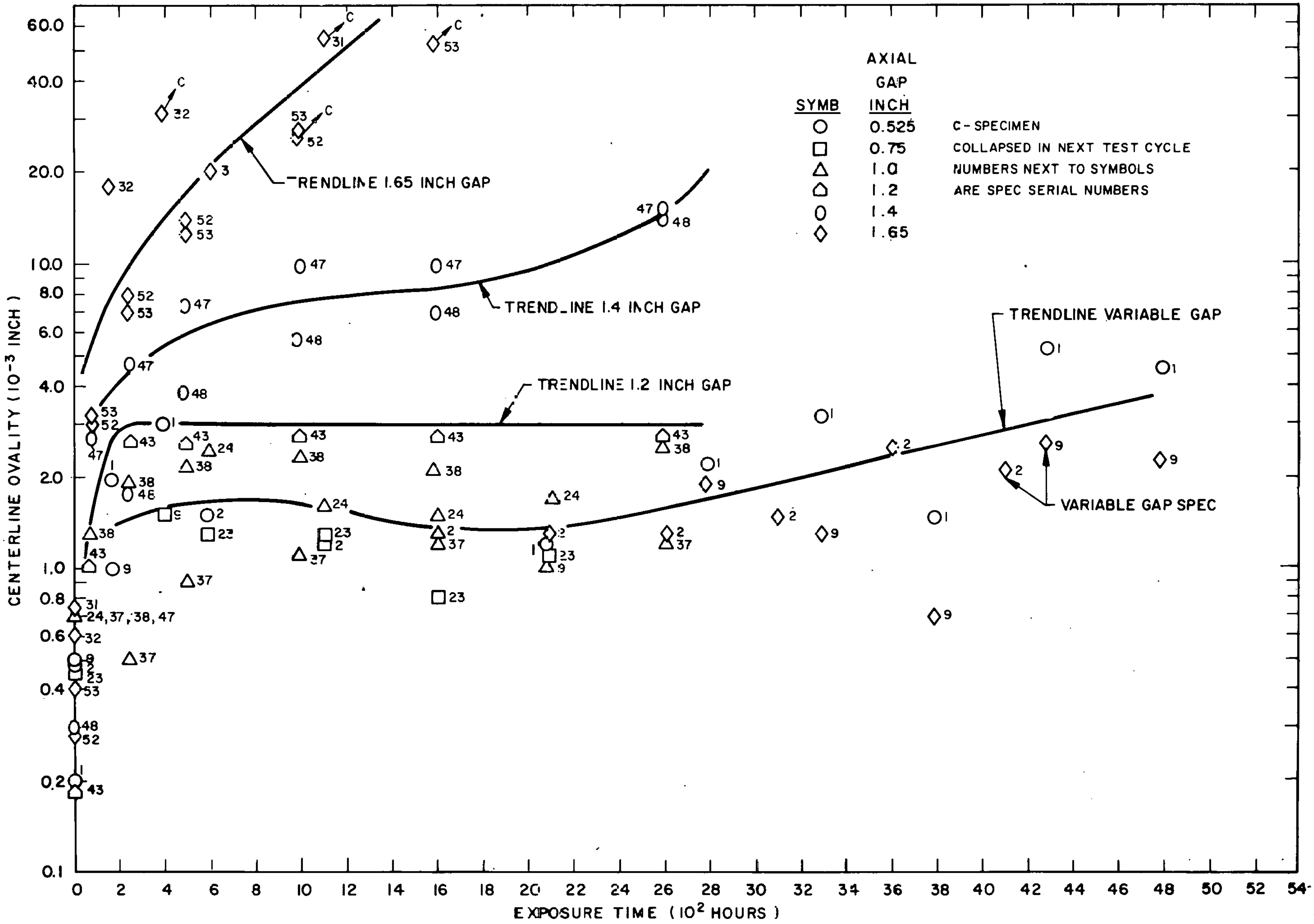


FIGURE 4.8
DIAMETER CHANGE OF DECAG-II SPECIMENS
TESTED AT 2000 PSIG AND 674 F

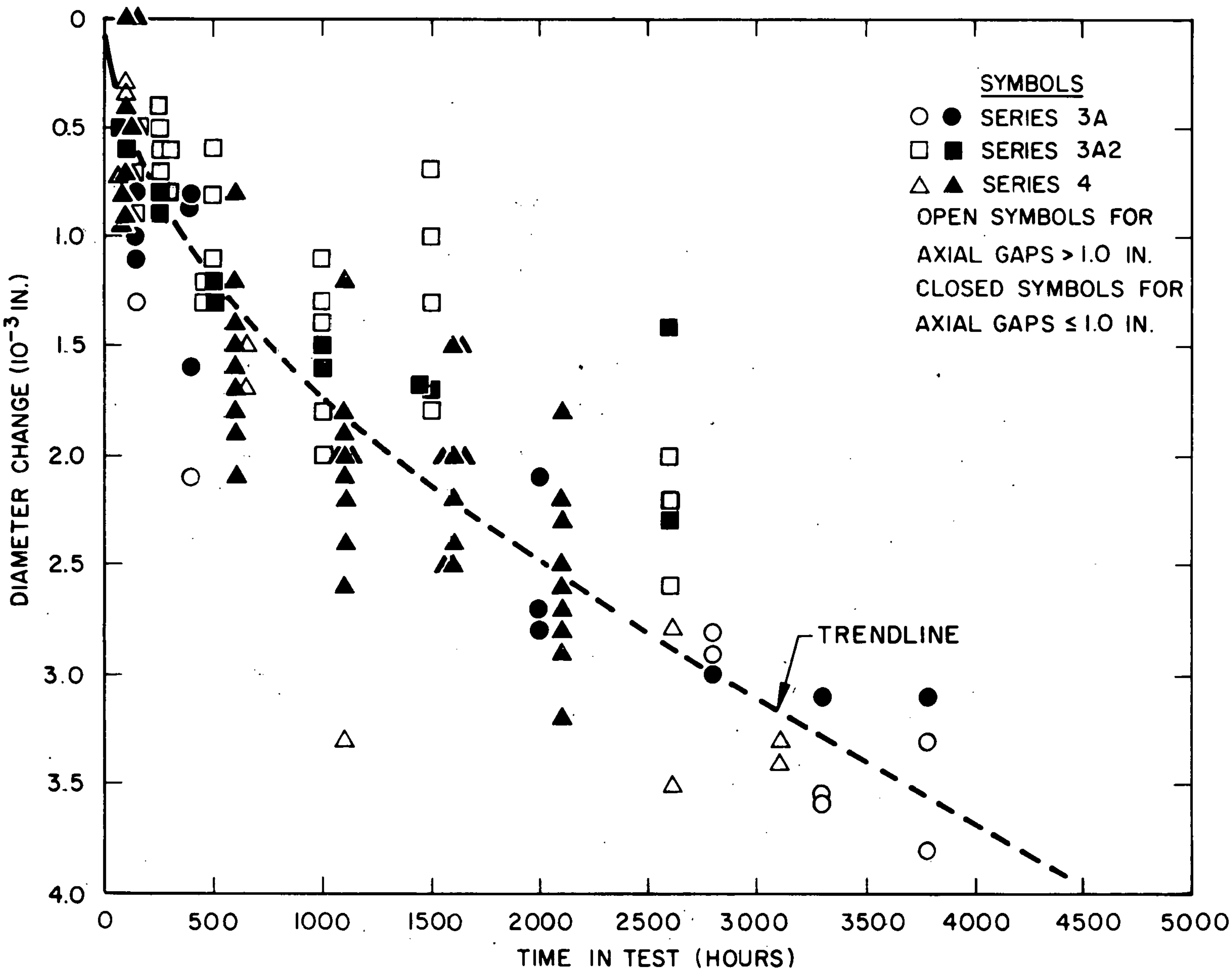


FIGURE 4.9
OVALITY OF PREOVALED DECAG-II SPECIMENS
TESTED AT 2000 PSIG AND 674 F

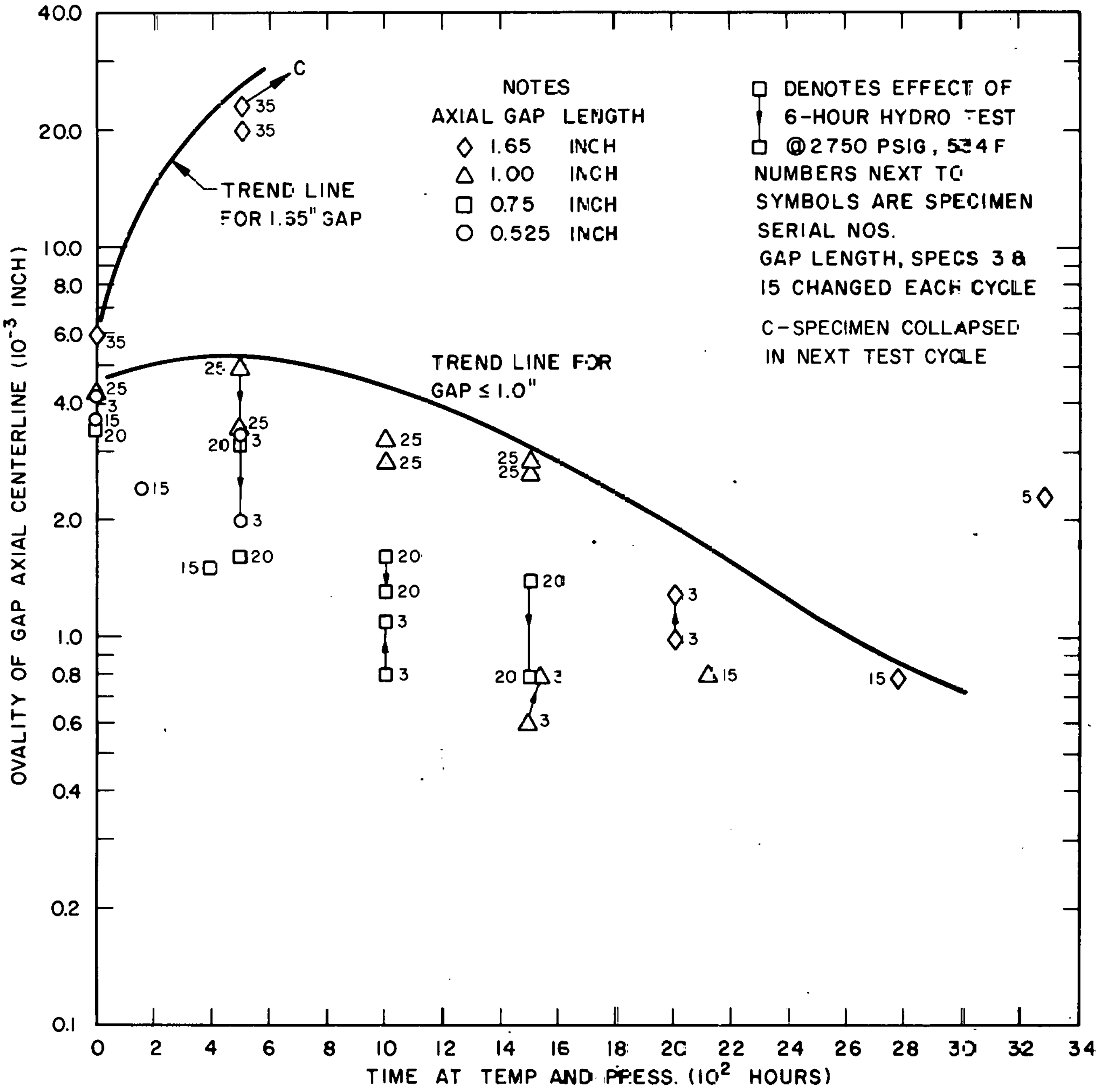


FIGURE 4.10
OVALITY OF DECAG – II SPECIMENS
TESTED AT 2000 PSI AND 636 °F

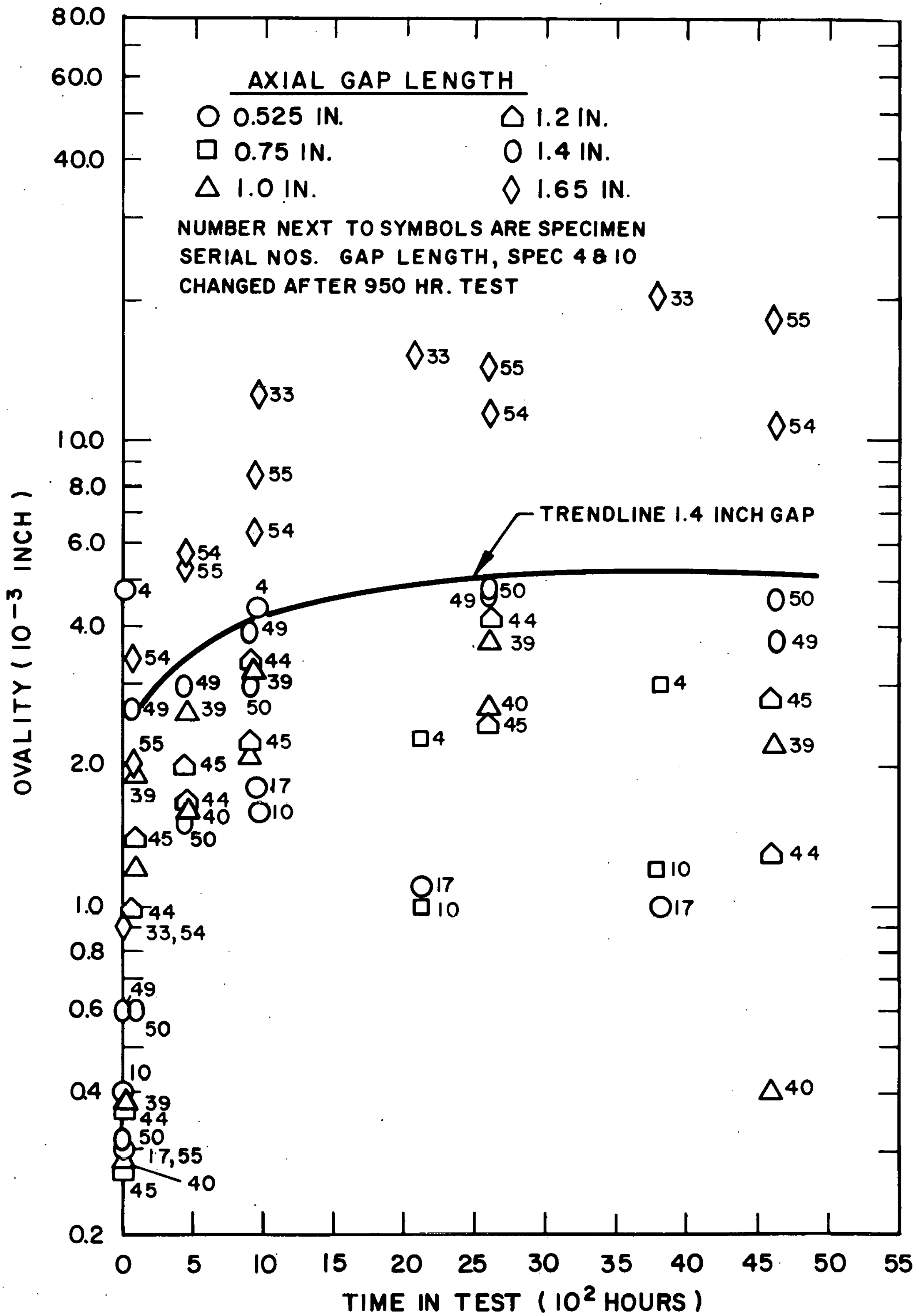
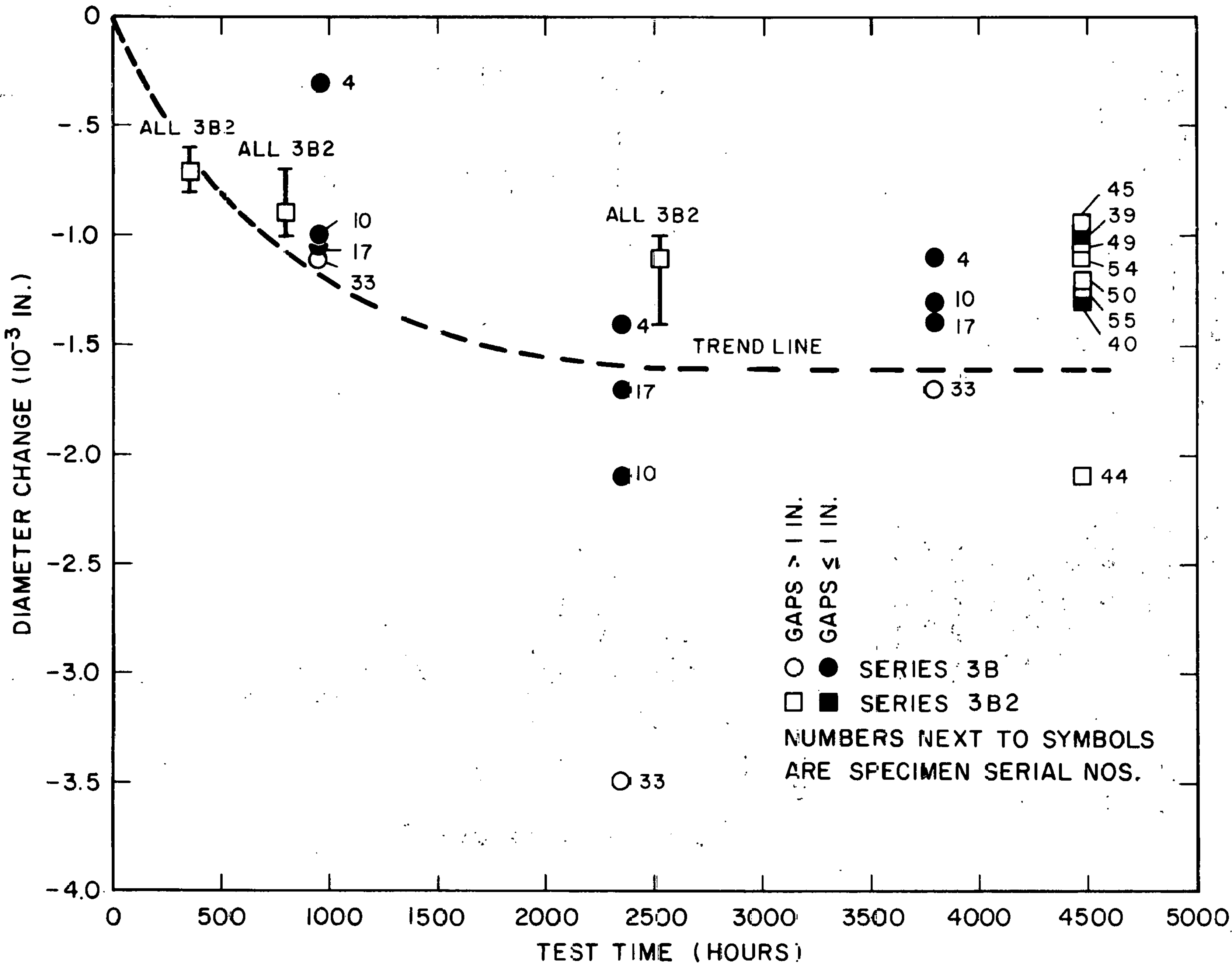


FIGURE 4.11
DIAMETER CHANGE OF DECAG - II SPECIMENS
TEST AT 2000 PSIG AND 636 F



A possible explanation of this behavior evolves from consideration of thermal creep which causes a decrease in specimen diameter as shown in Figures 4.2, 4.4, 4.6, and 4.8. The diameter decrease of most specimens is about 0.003 inch which is large enough to close the insert-to-cladding gap and provide support for the cladding. This gap closure results in the cladding becoming more nearly round in the regions over the inserts. If the axial gap is short enough, the unsupported length of tubing is relatively rigid and bending stresses are insufficient to cause an increase in ovality at the axial gap centerline. As the axial gap length increases the unsupported tubing becomes less rigid. Ovality increases at the axial gap centerline and continues to increase even after radial gap closure provides support for the tubing over the inserts. The axial gap length for which centerline ovality begins to show a continued increase throughout testing marks the boundary between stable and unstable performance.

The trendlines apply strictly for axial gaps existing from beginning-of-test. But in-reactor gaps are formed progressively due to fuel densification, cladding irradiation growth and axial ratchetting (Reference 14) during which time closing of the radial gap can reduce ovality as the cladding creeps down onto the fuel and conforms to it. From this more stable configuration ovality increases slowly. The long gap is more stable late-in-test than when it exists from beginning-of-test.

Several DECAG-II specimens were fabricated with short beginning-of-test axial gaps (0.525 inch) which were enlarged periodically during testing. These are Specimens 2 and 9 on Figure 4.7, Specimen 15 on Figure 4.9 and Specimen 4 and 10 on Figure 4.10. (Identified on figure by numbers beside data points.) For these specimens ovality behavior was initially that of the stable gap, that is, little or no increase in ovality. But even after the gaps were opened to 1.65 inches, short gap behavior persisted. For example, Specimen 9 (See Figure 4.7) had only 0.0012-inch ovality after 3782 hours at 2000 psig and 674F, including 1700 hours as a 1.65-inch gap specimen. All specimens which had 1.65-inch gaps from beginning-of-test collapsed in 1000 hours or less and attained high ovalities in a few hundred hours. Thus, the variable gap tests suggest that cladding over axial gaps longer than those approximated by the trendlines exhibits long term stability if the adjoining cladding is fully supported by fuel. As the axial gap grows, the adjoining cladding becomes fully supported due to the cladding shrinking onto the fuel.

5.2 Larson-Miller Parameter Equivalence

A major objective of DECAG-II Series 3 tests was to provide data for developing a test acceleration factor, based on temperature, which would relate deformation experienced by Series 4 specimens (at 674F) to that which would be experienced at lower temperatures more representative of light water reactor operation. The Larson-Miller Parameter (LMP) (Reference 13) was chosen as an empirical formulation for this purpose. The Larson-Miller Parameter is expressed as

$$LMP = T\,(20 + \log_{10} t) \qquad \text{(eq. 5.1)}$$

where: T = temperature (^{o}Rankine)

t = time (hours)

The Larson-Miller Parameter provides a time-temperature relationship between two otherwise similar tests performed at difference temperatures on the basis of deformations experienced in both tests. Thus, if the correlation is valid, similar specimens tested at equal pressures will experience equal deformations for equal values of LMP even though test temperatures are different.

Figure 5.1 presents diameter change data for all Series 3 specimens as a function of LMP. Average diameter change and the range of diameter changes for each Series 3 test are plotted on the figure. The range of diameter change was derived from measurements at three axial locations for all specimens of a given series. Exceptions to the three-measurement criterion occur for data with LMP $\geq$ 26,400. In this range diameter shrinkage was sufficient to close radial gaps; hence no change in diameter would be expected for portions of the cladding over inserts. Therefore, only data for unsupported locations were plotted. The data follow a common trend (approximated by the single smooth curve) thus indicating that these 2000 psig tests performed at 674F and 636F can be related by LMP.

The same procedure was applied to DECAG-I Series 26674 and 26625 tests which are 2600 psig tests conducted at 674F and 625F, respectively. Figure 5.2 presents diameter change versus LMP for these tests. Again, a single smooth curve represents the common data trends, with similar diametral decreases being experienced by both sets of specimens for equal LMP values.

Larson and Miller (Reference 13) developed their parameter to correlate constant stress tests of creep rupture at several temperatures. The correlation was applicable to a variety of materials, and the authors suggested that other types of deformation than creep rupture might be defined in terms of LMP. In the present context it is desirable to have a correlation relating ovality as a function of time and temperature. Figure 5.3 is a plot of the logarithm of ovality against LMP for 1.65-inch and 1.4-inch axial gap specimens from Series 3A2 (674F) and 3B2 (636F). There are two distinct populations based on axial gap length which are each satisfactorily described by a simple linear best fit line of the form

$$\log W = AL + B \qquad \text{(Eq. 5.2)}$$

where W = ovality
L = Larson-Miller Parameter
A&B = fitting constants

FIGURE 5.1
DIAMETER CHANGE OF SERIES 3 SPECIMENS
IN VERIFICATION OF LARSON - MILLER PARAMETER

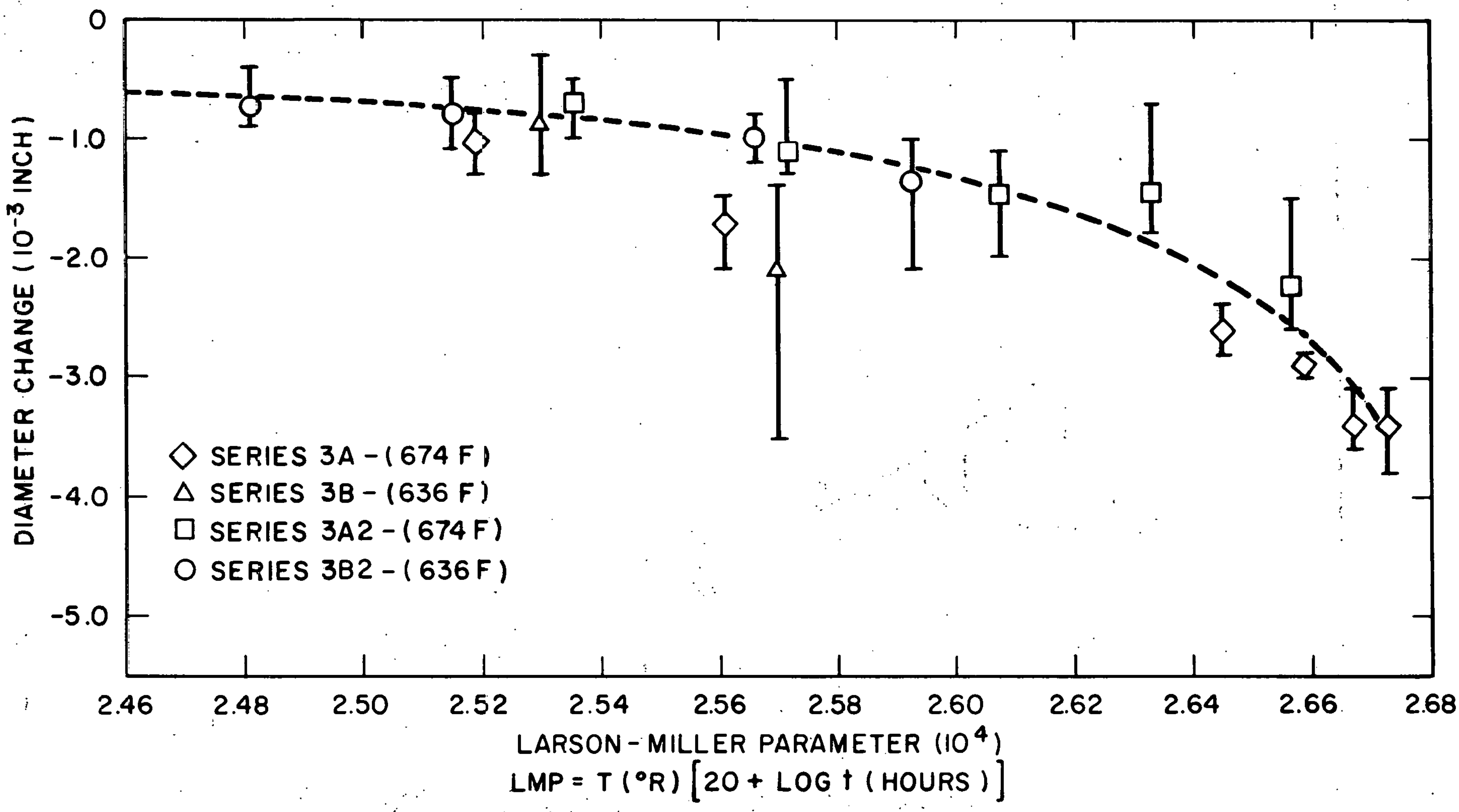


FIGURE 5.2
DIAMETER CHANGE AS A FUNCTION OF LARSON-MILLER PARAMETER
DECAG-I SERIES 26674 AND 26625

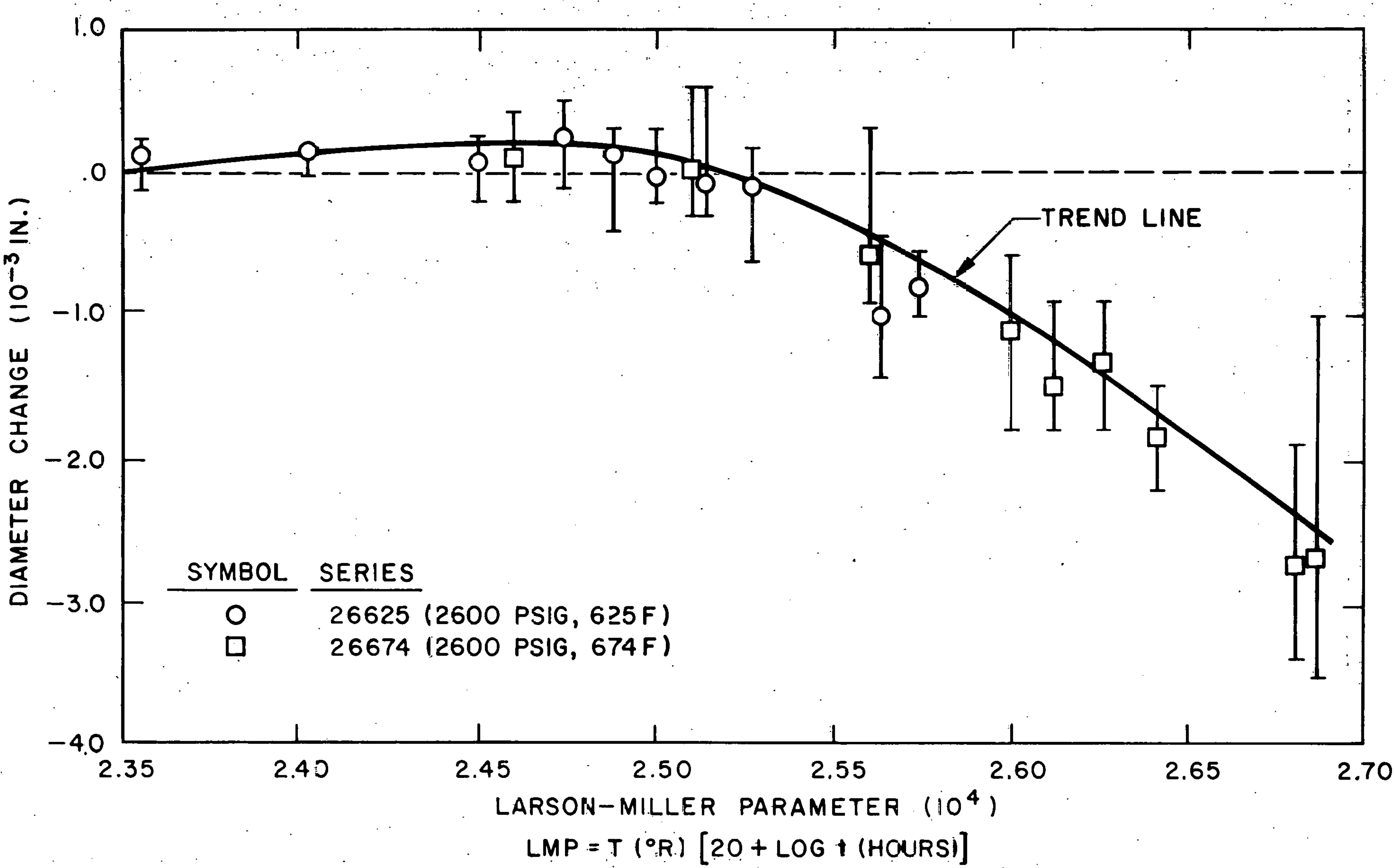
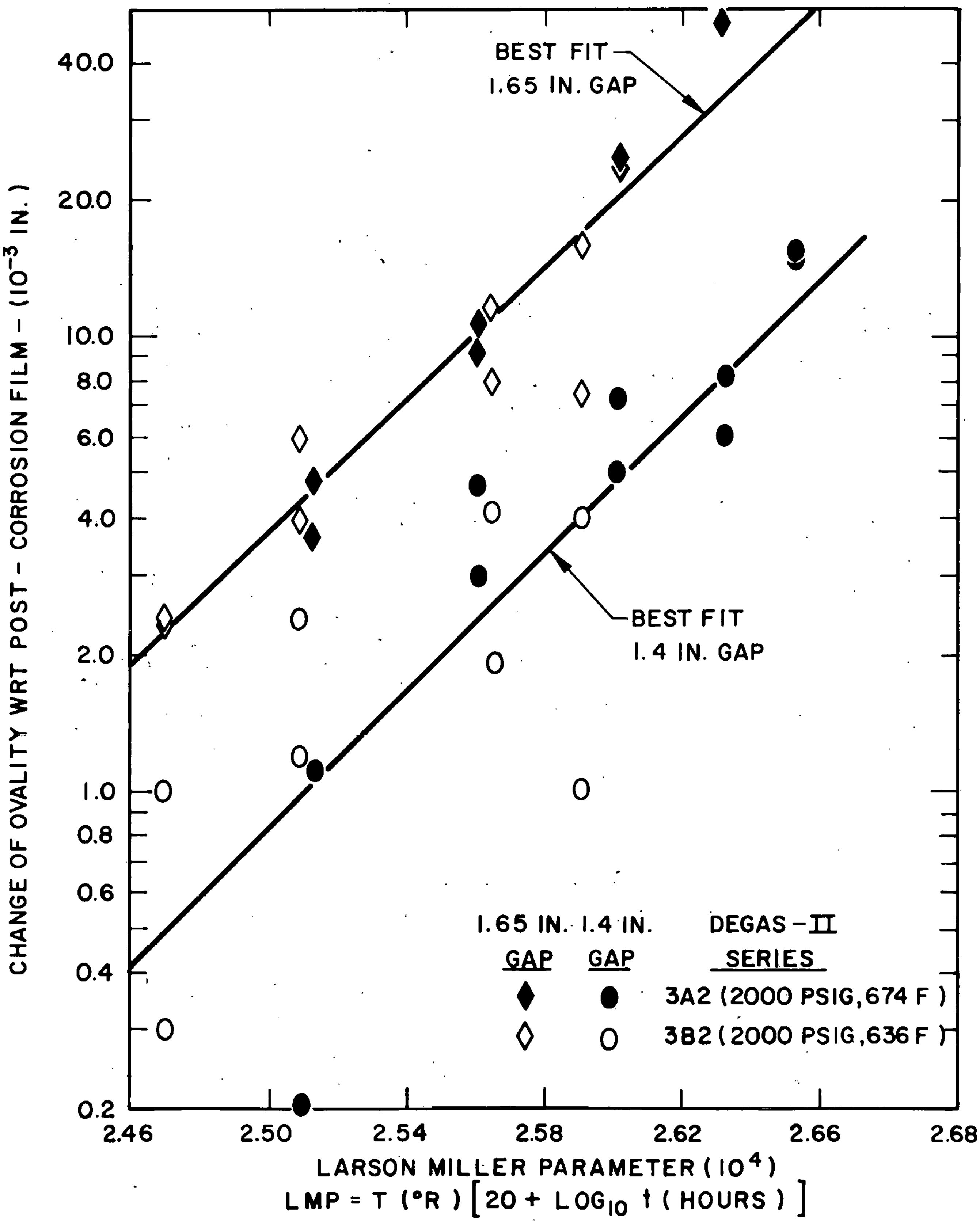


FIGURE 5.3
OVALITY OF DECAG - II, SERIES 3A2 AND 3B2 SPECIMENS AS A FUNCTION OF LARSON - MILLER PARAMETER



Thus, it appears that the Larson-Miller Parameter is satisfactory for interpreting DECAG-II Series 4 test ovality and diameter changes in relation to expected thermal performance of fuel rods at lower (operating) temperatures. To estimate time dependent deformation at 636F based on tests conducted at 674F, an approximate acceleration factor of six can be applied to the time scale of Figures 4.7 to 4.10.

6. SUMMARY AND CONCLUSIONS

The DECAG test program evaluated the effect of reactor operation on Zircaloy-4 cladding deformation into potential axial gaps in low flux, plenum regions of reactor fuel rods. These axial gaps result from cladding elongation, pellet densification, and axial ratchetting. The test program consisted of twelve series and subseries of tubing specimens containing fabricated axial gaps ranging in length from 0.25 to 2.50 inches, some of which were varied in increments from 0.525 to 1.65 inches during the test. Tests were conducted in autoclaves using either steam or water as the pressurizing medium. Test pressures ranged from 2000-2750 psig; test temperatures ranged from 534F to 674F. The higher temperatures were used to accelerate simulated lifetime. Both fully recrystallized (RXA) and stress relieved, highly cold worked (SRA) materials were tested. Specimens were fabricated both from thick wall (diameter-to-thickness ratio, D/t, of 15) and thin wall (D/t = 20 to 22) tubing.

The tests have verified the usefulness of the Larson-Miller Parameter in relating ovality and diameter deformation data to other temperatures.

Analysis of test data provides empirical evidence that stable long term operation of Zircaloy-clad fuel rods with axial gaps in low fluence regions is possible if axial gaps do not exceed critical lengths. Critical lengths are a function of temperature and fuel-to-cladding radial gap. Cladding will deform more slowly at lower temperature and lower pressures. The closing of fuel-to-cladding radial gaps tends to produce more stability in short lengths of unsupported cladding by reducing ovality, which in turn increases the critical axial gap length for stable operation.

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8. ACKNOWLEDGEMENTS

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APPENDIX 1

DATA TABLES

Table A1-1
DECAG-I Test - Series 26674
Snap Gage Ovality Measurements
(All Tests Cycles Performed at 2600 psig 674F)

Sample No.	Nom. Gap (Inch)	Pretest Ovality (10^{-3} in.)	Ovality at Midlength (10^{-3} in.) 50 hrs.	139 hrs.	378 hrs.	634 hrs.	840 hrs.	1098 hrs.	1440 hrs.	2051 hrs.	2870 hrs.	4276 hrs.	4923 hrs.
11	0.25	0.3	0.2	0.5	0.7	0.7	0.4	0.5	0.6	0.6	0.4	0.3	0.6
15	0.25	0.3	0.8	1.0	0.4	0.3	0.5	0.5	0.6	0.5	0.7	0.6	0.4
23	0.50	0.3	1.0	1.3	2.5	1.4	0.6	0.9	1.2	0.7	1.3	0.6	1.3
24	0.50	0.2	0.9	1.0	0.8	0.5	0.4	0.6	0.6	0.9	1.5	1.1	1.8
31	0.75	0.5	1.8	1.9	2.3	3.8	3.4	3.7	4.1	3.8	9.8	*	
33	0.75	0.2	0.8	1.3	1.4	1.4	1.2	1.4	1.5	1.4	7.8	11.2	14.0
42	1.00	0.5	2.3	2.6	6.5	9.5	16.2	18.7	*				
43	1.00	0.2	1.1	1.1	2.2	4.0	5.4	6.9	8.1	*			
54	1.25	0.2	2.5	3.8	*								
55	1.25	0.3	0.7	2.0	4.3	*							
63	1.50	0.2	2.5	*									
64	1.50	0.3	*										
71	1.75	0.2	*										
75	1.75	0.3	*										
83	2.00	0.2	*										
85	2.00	0.4	*										
92	2.50	0.4	*										
96	2.50	0.5	*										

*Specimen collapsed during this time interval.

Table A1-2
DECAG-I Test - Series 26674
Diameter Changes

(All test cycles performed at 2600 psig, 674F)

Sample No.	Pretest Diameter (Inch)	Change in Average Diameter WRT Pretest (10^{-3} in.) 50 hrs.	139 hrs.	378 hrs.	634 hrs.	840 hrs.	1098 hrs.	1440 hrs.	2051 hrs.	4276 hrs.	4923 hrs
11	0.5685	0.4	0.1	-0.4	-0.5	-0.6	-1.3	-0.9	-1.7	-1.9	-1.0
15	0.5685	0.2	-0.1	-0.7	-1.1	-1.1	-1.5	-1.6	-2.2	-3.3	-2.8
23	0.5683	0.4	0.2	-0.2	-0.9	-1.4	-1.8	-1.8	-2.0	-2.7	-2.7
24	0.5682	-0.2	-0.3	-0.7	-0.7	-1.3	-1.5	-1.3	-2.1	-3.4	-3.4
31	0.5686	0.2	0.0	0.3	-0.5	-0.8	-0.9	-1.0	-1.7	*	
33	0.5683	0.1	0.6	-0.3	-0.5	-1.0	-1.1	-1.3	-1.5	-3.8	-3.6
42	0.5691	-0.2	-0.2	-0.9	-1.0	-1.0	-1.7	*			
43	0.5686	-0.2	-0.3	-0.8	-0.9	-1.8	-1.9	-1.7	*		
54	0.5689	0.0	-0.7	*							
55	0.5690	0.0	-0.2	-0.8	*						
63	0.5687	-0.1	*								
64	0.5683	*									
71	0.5685	*									
75	0.5681	*									
83	0.5696	*									
85	0.5694	*									
92	0.5699	*									
96	0.5690	*									

*Specimen collapsed during this time interval.

Table A1-3
DECAG-I Test - Series 26625
Snap Gage Ovality Measurements
(All Test cycles performed at 2600 psig, 625F)

Sample No.	Nom. Gap (Inch)	Pretest Ovality (10^{-3} in.)	Ovality at Midlength (10^{-3} in.)										
			51 hrs.	138 hrs.	376 hrs.	631 hrs.	832 hrs.	1087 hrs.	1397 hrs.	2028 hrs.	2828 hrs.	4262 hrs.	5414 hrs.
13	0.25	0.7	1.2	1.3	2.0	2.0	2.5	2.2	2.2	2.5	2.1	2.0	1.9
14	0.25	0.2	0.4	0.4	0.4	1.0	0.8	0.7	1.0	1.1	0.9	0.7	0.6
22	0.50	0.8	0.7	0.7	1.8	1.2	1.6	1.6	1.3	1.4	1.3	1.0	1.3
26	0.50	0.4	0.6	0.6	0.8	0.8	1.1	1.1	0.9	1.0	0.8	0.7	0.5
34	0.75	0.2	0.7	0.7	0.6	0.5	0.7	0.6	0.3	0.6	0.7	0.5	0.6
35	0.75	0.2	0.3	0.3	0.5	0.4	0.6	0.5	0.3	0.8	0.2	0.4	0.5
44	1.00	0.3	0.8	0.9	1.3	1.6	2.0	1.8	3.3	2.6	2.6	2.2	3.1
45	1.00	0.2	1.0	1.1	1.8	2.3	3.1	3.5	3.5	5.8	7.3	10.2	9.7
52	1.25	0.3	0.5	0.5	1.0	1.5	1.9	2.3	2.4	3.7	6.4	9.3	11.6
53	1.25	0.2	0.4	0.4	0.6	0.8	1.0	1.5	1.6	2.9	6.0	10.7	13.1
61	1.50	0.3	*										
65	1.50	0.2	2.6	2.5	13.8	*							
74	1.75	0.2	*		13.8								
76	1.75	0.3	*										
82	2.00	0.3	*										
84	2.00	0.2	*										
91	2.50	0.5	*										
94	2.50	0.2	*										

*Specimen collapsed during this time interval.

Table A1-4
DECAG-I Test - Series 26625
Diameter Changes
(All test cycles performed at 2600 psig, 625F)

Sample No.	Pretest Diameter (inch)	Change in Average Diameter WRT Pretest (10^{-3} in.) 51 hrs.	138 hrs.	376 hrs.	631 hrs.	832 hrs.	1087 hrs.	1397 hrs.	2028 hrs.	4262 hrs.	5414 hrs
13	0.5684	0.1	0.2	0.2	0.5	0.2	0.3	0.3	0.1	-1.0	0.5
14	0.5686	0.2	0.0	0.1	0.2	0.2	-0.2	-0.2	0.2	-1.0	-0.8
22	0.5682	-0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.1	-1.3	-1.0
26	0.5695	0.1	0.2	0.0	0.1	0.0	0.1	0.1	-0.3	-1.0	-0.7
34	0.5684	0.1	0.2	0.2	0.2	0.2	0.0	0.2	-0.2	-1.0	-0.7
35	0.5691	0.1	0.1	0.1	0.2	0.0	-0.2	-0.1	0.1	-1.1	-0.7
44	0.5689	0.0	0.2	0.3	0.2	0.3	-0.2	0.2	-0.5	-1.4	-0.9
45	0.5691	-0.1	0.2	0.1	0.5	0.1	-0.1	-0.1	-0.6	-0.4	-0.8
52	0.5706	0.0	0.1	-0.2	0.2	-0.4	0.1	0.0	-0.3	-0.8	-0.6
53	0.5691	0.1	0.2	0.0	-0.1	0.1	-0.1	-0.1	-0.1	-1.0	-0.8
61	0.5686	*									
65	0.5686	-0.2	-0.1	-1.5	*						
74	0.5686	*									
76	0.5690	*									
82	0.5691	*									
84	0.5683	*									
91	0.5688	*									
94	0.5692	*									

*Specimen collapsed during this time interval.

Table A1-5
DECAG-I Test - Series 22674
Snap Gage Ovality Measurements
(All test cycles performed at 2200 psig, 674F)

Sample No.	Nom. Gap (Inch)	Pretest Ovality (10^{-3} in.)	Ovality at Midlength (10^{-3} in.) 54 hrs.	160 hrs.	355 hrs.	621 hrs.	753 hrs.	961 hrs.	1218 hrs.	1513 hrs.	1799 hrs.	2600 hrs.	4000 hrs.	4546 hrs.
12	0.25	0.3	0.4	0.4	0.6	0.7	0.8	0.9	1.0	1.2	1.0	0.6	0.1	0.4
16	0.25	0.4	0.4	0.9	1.5	1.6	1.6	1.5	1.7	1.3	0.9	0.6	0.7	0.4
21	0.50	0.3	0.2	0.3	0.6	0.9	1.0	1.3	1.2	1.5	0.7	0.5	0.4	0.6
25	0.50	0.5	0.5	0.5	0.5	0.8	0.7	1.1	0.7	1.0	1.1	0.9	0.9	0.5
32	0.75	0.3	0.4	0.4	0.5	0.4	0.7	0.8	0.6	0.6	1.0	1.5	1.9	1.3
36	0.75	0.4	0.6	0.8	1.3	2.4	2.6	3.7	3.5	3.1	4.1	4.0	3.9	3.9
41	1.00	0.4	0.5	0.6	0.7	0.9	1.1	1.4	1.2	1.6	3.6	3.5	10.5	5.2
46	1.00	0.3	0.5	0.5	1.1	1.6	1.7	2.7	3.6	3.4	4.2	4.6	6.4	6.0
51	1.25	0.2	0.4	0.9	1.4	2.7	3.1	4.1	4.9	4.9	7.9	12.9	46.2	*
56	1.25	0.2	0.2	0.3	0.4	1.0	1.2	2.0	2.4	3.1	3.7	5.3	9.6	10.9
62	1.50	0.6	1.0	1.1	2.5	3.7	4.4	6.7	12.2	18.3	*			
66	1.50	0.3	0.7	1.2	3.5	7.4	13.0	*						
72	1.75	0.4	0.5	0.6	1.6	5.5	*							
73	1.75	0.2	0.5	0.5	1.4	3.8	8.5	+						
81	2.00	0.4	0.4	0.5	2.3	*								
86	2.00	0.2	0.3	0.4	1.5	*								
93	2.50	0.3	0.4	0.7	2.8	*								
95	2.50	0.4	0.5	0.6	1.4	8.6	*							

*Specimen collapsed during this time interval.
+Specimen collapsed in less than 832 hours. Discovered during intermediate inspection for collapsed specimens only.

Table A1-6
DECAG-I Test - Series 22674
Diameter Changes
(All test cycles performed at 2200 psig, 674F)

Sample No.	Pretest Diameter (inch)	Change In Average Diameter WRT Pretest (10^3 in.) 54 hrs.	160 hrs.	365 hrs.	621 hrs.	753 hrs.	961 hrs.	1218 hrs.	1513 hrs.	1799 hrs.	2600 hrs.	4000 hrs.	4546 hrs.
12	0.5684	0.2	0.1	0.2	-0.2	-0.1	-0.2	-0.3	-0.9	-0.6	-0.8	-1.0	-1.0
16	0.5684	0.4	0.0	0.0	0.0	0.0	-0.2	-0.3	-0.5	-0.4	-0.7	-1.2	-0.4
21	0.5682	0.1	0.6	0.0	0.0	0.0	-0.2	-0.3	-0.6	-0.6	-0.8	-1.2	-1.1
25	0.5678	0.2	0.2	0.0	0.0	0.0	-0.2	-0.3	-0.7	-0.7	-0.8	-1.3	-0.6
32	0.5686	0.3	0.2	0.1	0.0	-0.2	-0.2	-0.2	-0.8	-0.4	-1.1	-1.6	-1.0
36	0.5690	0.0	-0.2	-0.1	-0.4	-0.4	-0.5	-0.3	-1.4	-0.6	-0.5	-0.6	-0.7
41	0.5689	0.1	0.1	0.1	0.0	-0.1	-0.1	-0.4	-0.9	-0.5	-0.6	-1.5	-1.6
46	0.5688	0.3	0.2	0.2	0.0	0.0	-0.2	-0.2	-0.1	-0.1	-0.7	-1.0	-0.8
51	0.5690	0.3	0.0	-0.3	-0.3	-0.4	-0.4	-0.7	-1.1	-0.6	-1.6	-1.9	*
56	0.5683	0.2	0.3	-0.1	-0.1	0.1	-0.1	-0.3	-0.4	-0.8	-0.9	-2.0	-1.3
62	0.5688	0.2	-0.1	0.1	-0.4	-1.3	-0.6	0.0	-0.3	*			
66	0.5679	-0.1	0.1	-0.5	-0.4	-0.9	*						
72	0.5684	0.2	0.0	-0.2	-0.9	*							
73	0.5690	0.2	0.0	-0.1	-0.4	-1.2	*						
81	0.5693	-0.7	-0.8	-0.6	*								
86	0.5686	-0.2	0.2	0.0	*								
93	0.5690	0.2	0.0	-0.2	*								
95	0.5694	0.2	0.1	0.0	-5.5	*							

*Specimen collapsed during this time interval.

Table A1-7
Ovality of DECAG-II Series 1 and 2 Specimens

Test Conditions										
Pressure, psig				2750	2750	2750	2500	2750	2500	2000
Temperature, F				534	534	534	534	450	450	674
Cycle Time, Hours				8	16	24	36	20	10	150
Total Time, Hours				8	24	48	84	104	114	264
Series/ID	GAP	Loc.*	Pretest	Ovality (10^{-3} inch)						
1/06	0.524	T	0.5	0.6	0.6	0.7	0.8	0.7	0.6	1.0
		C	0.7	0.8	0.8	1.0	1.1	1.1	0.8	1.7
		B	0.8	1.1	1.2	1.2	1.3	1.3	1.2	2.2
1/07	0.525	T	0.9	1.4	1.5	1.6	1.7	1.7	1.6	2.7
		C	0.7	1.3	1.4	1.6	1.7	1.8	1.6	2.9
		B	1.1	1.5	1.5	1.6	1.8	1.8	1.6	2.5
1/05	0.75	T	0.7	0.9	0.9	0.9	1.0	1.1	1.0	1.0
		C	0.4	0.4	0.4	0.5	0.5	0.5	0.5	1.5
		B	0.3	0.5	0.8	0.6	0.6	0.6	0.6	1.4
1/03	1.00	T	0.7	1.1	1.1	1.2	1.2	1.2	1.0	1.0
		C	0.6	1.2	1.2	1.4	1.3	1.4	1.2	2.4
		B	0.8	1.1	1.1	1.2	1.2	1.3	1.0	1.8
1/04	1.0	T	1.1	1.2	1.3	1.2	1.3	1.4	1.5	0.8
		C	0.6	0.5	0.6	0.5	0.6	0.6	0.5	0.4
		B	0.5	0.7	0.7	0.7	0.8	0.7	0.8	0.8
1/01	1.65	T	0.3	0.7	0.8	0.8	0.9	0.9	0.6	1.2
		C	0.6	1.1	1.2	1.3	1.3	1.5	1.4	5.2
		B	1.2	1.6	1.6	1.6	1.7	1.7	1.4	1.4
1/02	1.65	T	1.0	1.1	1.2	1.2	1.2	1.3	1.3	2.2
		C	0.3	0.5	0.7	0.8	1.0	1.0	1.0	5.8
		B	1.0	1.5	1.5	1.6	1.8	1.8	1.3	2.8
2/12	0.525	T	4.7	4.7	4.6	4.3	4.7	4.7	4.8	
		C	4.9	4.6	4.4	4.5	4.8	5.0	5.1	
		B	5.2	4.9	4.6	4.5	5.0	5.0	5.1	
2/16	0.525	T	4.0	3.0	2.8	2.4	2.9	3.0	3.0	
		C	4.7	3.6	3.6	3.2	3.7	4.0	3.8	
		B	4.3	3.6	3.6	3.4	3.6	3.9	3.8	
2/18	0.75	T	4.8	4.6	4.4	4.0	4.3	4.7	4.4	
		C	4.1	4.2	3.9	3.8	4.4	4.8	4.3	
		B	3.5	3.4	3.2	3.2	5.4	3.6	3.4	

Table Al-7 cont'd

Series/ID	GAP	Loc.*	Pretest	Ovality (10^{-3} inch)						
Test Conditions										
Pressure, psig				2750	2750	2750	2500	2750	2500	2000
Temperature, F				534	534	534	534	450	450	674
Cycle Time, Hours				8	16	24	36	20	10	150
Total Time, Hours				8	24	48	84	104	114	264
2/18	0.75	T	4.8	4.6	4.4	4.0	4.3	4.7	4.4	
		C	4.1	4.2	3.9	3.8	4.4	4.8	4.3	
		B	3.5	3.4	3.2	3.2	5.4	3.6	3.4	
2/26	1.0	T	4.1	4.2	3.9	4.0	4.1	4.5	4.4	
		C	4.2	4.4	4.2	4.3	4.7	4.9	4.7	
		B	3.8	3.6	3.6	3.6	3.7	4.0	3.9	
2/29	1.65	T	3.7	3.7	3.6	3.6	4.5	4.2	4.0	
		C	4.8	5.0	5.4	5.4	5.7	6.3	5.8	
		B	4.6	4.4	4.4	4.3	4.5	4.9	4.3	
2/36	1.65	T	4.4	3.4	3.5	3.5	3.8	3.6	3.6	
		C	4.3	4.2	3.8	4.2	4.5	5.0	4.7	
		B	3.8	2.9	2.8	2.6	3.0	3.0	2.9	

*T = top, C = center, B = bottom with reference to engraved serial numbers

Table A1-8

Changes in Average Diameter of DECAG-II Series 1 and 2 Specimens

Test Conditions									
Pressure, psig			2750	2750	2750	2500	2750	2500	2000
Temperature, F			534	534	534	534	450	450	674
Cycle Time, Hours			8	16	24	36	20	10	150
Total Time, Hours			8	24	48	84	104	114	264
Series/ID	**GAP**	**Loc.***	Ovality (10^{-3} inch)						
1/06	0.525	T	0.6	-0.2	-0.3	-0.3	-0.1	-0.3	-0.7
		C	0.9	-0.1	-0.2	-0.2	0.0	-0.1	-0.7
		B	0.6	-0.2	-0.3	-0.1	0.0	-0.1	-0.6
1/07	0.525	T	1.4	0.1	0.1	0.3	0.4	0.3	-0.5
		C	1.3	0.0	0.0	0.0	0.1	0.1	-0.6
		B	0.7	-0.1	-0.4	-0.1	-0.1	-0.3	-0.7
1/05	0.75	T	1.1	0.1	0.0	0.1	0.1	0.1	-0.5
		C	0.7	-0.1	0.0	-0.1	0.0	0.1	-0.8
		B	-0.3	-0.1	-0.2	-0.2	-0.2	0.0	-0.7
1/03	1.0	T	0.3	-0.2	-0.4	-0.2	-0.4	-0.1	-1.0
		C	0.7	0.0	-0.1	0.3	-0.1	0.1	-0.5
		B	-0.2	-0.2	-0.4	-0.3	-0.2	-0.2	-1.1
1/04	1.0	T	1.3	-0.1	0.0	0.1	-0.1	0.2	-0.5
		C	1.1	-0.2	0.0	-0.1	-0.1	0.0	-0.7
		B	1.0	0.0	-0.1	0.1	0.1	-0.1	-0.7
1/01	1.65	T	0.9	0.0	0.1	0.3	0.1	-0.1	-0.6
		C	1.1	-0.1	0.0	-0.1	0.1	0.1	-0.7
		B	0.9	-0.2	-0.3	0.2	-0.3	0.0	-0.9
1/02	1.65	T	0.6	0.1	-0.1	-0.1	0.0	-0.1	-0.6
		C	1.3	0.2	0.2	0.4	-0.2	0.2	-0.5
		B	1.2	0.0	0.0	0.3	-0.3	0.2	-0.5
2/12	0.525	T	0.3	-0.8	-0.8	-0.6	-0.5	-0.4	
		C	0.3	-0.4	-0.6	-0.5	-0.1	-0.2	
		B	0.1	-0.4	-0.5	-0.5	-0.4	-0.3	
2/16	0.525	T	-0.3	-0.7	-0.5	-0.6	-0.4	-0.3	
		C	-0.1	-0.5	-0.4	-0.4	-0.1	0.0	
		B	0.4	0.0	0.1	-0.1	0.1	0.2	

Table A1-8 cont'd

Test Conditions									
Pressure, psig			2750	2750	2750	2500	2750	2500	2000
Temperature			534	534	534	534	450	450	674
Cycle Time, H			8	16	24	36	20	10	150
Total Time, Hours			8	24	48	84	104	114	264
Series/ID	**GAP**	**Loc.***	Ovality (10^{-3} inch)						
2/18	0.75	T	-0.5	-0.5	-0.5	-0.4	-0.3	-0.4	
		C	0.4	-0.2	-0.2	-0.1	0.1	0.2	
		B	-0.1	-0.6	-0.6	-0.5	-0.5	-0.3	
2/26	1.0	T	0.7	0.1	-0.5	0.0	0.1	0.2	
		C	0.0	-0.4	-0.5	-0.6	-0.3	-0.2	
		B	-0.2	-0.4	0.0	-0.3	-0.2	-0.2	
2/29	1.65	T	0.3	0.0	-0.1	0.1	-0.3	-0.1	
		C	-0.1	-0.4	-0.8	-1.0	-0.5	-0.5	
		B	-0.2	-0.5	-1.0	-0.8	-0.6	-0.6	
2/36	1.65	T	0.0	0.1	-0.9	0.2	-0.5	-0.4	
		C	0.0	-0.1	-1.1	-0.3	-0.6	-0.5	
		B	0.1	-0.3	-0.3	-0.2	-0.4	-0.2	

*T = top, C = center, B = bottom with reference to engraved serial numbers

Table A1-9
Ovality of DECAG-II Series 5 Specimens

Test Conditions				
Pressure, psig	2200	2200	2750	2750
Temperature, F	645	645	534	534
Cycle Time, hours	20	64	24	24
Total Time, hours	20	84	108	132

Series/ID.	Gap (in.)	Loc.*	Pretest Ovality (10^{-3} in.)	Ovality (10^{-3} in.)			
5/06	0.525	T	0.6	1.7	2.1	2.0	2.1
		C	0.3	0.7	1.2	1.5	1.3
		B	0.6	1.5	2.0	1.6	1.9
5/07+	0.525	T	3.5	3.7	3.2	3.2	3.4
		C	4.4	5.0	4.8	4.9	4.9
		B	4.9	5.0	4.4	4.4	4.4
5/14	0.525	T	0.5	1.1	1.8	1.9	1.9
		C	0.9	0.9	1.5	1.8	1.4
		B	0.7	1.0	1.6	1.6	1.7
5/19	0.525	T	0.9	2.1	1.3	1.6	1.4
		C	0.8	1.1	1.1	1.2	1.4
		B	1.0	1.5	1.7	2.4	1.9
5/21+	0.75	T	3.8	3.0	2.8	2.6	2.7
		C	3.2	3.6	3.0	3.3	3.1
		B	4.7	4.4	3.8	4.4	3.8
5/22	0.75	T	0.8	1.4	2.7	2.7	2.6
		C	1.0	0.9	1.0	1.0	0.9
		B	0.7	1.0	1.5	1.3	1.3
5/27+	1.0	T	2.8	2.8	2.6	2.4	2.7
		C	4.3	5.6	5.7	5.9	5.8
		B	3.6	3.9	3.6	3.4	3.4
5/28	1.0	T	2.7	1.3	1.6	1.7	1.7
		C	0.5	0.5	1.1	1.2	1.1
		B	0.9	1.5	1.9	1.9	1.9
5/30	1.65	T	0.7	1.2	1.8	1.7	1.9
		C	0.9	1.7	5.3	6.0	6.0
		B	1.1	0.7	1.6	1.9	1.8
5/34+	1.65	T	4.0	3.7	3.0	3.3	2.9
		C	5.5	8.1	11.2	11.4	11.1
		B	3.9	4.3	3.6	3.3	3.6

*T = top, C = center, B = bottom with reference to engraved serial numbers
+Preovaled specimens

Table A1-10
Diameter Changes in DECAG-II Series 5 Specimens

Test Conditions							
Pressure, psig				2200	2200	2750	2750
Temperature, F				645	645	534	534
Cycle Time, hours				20	64	24	24
Total Time, hours				20	84	108	132

Series/ID.	Gap (in.)	Loc.*	Pretest Ovality (10^{-3} in.)	Diameter Change WRT Pretest (10^{-3} in.)			
5/06	0.525	T	0.5673	0.6	0.4	0.7	0.5
		C	0.5672	0.6	0.5	0.8	0.6
		C	0.5673	0.6	0.5	0.8	0.6
5/07+	0.525	T	0.5667	0.5	0.5	0.5	0.4
		C	0.5669	0.6	0.6	0.5	0.6
		B	0.5671	0.5	0.6	0.5	0.3
5/14	0.525	T	0.5672	0.7	0.7	0.7	0.8
		C	0.5676	0.5	0.3	0.6	0.3
		B	0.5673	0.7	0.5	0.6	0.5
5/19	0.525	T	0.5675	0.9	0.5	0.7	0.4
		C	0.5674	0.4	0.5	0.3	0.3
		B	0.5675	0.5	0.8	0.9	0.5
5/21+	0.75	T	0.5680	0.8	0.7	0.8	0.6
		C	0.5678	0.8	0.7	0.6	0.5
		B	0.5686	0.7	0.4	0.9	0.6
5/22	0.75	T	0.5675	0.8	0.7	0.7	0.8
		C	0.5673	0.4	0.3	0.1	0.1
		B	0.5673	0.7	0.4	0.6	0.6
5/27+	1.00	T	0.5676	0.1	0.3	0.1	0.1
		C	0.5677	-0.1	-0.1	-0.1	-0.2
		B	0.5677	0.5	0.5	0.4	0.5
5/28	1.00	T	0.5685	-0.1	-0.2	-0.1	-0.1
		C	0.5677	0.9	0.7	0.8	0.7
		B	0.5675	0.9	0.8	0.9	0.9
5/30	1.65	T	0.5681	-0.2	0.0	-0.2	-0.2
		C	0.5677	0.2	0.0	-0.2	-0.3
		B	0.5681	-0.4	-0.1	-0.2	-0.2
5/34	1.65	T	0.5670	0.7	0.8	0.6	0.7
		C	0.5673	0.4	0.3	0.4	0.3
		B	0.5671	0.8	0.8	0.9	0.7

* T = top, C = center, B = bottom with reference to engraved serial numbers
+ Preovaled specimens.

Table A1-11
Ovality of DECAG-II Series 3A Specimens

Test Conditions								
Pressure, psig	2200	2000	2000	2000	2000	2000	2000	2000
Temperature, F	674	674	674	674	674	674	674	674
Cycle Time, Hours	162	224	1700	696	500	500	500	500
Total Time, Hours	162	386	2086	2782	3282	3782	4282	4782

Series/ID	Gap (in.)	Loc.#	Pretest Ovality (10^{-3} in)	Ovality (10^{-3} inch)							
3A/1	0.525	T	0.6	2.4	1.9	0.3	0.4	0.5	0.6	0.4	0.4
		C	0.2	2.0	3.0	1.2	2.2	3.2	1.5	5.3	4.6
		B	0.9	1.9	1.9	0.6	0.7	0.3	0.4	0.8	0.6
3A/9	0.525+	T	0.7	1.1	0.6	0.3	0.2	0.4	0.5	0.5	0.7
		C	0.5	1.0	1.5	1.0	1.9	1.3	0.7	2.6	2.3
		B	0.5	1.2	1.3	0.2	0.8	0.7	0.3	0.8	0.6
3A/15*	0.525+	T	3.2	2.0	1.6	0.3	0.6	0.3	0.3	0.5	0.4
		C	3.6	2.4	1.5	1.2	2.2	1.5	1.6	3.8	2.9
		B	4.4	2.3	0.5	0.2	0.6	1.7	0.3	0.5	1.9
3A/32	1.65	T	1.0	1.4	1.8						
		C	0.6	18.0	31.3	**					
		B	0.6	1.4	1.5						

*Preovaled specimen.

+ Axial gaps of specimens 9 and 15 were enlarged by cutting specimen, maching insert and rewelding.
  Gap History - 0.525 inch, 0-162 hours
  0.75 inch, 162-386 hours
  1.0 inch, 386-2086 hours
  1.65 inch, 2086-end of test

T = top, C = center, B = bottom with reference to engraved serial numbers

** Specimen collapsed in this time interval.

Table A1-12
Diameter Change of DECAG-II Series 3A Specimens

Test Conditions											
Pressure, psig				2200	2000	2000	2000	2000	2000	2000	2000
Temperature, F				674	674	674	674	674	674	674	674
Cycle Time, Hours				162	224	1700	696	500	500	500	500
Total Time, Hours				162	386	2086	2782	3282	3782	4282	4282

Series/ID	Gap (in.)	Loc.#	Pretest Diameter (inch)	Diameter Change WRT Pretest (10^{-3} inch)							
3A/1	0.525	T	0.5677	-0.9	-1.7	-2.2	-2.1	-2.1	-2.1	-2.2	-2.4
		C	0.5678	-1.0	-1.6	-2.8	-3.0	-3.1	-3.1	-3.7	-2.9
		B	0.5680	-1.0	-1.7	-2.5	-2.7	-2.8	-2.6	-2.8	-2.9
3A/9	0.525+	T	0.5690	-1.7	-0.3	-2.4	-2.2	-2.3	-2.4	-2.4	-2.4
		C	0.5686	-1.1	-0.8	-2.7	-2.9	-3.6	-3.8	-3.5	-3.4
		B	0.5683	-0.9	-0.7	-2.1	-2.0	-2.2	-2.2	-2.2	-2.4
3A/15*	0.525+	T	0.5681	-0.8	-0.5	-2.1	-1.9	-2.1	-2.0	-1.9	-2.4
		C	0.5681	-0.8	-0.8	-2.4	-2.8	-3.6	-3.3	-3.4	-3.2
		B	0.5683	-0.9	-0.5	-2.1	-2.1	-1.5	-2.5	-2.2	-1.6
3A/32	1.65	T	0.5684	-1.0	-1.5						
		C	0.5683	-1.3	-2.1	**					
		B	0.5684	-1.1	-1.6						

*Preovaled specimen
÷See gap history, Table A1-11.
#T = top, C = center, B = bottom with reference to engraved serial numbers
** Specimen collapsed in this time interval.

Table A1-13
Ovality of DECAG-II Series 3B Specimens

Test Conditions			
Pressure, psig	2000	2000	2000
Temperature, F	636	636	636
Cycle Time, hours	954	1390	1542
Total Time, hours	954	84	3786

Series/ID.	Gap (in.)	Loc.#	Pretest Ovality (10^{-3} in.)	Ovality (10^{-3} in.)		
3B/4*	0.525+	T	4.7	3.3	1.4	1.8
		C	4.8	4.4	2.3	3.0
		B	4.4	3.3	1.1	1.8
3B/10	0.525+	T	0.6	2.4	1.8	1.5
		C	0.4	1.6	1.0	1.2
		B	0.5	1.9	1.0	1.3
3B/17	0.525	T	0.6	2.1	2.1	1.4
		C	0.3	1.2	1.1	1.0
		B	0.8	1.8	1.5	2.3
3B/33	1.65	T	1.1	2.5	0.6	2.1
		C	0.9	12.6	15.2	20.5
		B	0.8	2.3	1.0	2.3

*Preovaled specimen
+Axial gaps of specimens 4 and 10 enlarged by cutting specimen, machining insert and rewelding.
Gap History: 0.525, 0-954 hours
0.75, 954-end of test
T = top, B = bottom, C - center with reference to engraved serial numbers.

Table A1-14
Diameter Change of DECAG-II Series 3B Specimens

Test Conditions			
Pressure, psig	2000	2000	2000
Temperature, F	636	636	636
Cycle Time, hours	954	1390	1542
Total Time, hours	954	2344	3786

Series/ID.	Gap (in.)	Loc.#	Pretest Diameter (inch)	Diameter Change WRT Pretest (10^{-3} inch)		
3B/4*	.525+	T	0.5678	-0.9	-1.0	-1.2
		C	0.5675	-0.3	-1.4	-1.1
		B	0.5676	-0.5	-1.0	-0.9
3B/10	.525+	T	0.5685	-1.0	-1.4	-1.3
		C	0.5686	-1.0	-2.1	-1.3
		B	0.5685	-0.9	-1.5	-1.2
3B/17	.525	T	0.5684	-0.9	-1.4	-1.1
		C	0.5682	-1.0	-1.7	-1.4
		B	0.5684	-1.0	-0.6	-1.3
3B/33	1.65	T	0.5682	-0.8	-0.4	-1.1
		C	0.5682	-1.1	-3.5	-1.7
		B	0.5685	-1.3	-0.9	-1.5

*Preovaled specimen.
+See gap history, Table A1-13.
T = top, B = bottom, C = center with reference to engraved serial numbers.

Table A1-15
Ovality of DECAG-II Series 4 Specimens

Test Conditions																		
Pressure, psig				2750	2750	2500	2000	2750/ 2500	2000	2750/ 2500	2000	2750/ 2500	2000	2750/ 2500	2000	2000	2000	2000
Temperature, F				534	534	534	674	450	674	534	674	534	674	543	674	674	674	674
Cycle Time, Hours				24	24	36	500	4/2	506	4/2	500	4/2	500	4/2	500	500	500	500
Total Time, Hours				24	48	84	584	590	1096	1102	1602	1609	2109	2115	2615	3115	3615	4115
Series/ID	Gap (in.)	Loc.#	Pretest Ovality (10^{-3} in.)	Ovality (10^{-3} inch)														
4/02+	0.525	T	0.6	1.0	1.2	0.8	1.1	0.6	0.6	0.6	0.5	0.7	0.9	0.8	0.6	0.6	0.9	0.7
	0.75,1.0	C	0.5	0.8	1.0	0.5	1.5	1.0	1.2	0.8	1.3	0.8	1.3	1.3	1.3	1.5	2.5	2.1
	1.65	B	0.6	1.2	1.2	1.0	1.9	1.2	0.5	0.6	0.7	1.2	1.0	1.2	1.8	0.3	1.2	0.7
4/03*+	0.525,	T	3.8	3.7	3.4	3.4	1.2	1.3	0.9	0.9	0.8	0.9	0.5	0.6	0.5	0.3	0.5	0.7
	0.75,1.0	C	4.0	4.4	4.0	4.2	3.3	2.4	1.5	0.8	0.6	1.6	2.1	2.3	3.2	2.2	5.5	6.3
	1.65	B	4.6	4.0	4.2	4.2	2.8	1.3	0.8	1.1	0.9	1.0	1.0	0.9	1.0	0.7	0.9	1.1
4/05	0.525	T	0.5	0.8	0.8	1.0	2.2	1.9	0.9	0.8	0.7	0.8	0.6	0.7				
		C	0.5	1.1	0.4	1.0	2.2	1.8	1.1	1.0	0.8	0.9	0.8	0.7				
		B	0.6	0.8	0.6	1.0	2.0	1.7	1.0	0.9	1.0	0.7	0.8	0.7				
4/08	0.525	T	4.0	4.0	3.8	3.5	1.5	1.7	1.0	1.2	0.4	0.2	0.3	0.3				
		C	5.0	5.0	4.6	4.6	3.3	3.1	0.8	1.9	1.1	1.5	0.8	1.4				
		B	5.0	4.6	4.9	4.1	2.4	2.2	1.3	1.3	0.8	1.1	0.8	0.8				
4/11	0.525	T	5.2	5.4	5.2	5.0	2.9	2.5	1.3	1.5	1.0	1.0	0.9	1.0				
		C	5.0	5.0	5.0	4.8	4.3	3.8	3.0	3.1	1.1	2.6	2.2	2.4				
		B	4.4	4.4	4.6	4.1	2.0	1.9	1.2	1.4	1.1	1.2	0.9	0.9				
4/13	0.525	T	0.4	1.0	0.8	1.2	1.8	1.8	0.7	0.8	0.5	0.6	0.5	0.4				
		C	0.3	0.9	0.6	0.8	2.1	1.6	1.0	0.9	0.4	0.6	0.6	0.6				
		B	0.4	1.0	0.8	1.1	1.7	1.1	0.5	0.5	0.5	0.3	0.3	0.2				
4/20	0.76	T	3.8	4.0	3.5	3.4	1.5	0.9	0.8	0.8	0.5	0.7	0.5	0.7				
		C	4.5	4.5	4.2	4.2	3.2	2.3	2.1	1.9	1.0	2.3	1.6	2.0				
		B	4.0	4.2	3.9	3.4	2.0	1.5	0.7	0.6	0.6	0.5	0.4	0.4				
4/23	.75	T	0.4	0.5	0.8	0.8	1.7	1.1	0.6	0.3	0.4	0.5	0.4	0.4				
		C	0.5	1.1	0.2	0.4	1.3	1.6	1.2	1.2	0.8	1.0	1.1	1.0				
		B	0.5	0.3	1.0	0.6	1.7	1.1	0.7	0.8	0.5	0.4	0.4	0.5				
4/24	1.0	T	0.8	1.2	0.6	1.0	0.6	0.9	0.5	0.7	0.8	0.4	0.5	0.5				
		C	0.7	1.2	1.2	1.2	2.4	1.9	1.6	1.7	1.5	1.7	1.7	1.0				
		B	0.3	0.6	0.9	0.6	1.0	0.8	0.3	0.4	0.3	0.5	0.1	0.4				
4/25*	1.0	T	4.2	4.0	3.8	4.0	1.4	1.2	0.5	0.6	0.4	0.2	0.5	0.3				
		C	4.4	4.4	4.4	4.3	4.9	3.8	3.9	3.8	3.5	2.8	3.2	3.2				
		B	3.8	3.9	3.7	3.6	1.7	1.4	0.8	0.9	0.7	0.7	0.6	0.5				
4/31	1.65	T	0.8	0.9	1.2	1.4	1.8	1.7	1.8	1.9								
		C	0.7	1.1	1.3	1.6	20.0	19.3	54.5	1.1	++							
		B	1.0	1.2	1.4	1.4	0.9	1.6	0.9	1.1								
4/35	1.65	T	4.9	4.8	4.5	4.4	2.7	2.8										
		C	5.2	4.3	6.0	6.0	19.9	28.9	++									
		B	4.8	5.2	4.3	4.0	1.5	1.1										

*Designates preovaled specimens.
+These specimens were periodically cut apart and remachined to obtain larger gaps in simulation of axial gap growth.
T = top, B = bottom, C - center with reference to engraved serial number
++ Specimen collapsed during this test interval
**Series 4 terminated. Specimens 4/02 and 4/03 were combined with Series 3A for remaining cycles.

Table A1-16

Changes in Average Diameter of DECAG-II Series 4 Specimens

Test Conditions																		
Pressure, psig				2750	2750	2500	2000	2750/ 2500	2000	2750/ 2500	2000	2750/ 2500	2000	2750/ 2500	2000	2000	2000	2000
Temperature, F				534	534	534	674	450	674	534	674	534	674	543	674	674	674	674
Cycle Time, Hours				24	24	36	500	4/2	506	4/2	500	4/2	500	4/2	500	500	500	500
Total Time, Hours				24	48	84	584	590	1096	1102	1602	1609	2109	2115	2615	3115	3615	4115
Series/ID	Gap (in.)	Loc.#	Pretest Diameter (inch)	Average Diameter Change WRT Pretest (10^{-3} inch)														
4/02+	0.525,	T	0.5687	-0.4	-0.7	-0.6	-1.3	-1.7	-1.8	-1.5	-1.9	-1.9	-2.0	-2.0	-2.0	-2.1	-2.0	-2.3
	0.75,1.0	C	0.5690	-1.2	-1.1	-0.9	-1.7	-1.9	-2.4	-1.8	-2.5	-2.5	-3.2	-2.9	-3.5	-3.3	-3.7	-3.9
	1.65	B	0.5688	-0.9	-0.9	-0.8	-1.7	-1.9	-2.2	-2.1	-2.6	-2.4	-2.8	-2.6	-1.9	-2.2	-2.6	-2.9
4/30*+	0.525,	T	0.5694	-0.3	-0.6	-0.1	-1.9	-1.9	-2.3	-1.8	-2.2	-2.1	-2.4	-2.4	-2.3	-2.6	-2.6	-2.7
	0.75,1.0	C	0.5695	-1.0	-0.7	-0.7	-1.6	-1.8	-2.2	-1.7	-2.0	-2.3	-2.7	-2.7	-2.8	-3.4	-3.1	-3.3
	1.65	B	0.5694	-0.3	-0.6	-0.8	-1.3	-1.5	-1.7	-1.4	-1.8	-1.7	-1.9	-1.9	-1.7	-2.1	-2.0	-2.1
4/05	0.525	T	0.5683	-0.2	-0.4	-0.4	-1.3	-1.4	-2.0	-1.6	-2.0	-2.0	-2.3	-2.2	**			
		C	0.5682	-0.7	-0.7	-0.5	-1.4	-1.6	-2.1	-1.8	-2.4	-2.4	-2.8	-2.8				
		B	0.5683	-0.6	-1.1	-0.3	-1.7	-1.8	-2.4	-2.1	-2.2	-2.4	-2.6	-2.5				
4/08*	0.525	T	0.5679	0.0	-0.6	-0.3	-1.7	-1.5	-1.7	-1.5	-1.8	-1.8	-2.1	-2.1				
		C	0.5680	-0.5	-0.6	-0.4	-1.5	-2.1	-1.8	-2.0	-2.5	-2.6	-2.6	-2.7				
		B	0.5682	-0.1	-0.6	-0.4	-1.3	-2.0	-2.3	-2.2	-2.3	-2.2	-2.5	-2.5				
4/11*	0.525	T	0.5680	0.0	-0.5	-0.4	-1.5	-1.5	-1.8	-1.6	-1.9	-1.8	-2.1	-2.0				
		C	0.5676	0.1	-0.2	0.0	-1.7	-1.6	-1.9	-1.6	-1.5	-2.0	-2.2	-2.2				
		B	0.5676	0.2	-0.2	-0.2	-1.1	-1.3	-1.6	-1.3	-1.6	-1.4	-1.8	-1.7				
4/13	0.525	T	0.5680	-0.3	-0.4	-0.3	-1.1	-1.5	-1.9	-1.7	-1.9	-1.9	-2.3	-2.1				
		C	0.5681	-0.3	-0.6	-0.4	-1.2	-1.9	-2.0	-1.7	-2.0	-2.3	-2.5	-2.3				
		B	0.5682	-0.6	-0.6	-0.6	-1.3	-1.9	-2.1	-2.0	-2.1	-2.2	-2.4	-2.3				
4/20*	.75	T	0.5686	0.6	-0.7	-0.4	-1.5	-1.6	-1.8	-1.5	-1.8	-1.6	-2.4	-1.8				
		C	0.5683	0.9	-1.1	-0.9	-2.1	-2.1	-2.6	-2.1	-2.2	-2.7	-2.9	-2.9				
		B	0.5688	0.8	-1.1	-0.8	-1.7	-2.0	-2.4	-2.1	-2.3	-2.2	-2.5	-2.4				
4/23	.75	T	0.5690	0.2	-0.5	-0.4	-1.4	-1.6	-1.8	-1.6	-1.9	-1.9	-2.0	-2.0				
		C	0.5690	-0.2	-0.4	-0.7	-1.6	-1.8	-2.0	-1.8	-2.0	-2.1	-2.6	-2.5				
		B	0.5691	0.1	-0.7	-0.5	-1.5	-1.7	-1.9	-1.7	-1.9	-1.8	-2.1	-2.0				
4/24	1.00	T	0.5685	-0.1	-0.1	0.0	-0.9	-0.9	-2.0	-0.7	-0.8	-0.9	-1.0	-0.8				
		C	0.5684	-0.3	-0.7	-0.8	-1.7	-1.8	-2.0	-1.8	-2.0	-2.2	-2.5	-2.7				
		B	0.5692	0.2	-1.2	-0.6	-2.3	-2.3	-2.6	-2.3	-2.6	-1.7	-2.8	-2.6				
4/25*	1.00	T	0.5686	-0.1	-0.8	-0.2	-1.4	-1.7	-1.8	-1.4	-1.7	-1.8	-1.9	-1.9				
		C	0.5675	0.4	0.1	0.0	-0.8	-1.2	-1.2	-1.0	-1.5	-1.5	-1.8	-1.8				
		B	0.5685	-0.4	-0.2	-0.2	-1.1	-1.6	-1.6	-1.4	-1.5	-1.6	-2.6	-1.7				
4/31	1.625	T	0.5692	-0.6	-0.6	-0.4	-1.4	-1.4	-1.8	-1.5								
		C	0.5694	-1.4	-1.0	-0.4	-1.7	-1.7	-3.3	-2.9	++							
		B	0.5690	-0.9	-0.3	-0.5	-1.5	-1.5	-1.9	-1.6								
4/35*	1.625	T	0.5685	0.3	-0.5	-0.2	-1.3	-1.5										
		C	0.5681	1.3	-0.8	-0.3	-1.5	-1.7	++									
		B	0.5682	0.9	-0.5	0.0	-1.4	-1.4										

*Designates preovaled specimens.
+These specimens were periodically cut apart and remachined to obtain larger gaps in simulation of axial gap growth.
T = top, B = bottom, C - center with reference to engraved serial number
++Specimen collapsed during this test interval
**Series 4 terminated. Specimens 4/02 and 4/03 were combined with Series 3A for remaining cycles.

Table A1-17
Ovality of DECAG-II Series 3A2 Specimens

Test Conditions						
Pressure, psi	2200	2000	2000	2000	2000	2000
Temperature, F	645	674	674	674	674	674
Cycle Time, Hours	84	150	250	508	590	1000
Total Time, Hours	84	234	484	992	1582	2582
Larson-Miller Parameter	----	25148	25630	26034	26281	26549

Series/ID	Gap (in)	Loc.#	Pretest Ovality (10^{-3} in.)	Ovality (10^{-3} inch)					
3A2/37	1.0	T	0.6	1.1	2.6	2.5	2.5	2.1	1.0
		C	0.7	0.4	0.5	0.8	1.1	1.2	1.3
		B	0.3	0.6	0.4	0.3	0.3	0.3	0.4
3A2/38	1.0	T	1.0	1.1	1.2	0.8	0.7	0.8	0.7
		C	0.7	1.3	1.9	2.3	2.3	2.1	2.5
		B	0.1	1.3	0.4	0.2	0.3	0.6	0.1
3A2/43	1.2*	T	0.8	1.5	0.7	0.4	0.5	0.4	0.2
		C	0.2	1.0	2.6	2.7	2.7	2.7	2.6
		B	0.4	0.8	0.8	0.7	0.7	0.4	0.6
3A2/47	1.4	T	0.6	0.7	0.7	0.8	0.6	0.6	0.7
		C	0.7	2.7	4.8	7.4	10.0	9.6	15.9
		B	0.3	0.7	1.4	1.0	0.5	0.1	0.2
3A2/48	1.4	T	0.6	1.4	1.5	1.1	0.8	0.7	0.5
		C	0.3	0.7	1.8	3.7	5.7	6.9	14.8
		B	0.6	0.9	0.6	0.2	0.6	0.6	0.6
3A2/52	1.65	T	0.6	0.6	0.9	0.6	0.7		
		C	0.3	3.0	7.8	13.5	26.3	+	
		B	0.4	0.9	0.7	0.5	0.9		
3A2/53	1.65	T	1.0	1.5	1.6	1.1	1.3	1.3	
		C	0.4	3.2	6.9	12.4	27.5	52.5	+
		B	1.2	1.1	1.6	0.8	0.4	1.0	

* The replicate specimen with 1.2 inch gap was defective; no data are reported.
+ Collapsed during this test cycle.
# T = top, C = center, B = bottom with reference to engraved serial numbers.

Table A1-18
Diameter Change of DECAG-II Series 3A2 Specimens

Test Conditions						
Pressure, psi	2200	2000	2000	2000	2000	2000
Temperature, F	645	674	674	674	674	674
Cycle Time, Hours	84	150	250	508	590	1000
Total Time, Hours	84	234	484	992	1582	2582
Larson-Miller Parameter	----	25148	25630	26034	26281	26549

Series/ID	Gap (in)	Loc.#	Pretest Diameter (inch)	Diameter Change WRT Pretest (10^{-3} inch)					
3A2/37	1.0	T	0.5680	-0.8	-0.7	-1.1	-0.6	-1.5	-2.1
		C	0.5678	-0.5	-0.9	-1.3	-1.0	-1.7	-1.4
		B	0.5680	-0.5	-0.8	-1.2	-0.8	-1.5	-1.4
3A2/38	1.0	T	0.5685	-0.5	-0.8	-1.1	-0.9	-1.6	-1.7
		C	0.5682	-0.6	-0.8	-1.2	-1.0	-1.7	-2.3
		B	0.5684	-0.7	-0.6	-1.1	-0.7	-1.4	-1.5
3A2/43	1.2*	T	0.5686	-0.7	-0.8	-0.9	-0.5	-1.4	-1.5
		C	0.5684	-0.7	-0.7	-1.3	-0.7	-1.8	-2.2
		B	0.5683	-0.5	-0.7	-1.2	-0.9	-1.5	-1.6
3A2/47	1.4	T	0.5684	-0.7	-0.9	-1.1	-0.6	-1.3	-1.4
		C	0.5682	-0.7	-0.6	-1.2	-0.6	-1.0	-2.0
		B	0.5685	-0.2	0.1	-1.2	-1.2	-1.8	-1.9
3A2/48	1.4	T	0.5685	-0.5	-0.8	-1.3	-1.0	-1.5	-1.9
		C	0.5682	-0.5	-0.5	-0.8	-1.2	-1.3	-2.6
		B	0.5684	-0.6	-0.7	-1.3	-0.8	-1.6	-1.9
3A2/52	1.65	T	0.5682	-0.7	-0.9	-1.0	-0.7		
		C	0.5679	-0.6	-0.8	-1.1	-0.5	+	
		B	0.5681	-0.7	-1.0	-1.3	-0.7		
3A2/53	1.65	T	0.5687	-0.7	-0.8	-1.3	-0.8	-1.7	+
		C	0.5684	-0.9	-0.6	-0.6	-0.9	-0.7	
		B	0.5685	-0.6	-0.8	-1.1	-0.9	-1.5	

* The replicate specimen with 1.2 inch gap was defective, no data are reported.
+ Collapsed during this test cycle.
# T = top, C = center, B = bottom with reference to engraved serial numbers.

Table A1-19
Cvality of DECAG-II Series 3B2 Specimens

Test Conditions								
Pressure, psi				2200	2000	2000	2000	2000
Temperature, F				645	636	636	636	636
Cycle Time, Hours				84	350	466	1704	1968
Total Time, Hours				84	434	900	2604	4572
Larson-Miller Parameter				----	24208	25111	25648	25922
Series/ID	**Gap (in)**	**Loc.***	**Pretest Ovality (10^{-3} in.)**	**Ovality (10^{-3} inch)**				
3B2/39	1.0	T	0.8	1.0	1.1	1.2	1.2	0.7
		C	0.4	1.9	2.6	3.2	3.7	2.2
		B	0.7	0.8	1.0	0.8	0.6	0.2
3B2/40	1.0	T	1.0	1.4	1.3	1.3	0.8	0.2
		C	0.3	1.2	1.6	2.1	2.7	0.4
		B	0.7	1.0	0.5	0.5	0.1	0.4
3B2/44	1.2	T	0.8	1.0	1.0	0.8	0.6	1.1
		C	0.4	1.3	2.0	3.3	4.2	1.3
		B	1.0	1.5	1.7	1.7	1.7	0.8
3B2/45	1.2	T	0.7	1.4	1.5	1.4	1.2	0.3
		C	0.3	1.1	1.7	2.3	2.5	2.8
		B	1.1	1.5	1.2	1.2	1.1	0.7
3B2/49	1.4	T	0.5	0.3	0.1	0.5	0.4	0.1
		C	0.6	2.7	3.0	3.9	4.6	3.7
		B	0.3	0.2	0.3	0.3	0.3	1.4
3B2/50	1.4	T	0.4	1.3	1.3	1.2	0.8	0.4
		C	0.3	0.6	1.6	3.0	4.7	4.6
		B	0.5	1.4	1.4	0.4	1.2	0.4
3B2/54	1.65	T	0.7	1.1	1.0	1.1	0.7	0.5
		C	0.9	3.4	5.7	7.3	11.4	10.9
		B	0.4	1.0	1.1	1.3	0.9	0.2
3B2/55	1.65	T	0.7	0.8	0.6	0.6	0.3	0.1
		C	0.3	2.9	5.3	3.8	14.4	18.4
		B	0.7	1.7	1.7	1.5	0.5	0.3

*T = top, C - center, B = bottom with reference to engraved serial numbers.

Table A1-20
Diameter Change of DECAG-II Series 3B2 Specimens

Test Conditions								
Pressure, psi				2200	2000	2000	2000	2000
Temperature, F				645	636	636	636	636
Cycle Time, Hours				84	350	466	1704	1968
Total Time, Hours				84	434	900	2604	4572
Larson-Miller Parameter				----	24208	25111	25648	25922
Series/ID	**Gap (in)**	**Loc.***	**Pretest Diameter (inch)**	**Diameter Change WRT Pretest (10^{-3} inch)**				
3B2/39	1.0	T	0.5686	-0.5	-0.8	-0.8	-1.0	-1.4
		C	0.5682	-0.5	-0.6	-0.7	-1.0	-1.0
		B	0.5682	-0.3	-0.4	-0.6	-0.8	-1.2
3B2/40	1.0	T	0.5683	-0.6	-0.8	-1.0	-1.2	-1.5
		C	0.5680	-0.4	-0.7	-0.9	-1.0	-1.3
		B	0.5684	-0.5	-0.8	-1.0	-1.2	-1.2
3B2/44	1.2	T	0.5685	-0.6	-0.7	-1.0	-1.1	-1.3
		C	0.5685	-0.6	-0.7	-1.0	-1.1	-2.1
		B	0.5686	-0.7	-0.7	-1.0	-1.1	-1.3
3B2/45	1.2	T	0.5686	-0.7	-0.9	-1.0	-1.2	-1.5
		C	0.5684	-0.5	-0.7	-0.9	-1.0	-1.0
		B	0.5685	-0.7	-0.7	-0.9	-1.1	-2.0
3B2/49	1.4	T	0.5685	-0.5	-0.8	-0.9	-0.9	-1.3
		C	0.5685	-0.5	-0.7	-0.9	-1.1	-1.0
		B	0.5684	-0.5	-0.7	-0.9	-1.1	-2.0
3B2/50	1.4	T	0.5683	-0.6	-0.7	-0.7	-1.0	-1.4
		C	0.5682	-0.5	-0.7	-1.0	-1.1	-1.3
		B	0.5685	-0.6	-0.7	-0.5	-1.1	-1.1
3B2/54	1.65	T	0.5687	-0.7	-0.7	-1.0	-1.1	-1.4
		C	0.5686	-0.5	-0.8	-0.8	-1.4	-1.1
		B	0.5685	-0.4	-0.4	-0.7	-0.8	-1.1
3B2/55	1.65	T	0.5679	-0.5	-0.7	-0.7	-1.0	-1.3
		C	0.5677	-0.4	-0.6	-0.9	-1.1	-3.2
		B	0.5679	-0.7	-0.7	-1.1	-1.2	-1.5

* T = top, C = center, B = bottom with reference to engraved serial numbers.

Table A1-21
Ovality of DECAG-III Small Diameter RXA Test Specimens

Test Conditions									
Pressure, psi			2200	2750/ 2500	2000	2000	2000	2000	2000
Temperature, F			645	534	674	674	674	674	674
Cycle Time, Hours			84	48/36	358	500	300	500	300
Total Time, Hours			84	168	526	1032+	1338+	1838	2138
ID	**Loc.#**	**Pretest Ovality (10^{-3} in.)**	**Ovality (10^{-3} in.)**						
2717	T	0.8	0.1	0.6	0.6	0.5	0.2	0.6	0.6
	C	0.6	0.8	0.8	0.6	0.6	0.5	0.4	0.9
	B	0.5	0.3	0.4	0.2	0.4	0.3	0.3	0.3
2418	T	0.5	0.3	0.2	0.2	0.4	0.2	0.2	0.4
	C	0.3	0.6	0.4	0.6	0.4	0.4	0.6	0.5
	B	0.4	0.3	0.6	0.5	0.2	0.4	0.6	0.6
2420	T	0.3	0.6	0.4	0.4	0.2	0.4	1.0	0.5
	C	0.8	0.7	0.6	0.5	0.4	0.5	0.4	0.7
	B	0.4	0.4	0.3	0.3	0.5	1.0	0.3	0.4
2421	T	0.6	0.5	0.3	0.4	0.6	0.3	0.3	0.3
	C	0.2	0.2	0.1	0.2	0.3	0.2	0.1	0.2
	B	0.2	0.5	0.8	0.4	0.3	0.4	0.4	0.0
2422*	T	0.4	0.5	0.4	0.6	0.5	0.2	0.9	0.5
	C	0.2	0.2	0.5	0.4	0.2	0.2	0.4	0.3
	B	1.3	1.6	0.3	1.5	1.2	1.0	1.7	1.7
2423*	T	0.4	0.4	0.5	0.5	0.5	0.3	0.3	0.4
	C	0.4	0.4	0.4	0.3	0.4	0.5	0.4	0.5
	B	0.3	0.4	0.1	0.2	0.2	0.4	0.2	0.5
2258*	T	0.5	0.6	0.2	0.4	0.6	0.2	0.3	0.0
	C	0.4	0.6	0.6	0.4	0.5	0.2	0.5	0.6
	B	0.3	0.3	0.4	0.4	0.3	0.7	0.5	0.6

*Specimens with spring in plenum. Others are empty tubes.
+Data from examinations after hydrostatic and relief valve testing not shown
Total hours correct per Table 3.3 of text.
#T = top, C - center, B = bottom with reference to engraved serial numbers.

Table A1-22
Changes in Diameter of DECAG-III Small Diameter RXA Test Specimens

Test Conditions										
Pressure, psi			2200	2750/ 2500	2000	2000	2000	2000	2000
Temperature, F			645	534	674	674	674	674	674
Cycle Time, Hours			84	48/36	358	500	300	500	300
Total Time, Hours			84	168	526	1032+	1338+	1838	2138

ID	Loc.#	Pretest Diameter (inch)	Diameter Change WRT Pretest (10^{-3} in.)						
2417	T	.3044	0.0	0.1	0.1	0.4	-0.5	0.3	0.0
	C	.3044	0.1	0.3	0.2	0.2	-0.2	0.0	0.2
	B	.3040	0.0	0.3	0.0	0.2	0.5	0.1	0.0
2418	T	.3045	0.2	0.3	0.2	-0.2	-0.5	0.1	0.2
	C	.3043	0.3	0.3	0.3	0.3	-0.1	0.2	0.1
	B	.3041	0.1	0.2	0.1	0.2	0.5	0.0	0.1
2402	T	.3047	0.2	0.2	0.3	-0.3	-0.6	0.5	0.2
	C	.3048	0.0	0.2	-0.1	0.0	-0.3	0.0	0.0
	B	.3045	0.0	0.1	0.1	0.0	-0.2	-0.1	0.0
2421	T	.3045	0.5	0.5	0.6	0.9	-0.1	0.5	0.4
	C	.3047	0.0	0.2	0.1	0.6	0.0	0.1	0.1
	C	.3049	-0.4	-0.3	-0.5	0.2	-0.1	0.0	-0.8
2422*	T	.3049	0.1	0.3	0.2	0.1	-0.6	0.3	0.0
	C	.3047	0.1	0.2	0.2	0.2	-0.3	0.2	0.0
	B	.3044	0.2	0.6	0.1	0.1	0.3	0.2	0.0
2423*	T	.3049	0.1	0.1	0.2	0.2	-0.5	0.1	0.0
	C	.3048	-0.1	0.2	0.0	0.2	-0.3	0.1	0.0
	B	.3045	0.0	0.2	0.1	0.2	0.3	0.2	0.1
2258*	T	.3053	-0.1	0.2	0.2	0.3	-0.7	0.2	0.3
	C	.3051	0.0	0.3	0.2	0.3	-0.1	0.2	0.2
	B	.3048	-0.2	0.3	0.2	0.2	0.3	0.2	0.1

*Specimens with springs in plenum. Others are empty tubes.
+Data from examinations after hydrostatic and relief testing not shown. Total hours correct per Table 3.3 of text.
#T = top, C = center, B = bottom with reference to engraved serial numbers.

Appendix 2
Measurement Techniques Used in
DECAG Test Program

Ovality and diameter of the DECAG specimens were measured after each test cycle. These data were compared with pretest dimensional data and reported as average diameter change and ovality.

Maximum and minimum diameters at specified axial locations were obtained with a Pratt and Whitney standard measuring machine, Figure A2-1. This machine consists of a master bar, a dividing screw providing direct and vernier readout to .00001 inch, and a means of controlling measuring pressure, all mounted on a rigid bed. The master bar was not used for diameter measurements but the dividing screw scale was calibrated with certified Johansen blocks. The dividing screw which is operated by a handwheel moves the headstock spindle in and out over a one-inch travel and subdivides the inch into hundred thousandths of an inch (.00001 inch). The measuring pressure is controlled by an Electrolimit pressure tailstock which has a range of from one to two and one half pounds. Measurements of DECAG specimens were obtained with a one pound force limit in order to minimize the deformation inherent in pressing on thin-walled tubes. Specified axial locations identified in Appendix 1 as "T", "C", and "B" mean top, center, and bottom locations with reference to a scribed mark defining the "top" of the specimen. The T and B locations are located over the inserts but are sufficiently isolated from both the weld area and the unsupported axial gap. The C location is at the centerline of the axial gap.

Maximum and minimum diameters were obtained by rotating the specimens between the anvils of the head and tailstocks while maintaining a "zero" reading on the Electrolimit pressure meter. This assured that uniform force was applied for each measurement. The 0.375 inch diameter of the anvils assured that all measurements were on specimen diameters. Repeatability of measurements using this machine was found to be $\pm$.0002 in. for different operators.

Data obtained from this process are reported in Appendix 1 as (1) "Average OD", which is the average of the maximum and minimum diameters obtained in the measuring process, and (2) as "Ovality", which is the difference between maximum and minimum diameters.

Ovalities were obtained also with a Bendix-Cleveland Model PT-1033 Product-O-Ron, Figure A2-2. It is a shop instrument designed for the precision measurement of roundness and other attributes. In operation, the specimen is positioned on a work table carried by a vertical spindle in a fixture especially designed to assure concentricity and perpendicularity. The specimen is rotated past a stationary electronic gage head, the top of which is in contact with the work surface and connects with the recorder through a linear amplifier. The recorder table is mechanically connected to the work spindle by a positive drive timing belt which maintains constant angular position of the recorder with respect to the spindle at all times. Motor drive for spindle and recorder is provided by a 4 rpm constant speed DC motor. A record of the inspection is obtained on an electric writing chart via a 5-ma galvanometer connected to the linear amplifier. The amplifier provides 200X ampliciation on the coarse scale and 1000X amplification on the intermediate scale when used with the appropriate sensing tip on the gage head. This system was generally calibrated to provide .0001 inch per chart division (.1 inch) on the intermediate scale using Johansen blocks as standards. Examples of Product-O-Ron output are shown in Figure A2-3 and 4.

Ovality is defined here as the difference between the diameters of the smallest circumscribed circle and the largest inscribed circle on the Product-O-Ron traces. This quantity also may be interpreted as the difference between the maximum and minimum diameters, hence available from the precision diameter measurements described earlier. Comparative testing has shown that the Pratt and Whitney measurements are more accurate and more repeatable for determining ovality than are the Product-O-Ron data. Accordingly, both diameter and ovality information reported in Appendix 1 and analyzed in the text of this report were calculated from maximum and minimum diameter measurements obtained with the Pratt and Whitney measuring machine. Product-O-Ron traces were used to monitor deformation patterns such as the multi-lobe pattern of Figure A2-3.

Figure A2-1
Pratt and Whitney Standard Measuring Machine
Used for Diameter Measurements

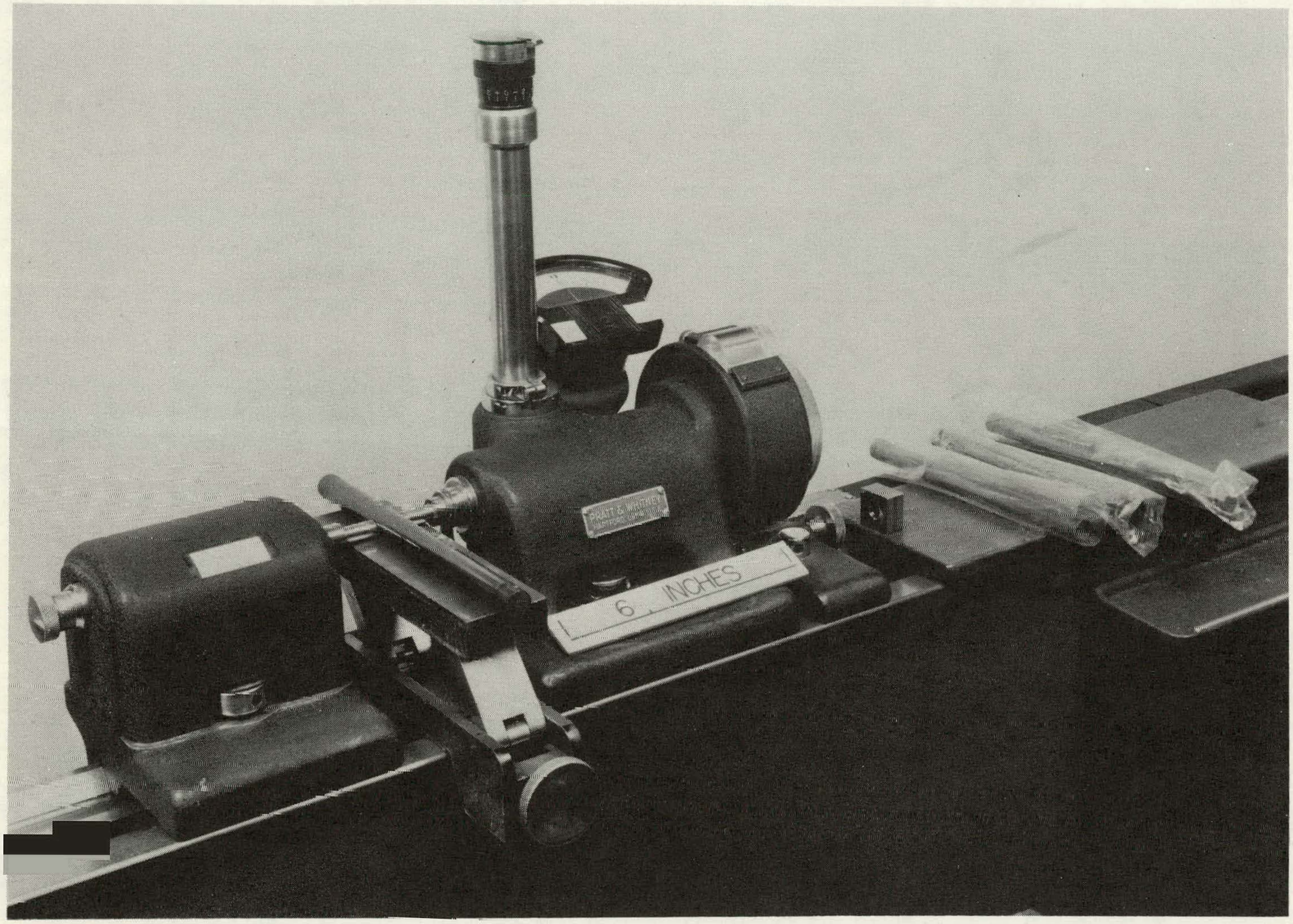


Figure A2-2
Bendix Cleveland Product-O-Ron
Used for Ovality Measurements

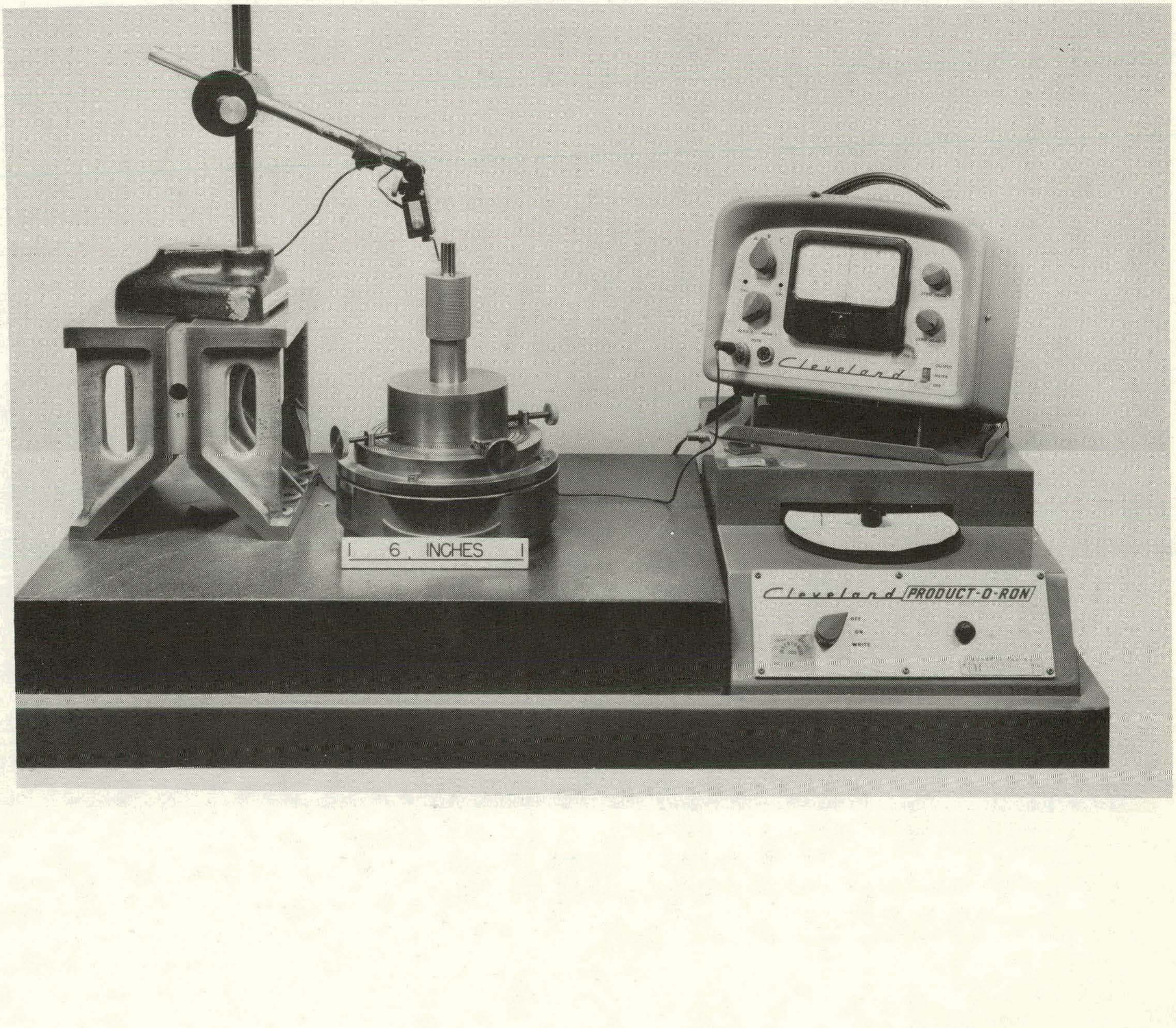
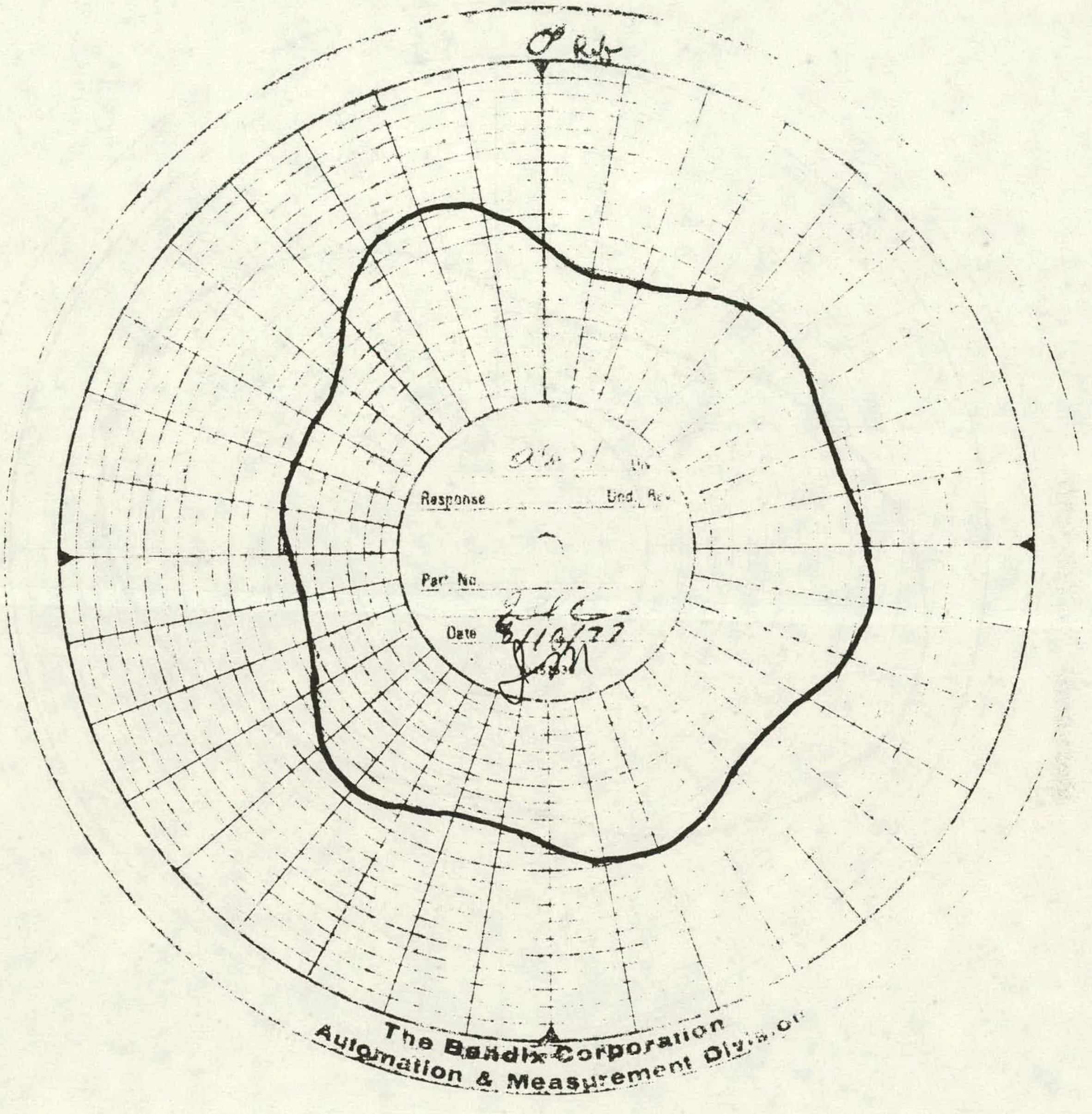


Figure A2-3
Product-O-Ron Ovality Measurement
Example of multilobe distortion pattern

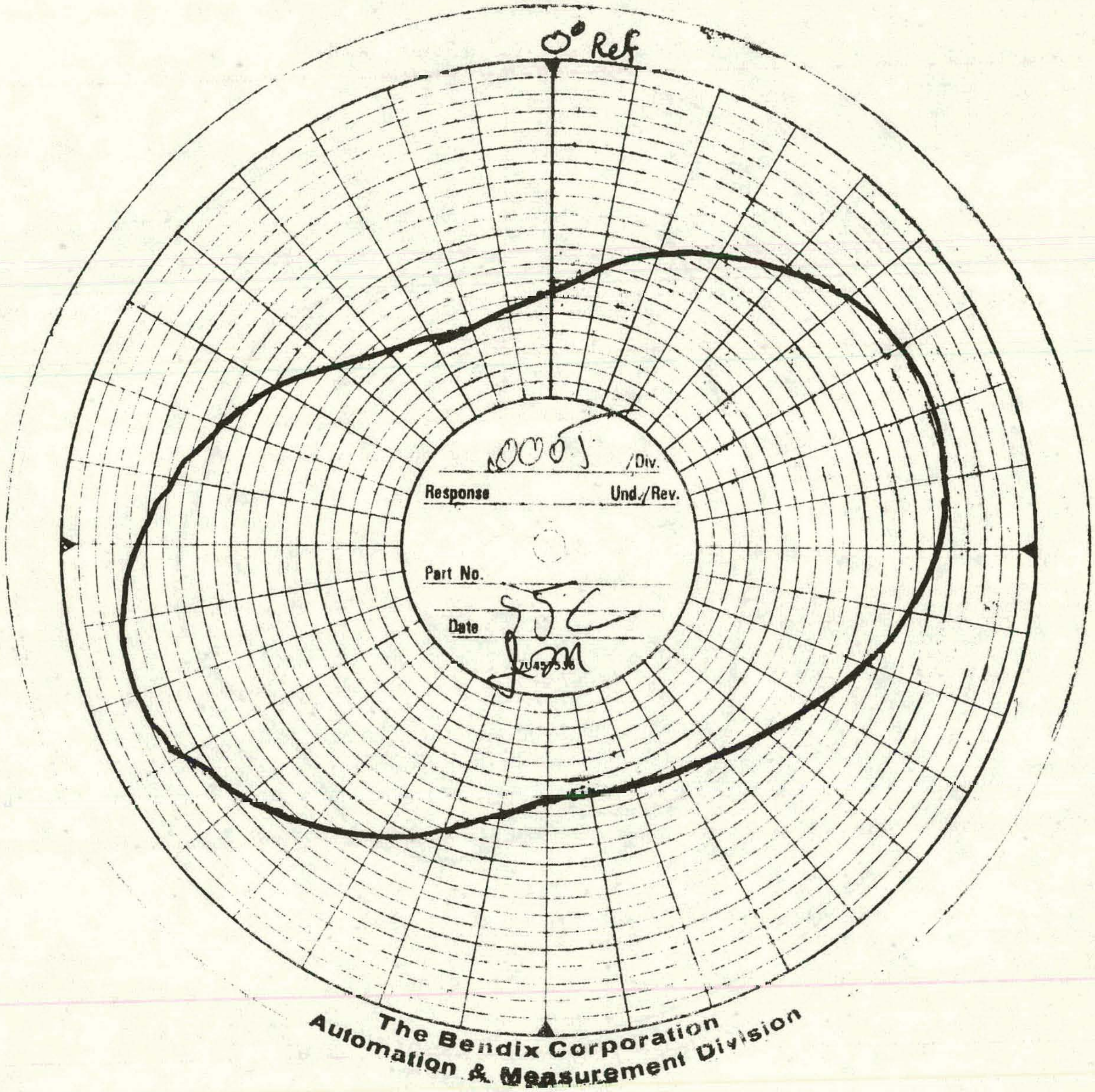


Specimen 4/25, 1.0 inch axial gap
Ovality at end of test (2000 hours) = .0008 inch

Figure A2-4

Product-O-Ron Ovality Measurement

Example of two-lobe distortion pattern



Specimen 3A2/55, 1.65 inch axial gap
Ovality at 2520 hours = 0.0105 inch

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