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Butyl Rubber O-Ring Seals: Revision of Test Procedures for Stockpile Materials

Linda A. Domeier, Kevin R. Wagter

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Sandia National Laboratories
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BUTYL RUBBER O-RING SEALS: REVISION OF TEST PROCEDURES FOR STOCKPILE MATERIALS

Linda A. Domeier and Kevin R. Wagter
Materials Processing Department
Sandia National Laboratories/California

ABSTRACT

Revised test procedures have been defined for butyl rubber O-ring seals which characterize actual O-ring test specimens in place of the test slab specimens now evaluated. This program was initiated by the W87 system group (Org. 2266) due to concern over the extent to which such test slab evaluations reliably assess the quality and performance of O-rings being accepted for W87 warhead use. Butyl rubber O-rings, in particular, provide critical environmental protection from moisture and oxygen for various components in the W87 and other weapon systems. The program also identified an alternative vendor to the current supplier.

Extensive testing showed little correlation between test slab and O-ring performance. New procedures, comparable in ease to those used with the traditional test slabs, were defined for hardness, compression set and tensile property testing on sacrificial O-ring specimens. Changes in the target performance values were made as needed and were, in one case, tightened to reflect the O-ring performance data. An additional study was carried out on O-ring and slab performance vs. cure cycle and showed surprisingly little sensitivity of the material performance to large changes in curing time.

Further aging and spectral characterization of certain materials indicated that two sets of test slabs from the current vendor were accidently made from EPDM rather than butyl rubber. Random testing found no O-rings made from EPDM. As a result of these findings, an additional spectroscopic test will be added to the product acceptance procedures to verify the type of rubber compound used.

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Introduction

Traditional acceptance testing methods for O-rings, within DOE and industry, have often relied on the testing of companion test slabs (typically 6 x 6 x 0.072 in.) rather than testing of the actual O-rings. The test slabs are cut into either discs for hardness and compression set testing or into dog-bone specimens for tensile testing. Concerns have persisted, however, over the extent to which such slab testing reliably assesses the quality and performance of O-rings, often over a wide range of sizes, made from the same batch of rubber.

The W87 group initiated a program in 1994 to investigate the testing of butyl rubber O-ring samples in place of test slab samples, to determine the extent to which O-ring and slab test results correlated, and to define appropriate procedures and target test values for the product acceptance testing of O-ring samples. Butyl rubber O-rings, in particular, provide critical environmental seals within the W87 and other weapon systems. Revised test procedures developed for these particular O-rings should also be applicable to O-ring seals made from other elastomeric materials.

A second goal of the program was to identify alternate vendors whose butyl rubber O-rings would provide performance equivalent to or better than that now provided. The current W87 specification (SS453883 in Appendix D) requires the use of Parker Seals proprietary B612-70 butyl rubber formulation, effectively excluding all other vendors. Difficulties with Parker and the quality of their materials have made it desirable to qualify at least one additional vendor for these seals and to switch the specification to a performance basis rather than one restricted to a specific formulation.

Program Outline

The program involved several stages including

1) a survey of potential vendors to identify those capable of providing suitable materials
2) procurement of O-ring and test slab materials for testing
3) procurement of testing equipment
4) preliminary testing to define procedures, to determine the sensitivity of the test data to various parameters, and to modify the procedures and equipment as needed
5) definition of proposed test procedures and equipment
6) procurement of additional batches of rings and test slabs from the vendors
7) complete testing of multiple batches of materials
8) definition of revised test procedures for incorporation into new material specifications.

A total of 19 vendors (see details in Appendix E) were contacted including the current vendor, Parker Seals. Only two vendors other than Parker were able to supply non-halogenated butyl rubber O-rings in sizes close to those requested. Those vendors were RD Rubber Technology Corp. and Precision Associates. RD Rubber is already a supplier of other O-ring seals to the DOE.

The W87 uses butyl O-rings ranging in size from 0.116 x 0.038 in. to 16.339 x 0.103 in. (inner diameter, ID, of O-ring x cross section, CS, diameter or thickness of rubber cord). Most of the rings are close to one inch in inner diameter with only two significantly larger (details in Appendix D). Four representative sizes, including the two larger sizes, were selected for testing. Vendors other than Parker were allowed to supply O-rings of similar dimensions if custom tooling would be required to produce the exact dimensions requested. Later tests were also conducted on the smallest O-rings currently supplied by Parker (0.116 x 0.038 in.) and on a smaller ring size from RD Rubber. Test slabs were also requested of each vendor and were to be prepared from the same batch of rubber used to fabricate the O-rings. The dimensions of the rings initially obtained from each vendor are shown below.

Parker Seals	RD Rubber	Precision
0.301 x 0.054 in.	0.551 x 0.070 in.	0.301 x 0.054 in.
1.364 x 0.070 in.	1.114 x 0.070 in.	1.364 x 0.070 in.
7.688 x 0.070 in.	7.185 x 0.103 in.	7.739 x 0.070 in.
16.339 x 0.103 in.	11.196 x 0.103 in.	16.995 x 0.139 in.

Existing ASTM methods were identified which describe procedures and equipment broadly suitable for the testing of O-ring samples. Commercial instruments and fixtures for hardness and compression set testing of rings were ordered. Tensile testing equipment was assembled including commercial fixtures as well as Sandia designed fixtures. Details of this equipment are discussed within each test section and vendor information is included in Appendix E.

O-rings of the sizes noted above were procured from each vendor and used in preliminary evaluations of the test equipment and probable test procedures based on the above ASTM procedures and equipment vendor recommendations. The sensitivity of the data to a range of test variables, including different operators, was investigated and appropriate changes in the equipment and procedures were made until robust procedures had been defined. Additional lots of O-rings were then procured from each vendor for additional testing and comparison to the initial results.

The data presented in the following discussions of each test therefore consists of two sets of data from two different lots of each O-ring size. A total of eight lots (4 ring sizes x 2 lots each) were thus evaluated from each vendor. In addition, single lots of two smaller ring sizes were examined, one from Parker and one from RD Rubber, providing a total of nine lots from those vendors. Standard tests were run on companion test slabs made from the same rubber batches, except in those cases where slabs were unavailable, for comparison to the O-ring data.

As a result of these multiple rounds of testing, proposed procedures (Appendices A-C) were developed for hardness, compression set and tensile acceptance testing for a wide range of O-ring sizes. Test values obtained during the program indicated a need to modify the test target values in several cases. No correlation was found throughout the program between test slab results and corresponding O-ring results.

An additional evaluation was carried out in cooperation with one vendor, RD Rubber Technologies, in which O-rings and test slabs were deliberately cured about 3-4 minutes rather than the normal 10 min. Undercuring has been a suspected cause of poorly performing materials and this test series was expected to define the sensitivity of the acceptance tests being used/proposed to such cure deviations. The surprising results showed comparable test behavior for materials cured for reduced periods and cured for the standard period. Subsequent DSC studies indicated that nearly complete cure was obtained with extremely short cure cycles, consistent with comments made by the vendor. While none of the performance tests could reliably distinguish materials processed with such varying cure times, it was, conversely, a desirable feature that O-ring properties appeared to be relatively insensitive to large process variations.

Aging tests being carried out at Allied Signal (Kansas City) on some of the study test slabs suggested unusually good compression aging behavior for a recent butyl rubber batch from Parker Seals. Further analysis on this sample showed, very unexpectedly, that it was prepared from EPDM, not butyl, rubber as ordered and labeled. Random analysis of other samples showed at least one additional Parker test slab to be prepared from EPDM rubber. No O-rings were found to be made from EPDM. As a result of this finding, an additional test is being proposed for the material specification to identify the type of rubber used, butyl vs. EPDM or others.

Current Butyl Rubber Performance Requirements and Tests

Current Kansas City acceptance tests for butyl rubber O-rings, as detailed in Appendix D, call for hardness, compression set and tensile testing of samples cut from test slabs prepared from the same batch of rubber as the O-rings being evaluated. Tests are carried out according to ASTM procedures. The only testing now carried out on the rings is a detailed dimensional and visual inspection per MIL-STD-413 which would be continued regardless of changes made in the physical test procedures.

Table I summarizes the current W87 physical test requirements, methods and samples used for butyl rubber materials. Density testing can be carried out on any suitably sized sample and no test method revisions were required. No measurement of tensile modulus is currently required and the possibility of adding such a requirement was included in the O-ring method development program. Neither are any measurements of oxygen or moisture permeability currently carried out in acceptance testing although experimental studies in this area have been conducted at Sandia, NM by Ken Gillen.

An extensive literature search revealed no systematic comparisons of rubber test methods using test slab vs. O-ring samples. Hardness testing, in general, has been criticized as a measure of material performance whether in rubber materials, polyurethanes or other polymers. Even the ASTM-D2240 method for hardness testing cautions that no simple relationship exists between hardness values and any fundamental rubber property. One paper suggested the use of tensile work (integration under the stress-strain curve) between 0-20% elongation as a useful parameter in elastomeric dog-bone samples and such testing is discussed in a following section.

General methods for testing rubber O-ring samples rather than test slab samples have been published as ASTM-D-1414. These procedures are typically vague and merely suggest the use of suitable O-ring specimens in the existing ASTM procedures listed in Table I. These procedures served as a starting point to evaluate O-ring testing, but did not provide the detailed procedures eventually needed to insure reproducible results. The ASTM-D-1414 recommendations are discussed in the following sections on hardness, compression set and tensile test method development.

Table I. Current Physical Testing Requirements for Butyl Rubber Test Slabs***

Property	Requirement	Test Method	Test Sample
Specific gravity	1.14±0.02	ASTM-D-297 (pycnometer or hydrostatic)	any suitable piece of test slab (or O-ring)
Hardness	65-75 Shore A pts before aging. Maximum change of 10 pts after aging*.	ASTM-D-2240	stack of 4-7 discs (1 in. diameter) cut from test slab or dog-bone end tabs)
Compression set**	15% maximum after aging 22 hours at 158 hours under 25% compression.	ASTM-D-395 Method B	stack of 4-5 discs (1 in. diameter) cut from test slab
Tensile strength	1600 psi minimum before aging. Maximum ±15% change after aging*.	ASTM-D-412	dog-bone samples cut from test slab
Tensile elongation	200% minimum before aging. Maximum ±15% change after aging*.	ASTM-D-412	dog-bone samples cut from test slab

* Hardness and tensile aging conditions: 70 hours at 212°F.

** 15% compression set maximum corresponds to a maximum reduction in original thickness of 15% x 25% = 3.75%.

*** Test slab dimensions were typically 6 in. x 6 in. with thickness ranging from about 0.077 to 0.100 inches.

O-Ring Hardness Testing (Additional tables and plots in Appendix F)

The blunt, heavily weighted Shore A durometers used to measure hardness on quarter inch stacks of discs cut from test slabs, as noted in ASTM-D-1414, are unsuitable for testing of O-rings. Shore (now a division of Instron) sells a micro-indentor and durometer, the Shore M, specifically for O-ring testing. This durometer is mounted on a hydraulic stand with holding fixtures to position the O-rings, features recommended by ASTM. Both dial and slightly more expensive digital models are available. The micro-indentors, unlike the blunt Shore A probes, actually puncture the O-ring with a needle surrounded by a collar which rests on the O-ring surface. The Shore M durometer is not identical in operation to that currently specified in ASTM-D-1414 and Shore is apparently working on a revision of that specification. Zwick, a German manufacturer, offers a durometer said to conform exactly to the ASTM standard. Difficulties in even obtaining information from Zwick, however, led to the early selection of Shore M durometers which are already widely recognized and used.

In comparing Shore A tests on stacked discs to Shore M tests on O-rings (see Table 2), there is a shift of approximately 5 hardness points. Slabs giving Shore A hardness values of 65-75 are prepared from the same rubber batch as O-rings giving Shore M hardness values of 70-85. Direct comparisons between the Shore A and M durometers (Table F-8 in the Appendix) on similar samples (flat calibration blocks and test slabs) did not show this large shift, indicating good correlation between the two durometer types, and suggest that most of the difference is due to the change in sample geometry (thickness and curvature) and possibly differences in the degree of cure. Later studies on variably cured samples showed little correlation of hardness with cure time and point to the change in sample geometry as the key factor.

In the direct comparisons of Shore A and M dial-type durometers on flat blocks and slabs, it was also found that Shore M durometers were much less sensitive to either changes in sample thickness or the time delay between durometer impact and hardness reading (Table F-8). Shore M digital durometers, unlike the dial durometers, are designed to automatically take a reading one second after impact and eliminate any operator influence on the time from impact to reading. The heavier weight (1 Kg) used with Shore A durometers would account for the greater sensitivity of Shore A readings to sample thickness and time delay. As discussed below, there were small changes noted in Shore M hardness values when two stacked O-rings were compared to single O-ring samples.

Initial O-ring tests utilized a dial durometer (Shore Model 714) mounted on a hydraulic stand. This was eventually replaced with an automated digital durometer (Shore Model 2000, see Fig. 1) to increase resolution (from 0.5 to 0.1 pts) and to eliminate operator variables such as reading time after contact and dial position judgments. The hydraulic stand eliminates operator differences in lowering the durometer and impacting the O-rings and also insures correct positioning of the ring so that it is impacted near its midpoint. It was important to exercise the hydraulic stand about ten times immediately before taking a series of readings to insure reproducible operation and hardness values. The platform area of the hydraulic stand can readily support smaller O-rings but left the larger 7 and 16 inch rings drooping over the edges. Difficulties in reproducibly positioning these rings for measurement led to the use of an adjacent "Lab-Jack" stand covered with cardboard which allowed the larger rings to lay flat while being rotated through the double pin fixtures for measurement.

A series of double pin inserts were ordered to accommodate different ring thicknesses and these are easily interchanged according to the ring size being measured. Taller double pin inserts capable of holding two stacked O-rings are also available and suggested by ASTM-D-1414. As shown in Table F-5 in Appendix F, there was a reduction of about 2 hardness points, slightly less for the thinner rings, when a double ring rather than single ring sample was used. This difference was not significant enough to preclude adjusting the target values for ring hardness testing and also required far more care in positioning the samples for measurement. The increased difficulty of using two rings outweighed any partial benefits in matching Shore A and Shore M measurements and a single ring procedure was selected. This slight sensitivity of Shore M hardness values to sample thickness was later seen during the testing of large numbers of single O-rings of varying thickness. A drop in hardness of 2-3 points was noted at higher thickness although the drop was neither large enough or consistent enough to warrant any change in hardness target values with different O-ring thicknesses.

Table 2 and Plot 1 summarize the hardness data obtained on a series of O-ring (Shore M) and test slab (Shore A) lots obtained from the three vendors. Test slabs generally fell near the target of 65-75 points while ring samples made from the same rubber batches gave values of 70-85. As noted above, this higher range is attributed primarily to the change in sample geometry from flat discs to ring cross sections. There was no noticeable correlation of test slab data and O-ring data made from the same batch of rubber. RD Rubber materials gave slightly lower hardness values than Parker and Precision, even after aging. Tables F-1 and F-9 through F-15 provide more detailed data on the Table 2 tests.

The sampling scheme used for this study was generally 2 points each on 5 separate rings (10 data points total) for smaller O-rings and 8 points each on 3 separate rings (24 data points) for the larger rings having inner diameters of about 7 and 16 inches. The same rings and sampling rates were used before and after aging although the measurement sites were offset to avoid re-puncturing of the ring. While the data reported here for the larger rings utilized 8 measurements per ring on 3 rings before and after aging, analysis of that data indicated that 4 measurements per ring on 3 rings provided equivalent precision. Table F-2 and Plots F-3 and F-4 in Appendix F show that no loss of precision was incurred by reducing the number of measurement points while clearly reducing the time required.

Using the current slab hardness criteria of 65-75 Shore A points, Sandia tests would have rejected one RD Rubber slab lot as too low (14810). The proposed ring criteria of 70-85 Shore M points would have rejected no O-ring lots. A tighter 70-80 ring criteria would have rejected 3 Parker ring lots.

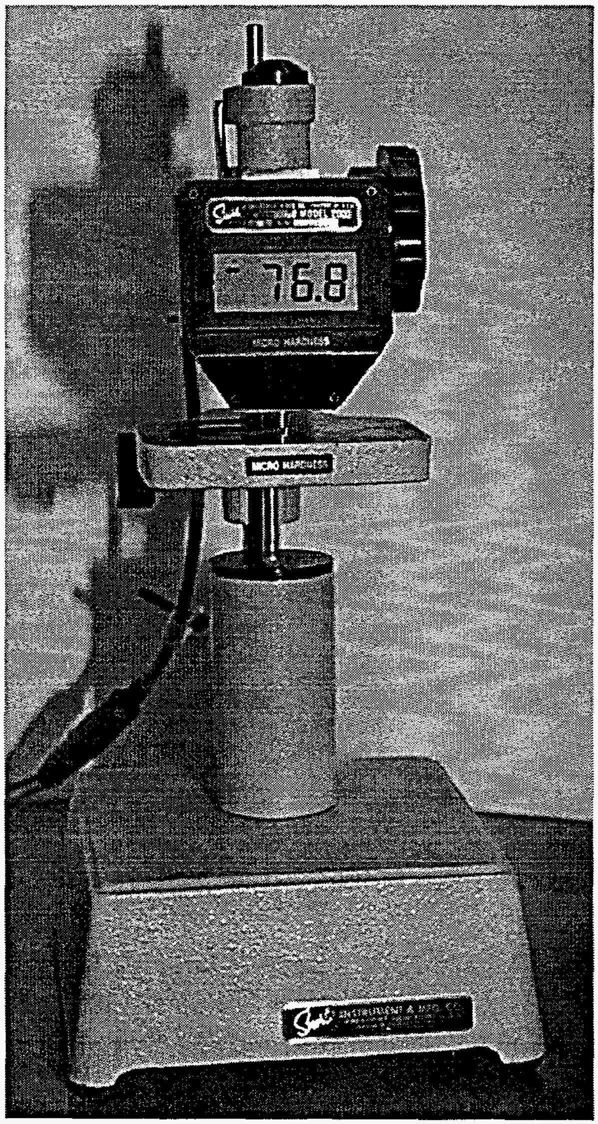
With one exception, all the materials gave higher hardness values after aging. Both the ring and slab samples generally showed a much smaller increase than the currently allowed 10 point variation. As discussed in the section on curing studies, there appeared to be a greater hardness change in less cured materials. A reduction of the allowed hardness change on aging from 10 points to 4 points would therefore help screen out undercured rings while having little total effect on the acceptance rate. Such a reduced aging variation should help insure somewhat greater uniformity in the rings being accepted.

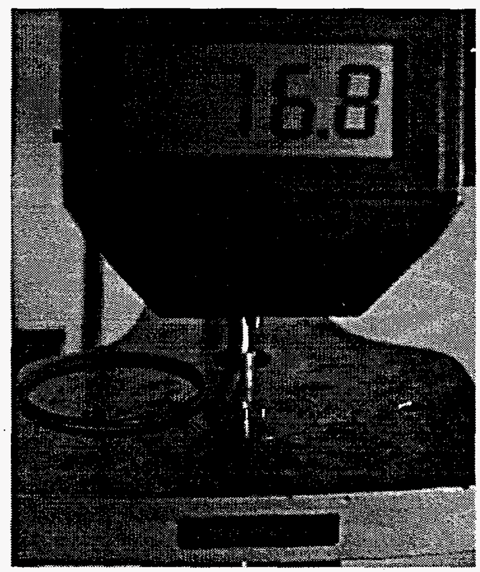
A recognized contributor to uncertainty in hardness values is calibration of the individual durometers, a problem which has previously resulted in round-robin testing of Shore A durometers using test slab discs. Calibration by Shore of the durometers is stated to assure only that the durometer will measure within ±3 pts of the stated values on calibration blocks supplied by Shore. Round-robin testing amongst three Shore M digital durometers (two at Sandia, CA and one at Kansas City) showed surprisingly good agreement, only a 1-2 point spread, with one of the Sandia durometers consistently giving the highest value and the KC durometer the lowest value. The only exception was noted in tests on a large O-ring. An assortment of standard blocks and O-rings was also evaluated as shown in Table F-7. While the agreement found here was quite acceptable, the stated precision of the durometers suggests that an overly rigid specification on O-ring hardness would probably result in unnecessarily low acceptance rates. The recommended hardness target for O-rings is therefore a 15 point range (70-85) instead of the 10 point range (65-75) now used with the test slabs. The allowed change on aging, however, would be reduced from 10 to 4 points as discussed above.

In a related study, the same Shore M dial and digital durometers were used by three different operators to measure the hardness of a set of O-rings. Measurement sites were systematically offset to avoid repuncture while still measuring in similar ring areas. Table F-6 shows some variation with operator, giving up to a 2 point spread in average value per ring. Uncontrolled sources of variation during this series included the ambient temperature and whether the hydraulic stand was properly "exercised" prior to taking readings. Generally good agreement was obtained even with the dial durometer although the digital version was clearly easier to use and provided higher precision.

The recommended procedure for hardness testing of O-rings is described in Appendix A and the recommended test values are summarized along with the other test changes in Table 12.

Figure 1. Shore M (Model 2000) Hardness testing apparatus with digital durometer, hydraulic stand and interchangeable double-pin inserts to position the O-rings.



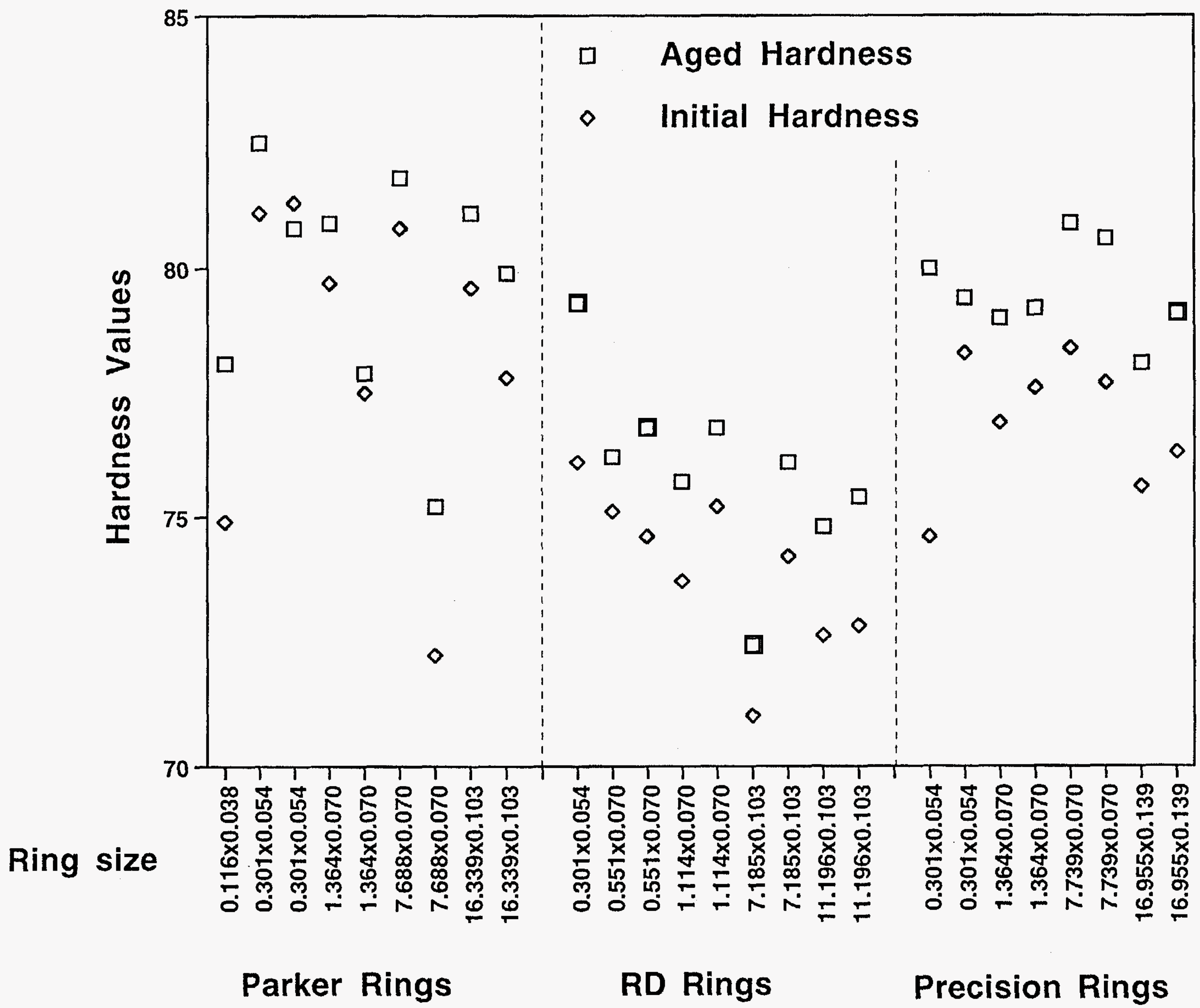


O-ring is removed from double pin holder for viewing. Pins are spaced to correspond to the cross section of the O-ring being tested.

Table 2. Hardness Data: Slabs and O-Rings

Vendor	Rubber Batch	± Aging	Test Slab Data			O-Ring Data (Standard Deviations from ±0.3 to ±1.8, avg. ±0.7)				
			Vendor	KCP	Sandia	0.116x0.038	0.301x0.054	1.364x0.070	7.688x0.070	16.339x0.103
Parker	316104	unaged	72, 75	65	72.3		81.1	79.7	80.8	79.6
		aged		65	74.5		82.5	80.9	81.8	81.1
Parker	316710	unaged	72		69.0		81.3			77.8
		aged			70.3		80.8			79.9
Parker	317403	unaged	70		72.8			77.5		
		aged			75.8			77.9		
Parker	317851	unaged	67, 69	73	73.0				72.2	
		aged		73	73.3				75.3	
Parker	318466	unaged			72.8	74.9				
		aged			74.0	78.1				
						0.301x0.054	0.551x0.070	1.114x0.70	7.185x0.103	11.196x0.103
RD	14810	unaged	65, 65	64	63.3		75.1	73.7	71.0	
		aged			68.5		76.2	75.7	72.4	
RD	14936	unaged	66, 66	68	NA					72.6
		aged								74.8
RD	15107	unaged	70		65.5	76.1	74.6	75.2	74.2	72.8
		aged			64.8	79.3	76.8	76.8	76.1	75.4
							0.301x0.054	1.364x0.070	7.739x0.070	16.955x0.139
Precision	17405	unaged	NA		NA			76.9		
		aged						79.0		
Precision	19052	unaged	NA		72.8		74.6		78.4	
		aged			74.8		80.0		80.9	
Precision	19422	unaged	NA		NA					75.6
		aged								78.1
Precision	19895	unaged	73		71.5		78.3	77.6	77.7	76.3
		aged			75.5		79.4	79.2	80.6	79.1
Precision	19921	unaged	73		NA					
		aged								

Plot 1. Hardness Values of Aged and Unaged O-Ring Samples



O-Ring Compression Set Testing (Additional tables and plots in Appendix G)

Compression set testing is probably the most important performance test carried out on O-ring sealant materials as it most closely approximates real performance requirements. The major challenge faced in compression set testing of O-rings vs. much thicker stacks of test slab discs was the higher precision needed in initial and final thickness measurements. The current specification calls for a 15% maximum compression set after aging under 25% compression. This translates to an overall loss of thickness of 15% x 25% or 3.75% of the initial thickness. For ring thicknesses as low as 0.038 inches, the corresponding maximum thickness loss would be 0.0014 inches. Additional challenges were posed by the non-uniformity of thickness around typical rings and the need, therefore, to insure that the same cross section location, both around and through the ring, was being measured before and after aging.

The dial or spring micrometers specified in D-1414 were found to provide inadequate resolution and a laser micrometer, similar to one already used at Kansas City, was acquired. Both the precision and ease of operation were improved with the laser micrometer which is shown in Figure 2. Laser micrometers provide resolution of ±0.00001 inches, ten times that of the Shore micrometers, and the level of operator skill required was significantly reduced. Samples are simply placed on the fixture and the thickness measurement recorded.

The compression set aging apparatus, available from at least two vendors, is simply a set of chrome plated steel plates which are bolted together (see Fig. 2). The distance between the plates is fixed by using spacers of the desired thickness. The same apparatus used to compress the stacks of test slab discs is suitable for the O-ring samples and simply requires the use of thinner spacers. Compression tests typically call for the sample to be compressed 25% (i.e. to 75% of its initial thickness). Spacers were ordered corresponding to 75% of each of the ring thicknesses to be evaluated and samples were compressed to 75% of their nominal thickness. No adjustments were made for variations from this nominal thickness as is done with the thicker stacks of discs.

Slices about 2 in. long from larger O-rings are suggested in ASTM-D-1414 as samples. Shorter segments, with less curvature, tended to roll more easily and were difficult to position reproducibly with exactly the same ring cross-section exposed for measurement and compression. For smaller rings it is suggested in ASTM-D-1414 that a 1/8 in. section be removed and the remainder of the ring used as a sample. D-1414 strongly recommends that whole O-rings not be used as samples due to trapped air and potentially different aging conditions on the inside of the ring. It was found convenient in the Sandia tests to simply slice smaller O-rings into halves, each of which could be used as a sample in the compression set test. Ring segments were conveniently marked on their outside circumference with dots of ordinary white correction fluid to allow measurement of the same cross section location before and after aging. This can be seen in the detail in Fig. 2.

Early testing pointed out the need for careful removal of the ring segments from the compression apparatus. Segments needed to be gently scraped from the metal surface using a sheet of paper or similar "blade" so as to avoid any peeling or stretching of the segment. Mold release on the metal surface assisted this process, especially on poorly plated or degraded surfaces.

Laser micrometer measurements were carried out to determine the rate at which compression set aged samples rebounded and whether the 30 minute delay currently specified between sample removal from the hot apparatus and thickness measurement was critical in any way. Ring segments were removed from the apparatus, immediately placed in the laser micrometer fixture, and analyzed for height vs. time. Cooling effects, leading to contraction, compete with rebound expansion during the initial measurements, especially in the larger rings. Plot G-6 in the Appendix shows the overall thickness recovery rate in the laser micrometer for two ring sizes. In both cases the data indicates that the 30 minute waiting period is adequate to reach a relatively stable thickness. Most of the rebound is virtually instantaneous and shorter or longer waiting periods, for example 20 min. to 40 min., would have no significant effect on the results. The recommended 30 min. waiting period should be adhered to as closely as possible, especially with thicker ring sizes, to insure good reproducibility.

Table 3 and Plot 2 summarize the compression set data obtained on a series of O-ring and test slab lots obtained from the three vendors. Ring samples, in general, showed significantly lower compression set values (5-12%) than the stacks of discs (6-20%). There was again no correlation of ring and test slab data and there was no consistent trend of compression set with ring thickness. Precision rings and slabs showed higher compression set than Parker or RD Rubber materials. The compression set values on their test slabs were well above the current 15% allowed and would have been cause for rejection.

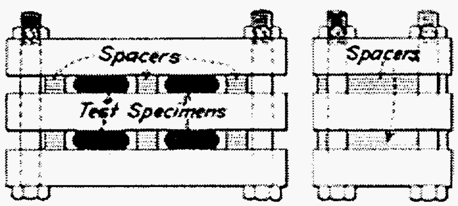
As a result of this testing it was decided that the allowable compression set, measured on ring samples in place of disc stacks, could be reduced from 15% to 10% with no significant decrease in acceptance rate. The lower allowed value should ensure greater uniformity in the rings accepted and perhaps better long term performance as well. Using this 10% maximum compression set criteria and rounding the hardness data to the nearest whole integer would have rejected 1 of the Parker ring lots, none of the RD ring lots, and 5 of the Precision ring lots.

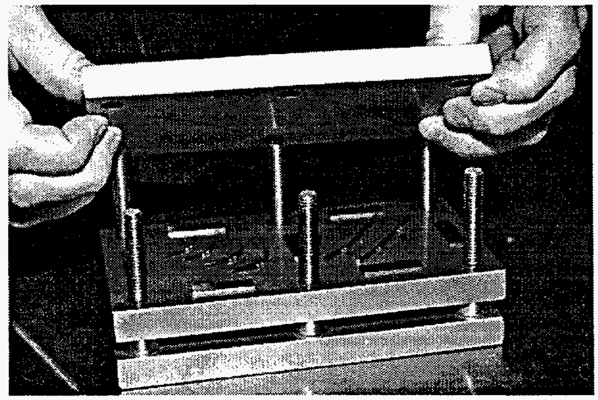
Even with the more precise laser micrometer, there was concern over the magnitude of the standard deviation values relative to the actual change in thickness being measured. Table G-1 summarizes the standard deviations typically observed and also the change in thickness observed after compression set aging. The ring samples show an average change in thickness which is roughly 2-3 times the average standard deviation of the thicknesses being measured. This largely reflects the non-uniform thickness of the original rings and would not be improved by a more precise measuring instrument. Given that the ring samples, although non-uniform, are at least being measured in the same locations before and after, this is probably an acceptable situation and one which is inherent to testing real ring samples.

The sampling scheme used in these tests was, as in the hardness tests, generally 2 points each on 5 separate rings (10 data points total) for smaller O-rings and 8 points each on 3 separate rings (24 data points) for the larger rings having inner diameters of about 7 and 16 inches. The same rings and the same thickness measurement sites were used before and after compression aging. This is detailed in the procedure in Appendix B. While the data reported here for the larger rings utilized 8 thickness measurements per ring on 3 rings (24 data points) before and after aging, analysis of that data again indicated that the use of 4 measurements per ring provided equivalent precision. Table F-2 and Plots G-1 and G-2 in the appendices show that no loss of precision was incurred by reducing the number of measurement points while clearly reducing the time required.

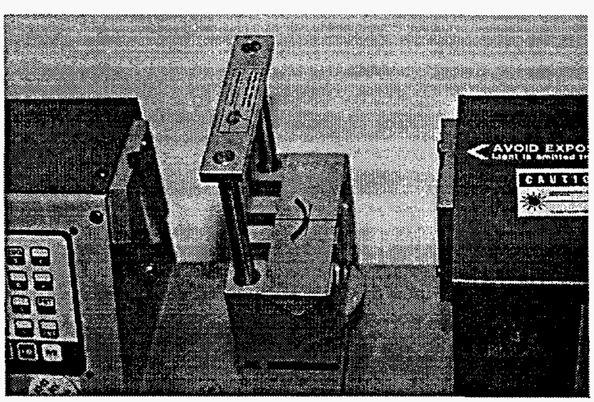
The recommended procedure for compression set testing of O-rings is described in Appendix B and the recommended test values are summarized along with the other test changes in Table 12.

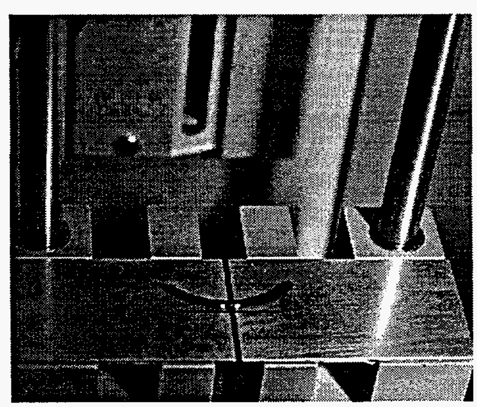
Figure 2. Compression set apparatus and laser micrometer used for thickness measurements.





Compression set apparatus with spacers and O-rings.



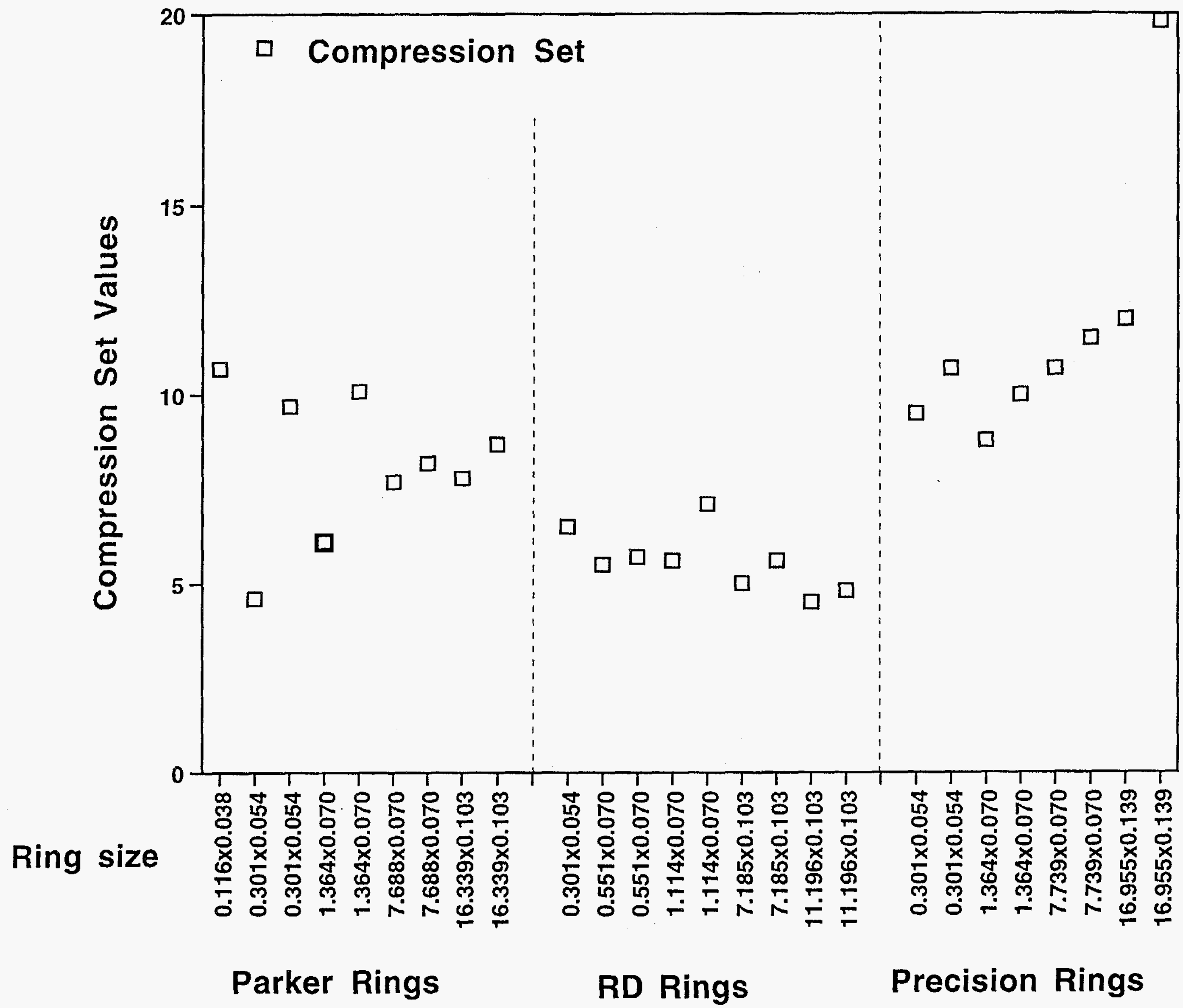


Laser micrometer (Model 183) with fixture insert and O-ring marked and positioned for thickness measurement.

Table 3. Compression Set Data: Slabs and O-Rings

Vendor	Rubber Batch	Test Slab Data			O-Ring Data				
		Vendor	KCP	Sandia	0.116x0.038	0.301x0.054	1.364x0.070	7.688x0.070	16.339x0.103
Parker	316104	11.0	14.5	11.0		4.6	6.1	7.7	7.8
Parker	316710			9.9		9.7			8.7
Parker	317403			10.4			10.1		
Parker	317851	10.0	9.8	15.9				8.2	
Parker	318466			18.9	10.7				
					0.301x0.054	0.551x0.070	1.114x0.70	7.185x0.103	11.196x0.103
RD	14810	7.0	6.3	5.9		5.5	5.6	5.0	
RD	14936	6.3	8.7	NA					4.5
RD	15107	10.5		12.6	6.5	5.7	7.1	5.6	4.8
						0.301x0.054	1.364x0.070	7.739x0.070	16.955x0.139
Precision	17405	NA		NA			8.8		
Precision	19052	NA		24.0		9.5		10.7	
Precision	19422	NA		NA					12.0
Precision	19895	14.3		22.8		10.7	10.0	11.5	19.8
Precision	19921	22.2		NA					

Plot 2. Compression Set Values of O-Ring Samples



O-Ring Tensile Strength and Elongation Testing (Additional tables and plots in Appendix H)

ASTM-D-1414 recommends the use of whole O-rings for ring tensile testing along with the use of rotating ball-bearing spools and lubrication to minimize local stresses. A crosshead speed of 20 in./min. is suggested. All tests in this program were carried out on whole O-rings to avoid the inherent fixturing and stress localization problems associated with ring segment samples.

When the effects of such variables as fixture rotation, lubrication, multiple looping of larger rings, and test speed were evaluated there was little variation noted with any of these parameters. Table H-1 summarizes these early results. As part of this initial evaluation, a very simple set of grooved, split-spool fixtures was designed and fabricated. These non-rotating fixtures are shown in Fig. 3 and the design drawings are included in Appendix L. The interchangeable spools of different diameters can readily accommodate a wide range of O-ring sizes and were particularly suited for testing the very small rings typical of many W87 parts. Rod fixtures with optional rotation were obtained commercially. No significant differences in test values were noted among the three types of fixtures. While lubrication is still recommended and was used throughout this program, no significant effects were noted when it was not used with any of the fixture types evaluated. Similarly, no effects were noted when rings were fixtured with either 1, 2 or 3 loops. These initial looping tests utilized a rotating fixture. The non-rotating fixtures are probably more suitable for multi-looped rings as there is no potential interaction of the cross-over sites with the fixture.

Following these initial tests, the very simple, non-rotating split-spool fixtures in Fig. 3 were selected for further O-ring tensile testing. Similar fixtures can be fabricated and supplied to vendors and a set has already been provided to Kansas City. O-rings are simply slipped over the grooved top and bottom fixtures, the fixture gap is adjusted according to the O-ring and spool sizes to set the zero elongation point, and the ring is then stretched to failure. Tables in the proposed method in Appendix C detail the spool diameter to be used with each ring size and provide starting crosshead distances for the O-ring sizes used in the W87. Extensometers were not used and sample elongations were calculated from crosshead distances.

Test speeds in the initial studies above were varied between 10 and 20 in./min. and showed little effect on the data. Most of the data acquired during the program was taken at 20 in./min. as recommended by ASTM. A more detailed study of test speed effects was carried out near the end of the program and was motivated by potential difficulties noted in measuring modulus on smaller O-rings. At 20 in./min. these rings are stretched and broken very quickly, sometimes within seconds. That evaluation of test speed is discussed in a following section, but Plots H-2 and H-3 illustrate the effects on tensile strength and elongation when test speeds were varied over a wider range. Strength increased about 10-20% over the 5-20 in./min. range while elongation was essentially unaffected.

Test speeds eventually recommended for ring acceptance testing were 5 in./min. for all the smaller W87 rings and 20 in./min. for the two larger rings with inner diameters of about 7 and 16 inches. This should increase the precision of the tests and also allow the use of strip chart recorders in place of computerized data systems if desired. All rings were also tested with only one loop except for the two larger rings which were tested with a triple loop. No rings were double looped.

Tables 4 and 5 and Plots 3 and 4 summarize the tensile strength and elongation data obtained on a series of O-ring and test slab lot obtained from the three vendors. Unlike the hardness and compression set results, there was a clear correlation of tensile strength and elongation with ring size. The lower strength and elongation seen in larger rings may simply reflect a higher number of potential defects with increasing volume as suggested in "Rubber Technology Handbook", W. Hofmann (Hanser Publishers, 1989). This variation with ring size led to wide overall ranges in both tensile strength (1100-2500 psi) and elongation (170-400%). A range of tensile strength (1450-2300 psi) and elongation (150-250%) were also noted for the test slab data, however, which was all gathered on samples with identical dimensions. There was again no significant correlation of slab and ring data from the same rubber batches. Slabs were cut with a stencil into dog-bone specimens, five per slab, for testing.

Both the initial strength and elongation decreased as ring size increased. A graduated range of minimal strength and elongation target values will therefore be required for ring testing in place of the single values now used with the test slabs. Final decisions on these targets will be made after additional testing at Kansas City, but a preliminary set of tensile strength and elongation requirements are shown in Table 6. As future tests on all but the larger rings will be carried out at 5 in./min. instead of the 20 in./min. used in this study, the strength and elongation values on smaller rings are expected to decrease slightly and the values shown in Table 6 were selected with that in mind.

Using the current slab criteria, the Sandia tests would have failed all the Parker slab lots (either for strength or elongation or both) and none of the RD Rubber or Precision slabs. Kansas City tests on the slabs, where available, were all passing. Using the proposed ring criteria in Table 6, the Sandia tests would have failed 1 of the Parker ring lots (for strength), none of the RD Rubber ring lots, and 1 of the Precision lots (for strength). Strength values obtained at slower speeds may be 10-20% lower and would increase the rejection rate, particularly of some of the Parker materials.

Aging of the samples gave roughly equal increases and decreases in tensile strength. Elongation decreased with aging in about 2/3 of the tests. The allowable ±15% percent change on aging, particularly of elongation, would have eliminated all but one lot of the O-rings received from Precision. All the Parker rings and all but one of the RD Rubber lots were within this 15% change on aging, however. No modification in the current aging specification appeared to be warranted.

Most of the tensile tests in this study utilized 8 rings for the initial properties and another 8 rings for the aged properties. Smaller numbers were used in some cases due to limited availability. A more convenient sample size for future acceptance testing would be 5 rings each before and after aging.

Based on discussions with the Kansas City personnel, it was decided that tensile testing on aged samples would probably not be required for acceptance of every O-ring lot received. Complete tensile testing (aged and unaged samples) would instead be required as a vendor qualification test on a regular interval to be decided. Factors in this decision were the absence of significant tensile stresses on the O-rings as used in compression and the large number of rings required for tensile testing.

The recommended procedure for tensile testing of O-rings is described in Appendix C and the recommended test values are summarized along with the other test changes in Table 12.

Figure 3. Insert mount and split-spool, interchangeable fixtures for O-ring tensile testing. Insert and split spools fabricated according to Sandia drawings.

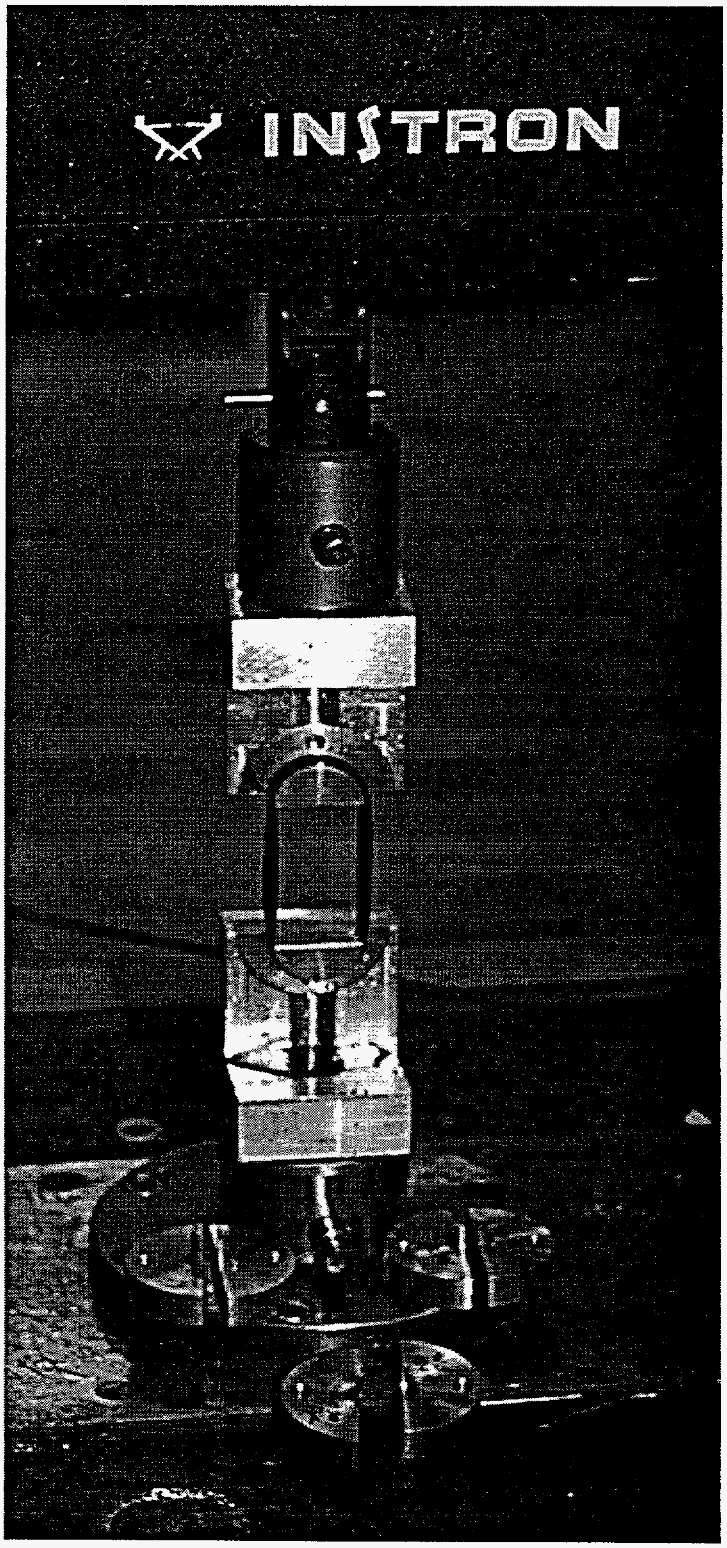


Table 4. Tensile Strength Data: Slabs and O-Rings

Vendor	Rubber Batch	± Aging	Test Slab Data			O-Ring Data (Standard Deviations from 38 to 517, avg. 241)				
			Vendor	KCP	Sandia	0.116x0.038	0.301x0.054	1.364x0.070	7.688x0.070	16.339x0.103
Parker	316104	unaged	1777, 1892	1742	1563		1959	1591	1447	1309
		aged			1458		1964	1573	1561	1430
Parker	316710	unaged	1721		2503		2015			1294
		aged			2282		2032			1430
Parker	317403	unaged	1942		1590			1790		
		aged			1764			1708		
Parker	317851	unaged	1762, 1914	1832	2530				1469	
		aged			1940				1671	
Parker	318466	unaged			1459	1891				
		aged			1630	1823				
						0.301x0.054	0.551x0.070	1.114x0.70	7.185x0.103	11.196x0.103
RD	14810	unaged	2176, 2176	2418	2218		2524	2142	1734	
		aged			2170		2414	2063	1782	
RD	14936	unaged	2321, 2321	2403	NA					1334
		aged			NA					1458
RD	15107	unaged	2121		2123	2237	1965	2039	1579	1436
		aged			2010	2423	1864	2153	1255	1396
							0.301x0.054	1.364x0.070	7.739x0.070	16.955x0.139
Precision	17405	unaged	NA		NA			2078		
		aged			NA			1971		
Precision	19052	unaged	NA		1711		2218		1578	
		aged			1696		2162		1653	
Precision	19422	unaged	NA		NA					1129
		aged			NA					832
Precision	19895	unaged	2030		1657		2233	1935		1315
		aged			1565		2138	1937		1379
Precision	19921	unaged	2032		NA				1496	
		aged			NA				1616	

Plot 3. Tensile Strength of Aged and Unaged O-Ring Samples

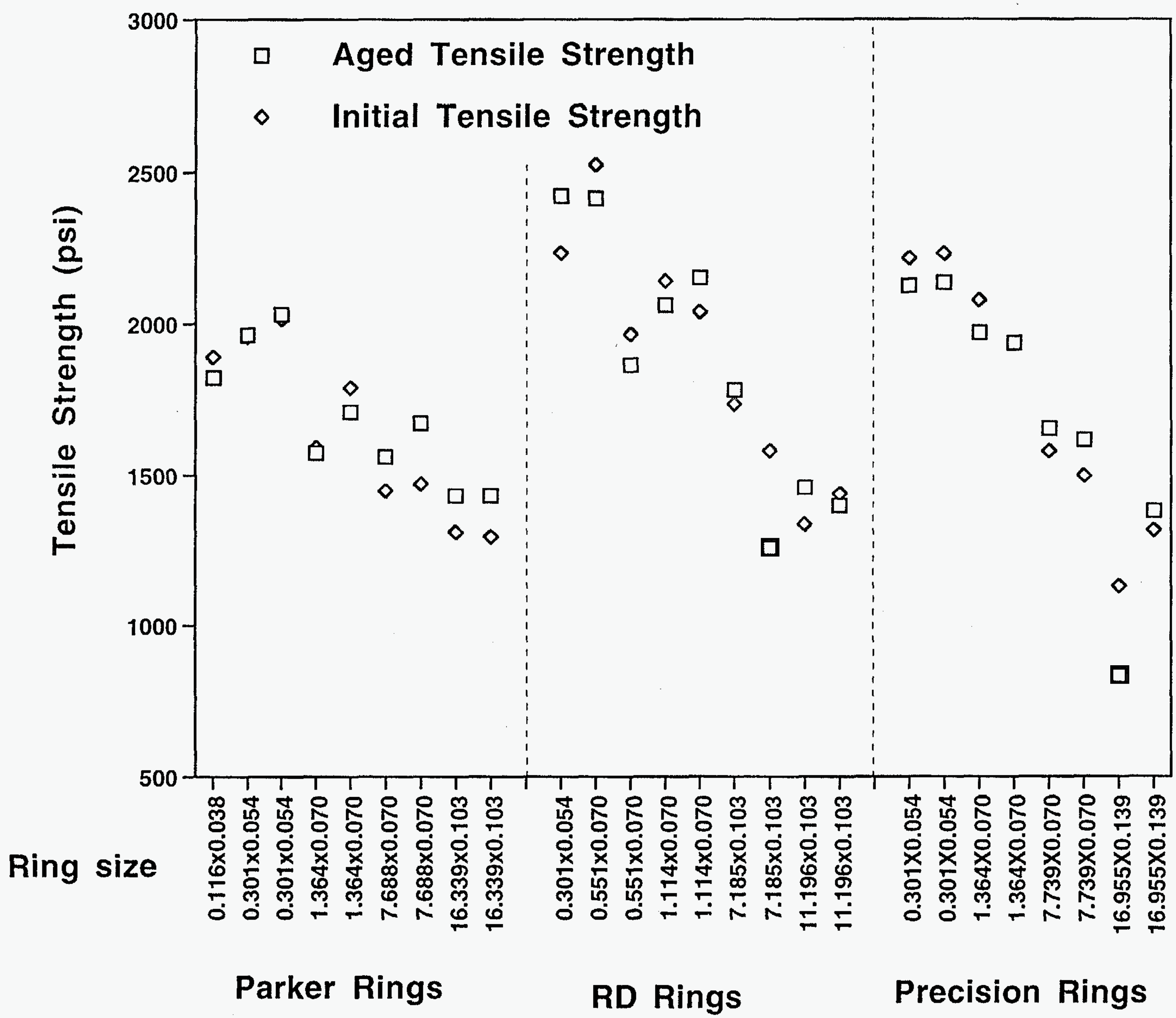


Table 5. Tensile Elongation Data: Slabs and O-Rings

Vendor	Rubber Batch	± Aging	Test Slab Data			O-Ring Data (Standard Deviations from 4 to 85, avg. 30%)				
			Vendor	KCP	Sandia	0.116x0.038	0.301x0.054	1.364x0.070	7.688x0.070	16.339x0.103
Parker	316104	unaged	215, 239	290	199		259	209	178	168
		aged			166		261	210	188	177
Parker	316710	unaged	233, 264	260	186		272			188
		aged			172		271			203
Parker	317403	unaged	286		221			281		
		aged			221			269		
Parker	317851	unaged	421?		178				362	
		aged			152				341	
Parker	318466	unaged			535	278				
		aged			588	264				
						0.301x0.054	0.551x0.070	1.114x0.70	7.185x0.103	11.196x0.103
RD	14810	unaged	372, 372	300	273		402	314	231	
		aged			247		344	293	220	
RD	14936	unaged	273, 273	230	NA					180
		aged			NA					184
RD	15107	unaged	320		243	308	293	296	215	175
		aged			220	303	261	300	171	152
							0.301x0.054	1.364x0.070	7.739x0.070	16.955x0.139
Precision	17405	unaged	NA		NA			313		
		aged			NA			261		
Precision	19052	unaged	NA		276		380		192	
		aged			208		300		152	
Precision	19422	unaged	NA		NA					188
		aged			NA					114
Precision	19895	unaged	312		229		369	275		223
		aged			197		289	247		179
Precision	19921	unaged	311		NA				226	
		aged			NA				181	

Plot 4. Tensile Elongation of Aged and Unaged O-Ring Samples

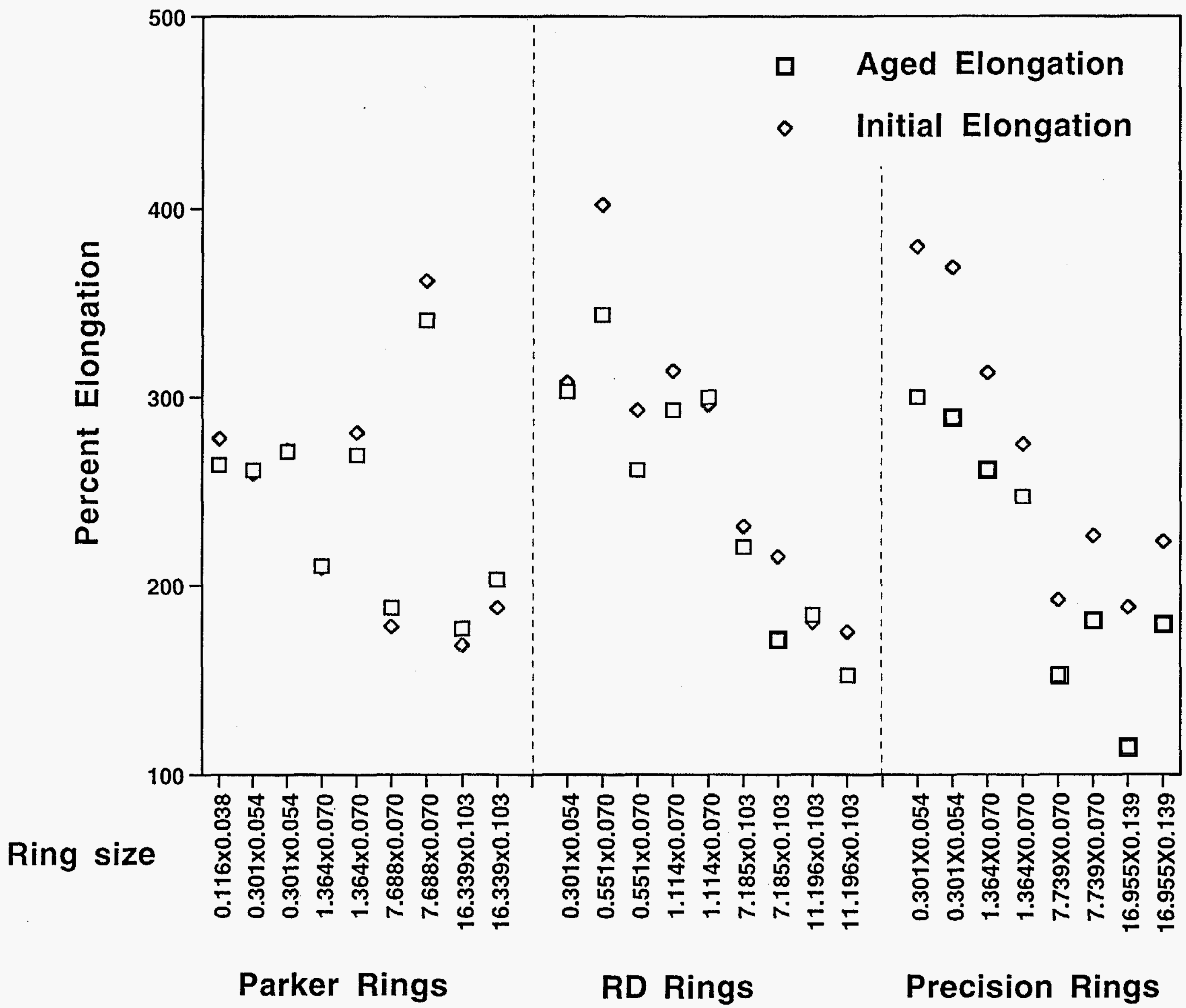


Table 6. Preliminary Tensile Strength and Elongation Requirements for O-Ring Testing

Ring size	Initial Tensile Strength Minimum Value	Initial Tensile Elongation Minimum Value
less than 0.5 inch inner diameter and less than 0.060 inch cross section	1800 psi	225%
between 0.5 and 2 .0 inch inner diameter and over 0.06 inch cross section	1600 psi	200%
between 7 and 8 inch inner diameter and over 0.06 inch cross section	1400 psi	175%
over 10 inch inner diameter and over 0.06 inch cross section	1200 psi	150%
test slab dog-bones	1600 psi	200%

O-Ring Tensile Modulus and Work Testing (Additional tables and plots in Appendix I)

Tensile modulus is not currently measured as part of the test slab acceptance testing. While developing procedures for ring tensile strength and elongation testing, it was opportune to also measure modulus over a variety of elongations and to evaluate the possible value of including modulus as one of the acceptance tests. A literature report (C. Peacock, "Quality Control Testing of Rubber Shear Modulus," Elastomerics, p. 42-45, May 1992) suggesting that measurements of the integrated work up to 20% elongation might also provide a useful measure of elastomer performance led to inclusion of that parameter in the tensile test evaluation.

All the moduli were measured at a crosshead speed of 20 in./min. A study of tensile properties vs. test speed prompted by the rapid elongation and failure of smaller rings at this high speed is discussed in the following section. A modest increase in modulus (measured between 10-20% elongation) was noted in that study as the test speed increased from about 5 to 20 in./min.(see Table I-1).

Tensile moduli were measured over 5 different elongation ranges: 5-10%, 10-15%, 5-15%, 10-20% and 0-25%. These particular values were computer generated averages of the tangent to the stress-strain curve at each data point within that range. The highest moduli were generally observed in the 5-10% elongation range and the lowest moduli were generally observed in the 10-20% elongation range, reflecting a slight bending in the stress-strain slope.

A more simple and preferred modulus calculation would be the linear modulus defined by the stress at a given elongation. Such measurements would not require the computerized data handling required in the initial Sandia tests and would be compatible with basic strip chart recorder instruments. Such modulus measurements were carried out at Kansas City and also at Sandia and this simple linear modulus or stress at 25% elongation calculation is recommended in the test procedure in Appendix C.

Comparisons of the linear modulus to the computer generated tangential modulus values showed close agreement with the smaller rings. The larger ring sizes, 7 in. ID and up, showed slightly higher moduli with the simple linear calculation.

ASTM-D-1414 also describes the measurement of tensile "moduli" or stress at a defined elongation for typically 100 or 200% elongation. A limited amount of such "modulus" data was obtained at 100, 200 and 300% elongation during the initial trials with different fixtures as described in the preceding section. The highly non-linear nature of the stress-strain curves over these long elongations, however, led to the use of shorter elongation ranges in the present evaluations

Calculations of tensile work, over the 0-20% elongation range, were carried out by computer integration and summation of the rectangular areas under each data point in the stress-strain curve. Each rectangle was bounded by the stress at a given point and by the elongations midway between that point and its neighbors. Calculations of tensile work in units of absolute elongation (i.e. inch-lb. per square inch) reflected primarily the size of the O-ring and more meaningful results were obtained in units of percent elongation or percent-lb per square inch.

As described in the preceding section, tensile tests were carried out by setting both the force and elongation to zero at a starting crosshead distance calculated from the nominal ring diameter and the spool diameter. Tables in the proposed method in Appendix C provide these starting crosshead distances for O-ring sizes used in the W87.

Tables 7 and 8 and Plots 5 and 6 summarize the tensile modulus and work data obtained on a series of O-ring and test slab lot obtained from the three vendors. The modulus table and plot show only the simple linear data obtained with the 0-25% elongation range. All the tangential modulus data over different elongation ranges is detailed in additional tables and plots in Appendix I. Work, as noted above, was measured over the 0-20% elongation range.

Unlike the tensile strength and elongation data, there was no significant correlation of tensile modulus or work with ring size. More detailed data is again included in the Appendix. These results suggest that modulus and work, like hardness and compression set, are more reflective of bulk properties and are less sensitive to defects than strength and elongation measurements. There was again no significant correlation of slab and ring data from the same rubber batches.

Linear modulus values for the RD Rubber rings all fell between about 360-510 psi before aging and 390-560 psi after aging. Parker and Precision rings showed much higher moduli and also greater variability. A minimum modulus of 350 psi before aging would accept all the rings tested. A maximum change on aging of +15% (not ±15%) would have excluded two Parker ring lots, one RD Rubber lot and three Precision lots. All but one Parker ring lot and two slab lots showed a higher modulus after aging and suggests that a loss of modulus is not typical of most butyl rubber materials and is probably undesirable.

Future tensile measurements at 5 in./min. instead of the 20 in./min. used here may reduce the observed values about 10%. None of the stiffer Parker or Precision ring materials would be rejected by a small reduction in the measured modulus. The lower modulus RD Rubber materials would be more borderline and may require adjustment of the tentative 350 psi minimum or perhaps an adjustment in the RD Rubber formulation. The RD Rubber materials also gave lower tensile work, hardness and compression set values than those from Parker and Precision. These lower RD Rubber values, clearly desirable in compression set, also tended to be more uniform than those from the other vendors. Overall, the RD Rubber formulation may provide a more desirable balance of properties.

Tensile work values (see Table 8 and plot 6) showed trends similar to those observed in the tensile modulus measurements and offered no particular insights into material quality. No unusual correlation with compression set results or other parameters was noted in either the lot to lot comparisons or the cure study comparisons. The results do not suggest any future use of tensile work measurements for acceptance testing.

As noted in the preceding section, it is anticipated that tensile testing would no longer be required for acceptance of each lot of O-rings but would instead be utilized in a periodic manner for vendor qualification.

The recommended procedure for tensile testing of O-rings is described in Appendix C and the recommended test values are summarized along with the other test changes in Table 12.

Table 7. Linear Tensile Modulus (0-25% Elongation) Data: Slabs and O-Rings

Vendor	Rubber Batch	± Aging	Test Slab Data	O-Ring Data (Standard Deviations from 6 to 96, avg. 27)				
			All Sandia results	0.116x0.038	0.301x0.054	1.364x0.070	7.688x0.070	16.339x0.103
Parker	316104	unaged	761		754	683	896	868
		aged	1120		780	736	860	906
Parker	316710	unaged	981		812			819
		aged	956		819			842
Parker	317403	unaged	922			639		
		aged	1056			675		
Parker	317851	unaged	973				489	
		aged	958				586	
Parker	318466	unaged	569	527				
		aged	690	581				
				0.301x0.054	0.551x0.070	1.114x0.70	7.185x0.103	11.196x0.103
RD	14810	unaged	579		358	369	418	
		aged	589		403	387	435	
RD	14936	unaged	NA					465
		aged	NA					496
RD	15107	unaged	641	447	367	389	507	477
		aged	666	493	414	431	553	560
					0.301x0.054	1.364x0.070	7.739x0.070	16.955x0.139
Precision	17405	unaged	NA			577		
		aged	NA			658		
Precision	19052	unaged	731		554		788	
		aged	823		628		919	
Precision	19422	unaged	NA					576
		aged	NA					660
Precision	19895	unaged	766		516	585		614
		aged	803		642	623		729
Precision	19921	unaged	NA				760	
		aged	NA				834	

Plot 5. Linear Tensile Modulus (0-25% Elongation) of Aged and Unaged O-Ring Samples

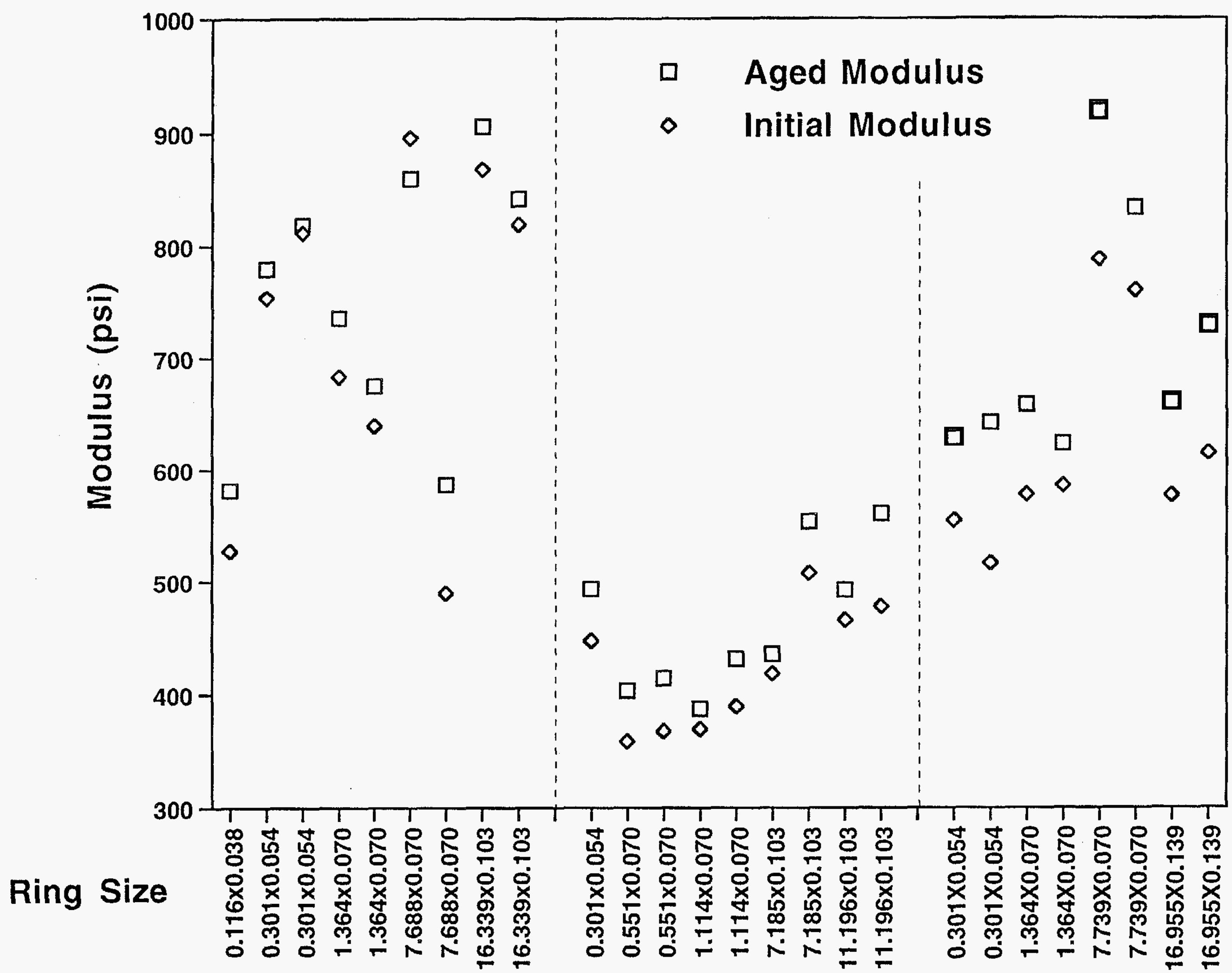
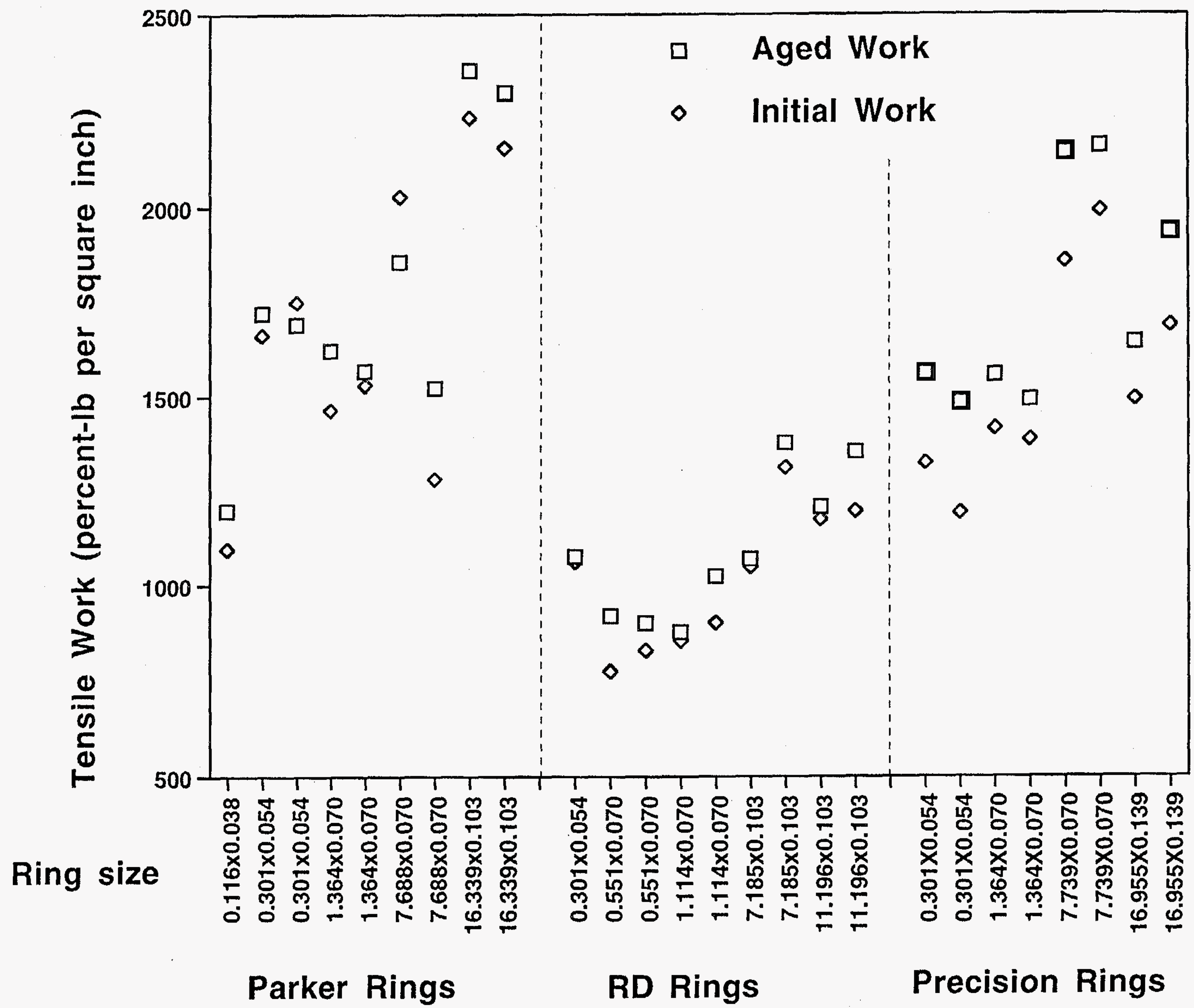


Table 8. Tensile Work Data (0-20% Elongation): Slabs and O-Rings (Data in percent-lb/sq.in.)

Vendor	Rubber Batch	± Aging	Test Slab Data	O-Ring Data (Standard Deviations from 17 to 274, avg. 82)				
				0.116x0.038	0.301x0.054	1.364x0.070	7.688x0.070	16.339x0.103
Parker	316104	unaged	2278		1662	1464	2027	2233
		aged	3484		1720	1622	1856	2354
Parker	316710	unaged	2617		1749			2155
		aged	2553		1691			2297
Parker	317403	unaged	2777			1530		
		aged	3212			1568		
Parker	317851	unaged	2532				1280	
		aged	2617				1522	
Parker	318466	unaged	1387	1095				
		aged	1265	1197				
				0.301x0.054	0.551x0.070	1.114x0.70	7.185x0.103	11.196x0.103
RD	14810	unaged	1674		774	853	1048	
		aged	1627		918	876	1068	
RD	14936	unaged	NA					1172
		aged	NA					1206
RD	15107	unaged	1815	1061	828	900	1310	1194
		aged	1846	1076	900	1023	1375	1352
					0.301x0.054	1.364x0.070	7.739x0.070	16.955x0.139
Precision	17405	unaged	NA			1414		
		aged	NA			1556		
Precision	19052	unaged	2298		1322		1857	
		aged	2472		1561		2143	
Precision	19422	unaged	NA					1492
		aged	NA					1642
Precision	19895	unaged	2336		1190	1384		1686
		aged	2405		1483	1491		1934
Precision	19921	unaged	NA				1990	
		aged	NA				2159	

Plot 6. Tensile Work (0-20% Elongation) of Aged and Unaged O-Ring Samples



O-Ring Tensile Properties vs. Test Speed

Because of the wide range of O-ring sizes being tested at a 20 in./min. fixture speed during the above evaluations, there was a correspondingly wide range of ring elongation rates. As shown in Table 9, a fixture speed of 20 in./min. corresponds to ring elongation rates, in percent/minute, ranging from 235%/min. for the largest rings up to 4230%/min. for the smaller rings. A typical ultimate elongation of 200% is reached for the smaller rings in only about 3 seconds, limiting the amount of data points to be measured. Concern over the possible effects of such different percent elongation rates led to a series of tensile tests in which the fixture speed was adjusted to provide ring elongation rates of either 20 or 200%/min. for each of the different O-ring sizes. Each ring was also tested at the fixture speed, 20 in./min., used in the tensile tests reported in the above section.

The tests in this series were carried out on rings previously obtained from Lutz, a distributor for Precision, before it was known Lutz was not the manufacturer.

As shown in the Table and in Plot 7, most properties demonstrated only a modest sensitivity to test speed. Individual plots of tensile strength (Plot H-2), tensile elongation (Plot H-3) and tensile modulus (Plot I-7) have been referred to in the preceding sections and are contained in the appendices. The very low fixture rates used to achieve 20%/min. in some cases did significantly reduce the observed tensile properties. Within the fixture speed range of 5-20 in./min., however, most rings gave only moderate increases, if any, in tensile values.

The major benefit to be gained from reducing the tensile test speed is a longer time to ring failure and larger number of data points with more resolution. It was considered impractical to use different fixture speeds for each ring size for routine testing and, based on the relative insensitivity of the data to test speed, unnecessary. A compromise recommendation calls for two fixture speeds to be designated: 20 in./min. for the two largest W87 ring sizes and 5 in./min. for the remaining O-rings, all less than 2 in. in inner diameter. That recommendation is contained in the proposed procedure in Appendix C. Using the reduced speed should provide a failure time for the 0.301 in. ID rings of over 10 seconds and even the smallest 0.116 in. ID rings should require about 4 seconds to break.

As noted in the preceding sections, a reduction in fixture speed from 20 to 5 in./min. might be expected to reduce the observed tensile values 10-20%. The proposed strength and elongation values already reflect this expectation. The proposed modulus requirement of 350 psi would have rejected none of the Lutz rings tested in this series. The lower moduli typical of RD Rubber materials might be more affected by the lower test speed and possibly lead to a higher rejection rate.

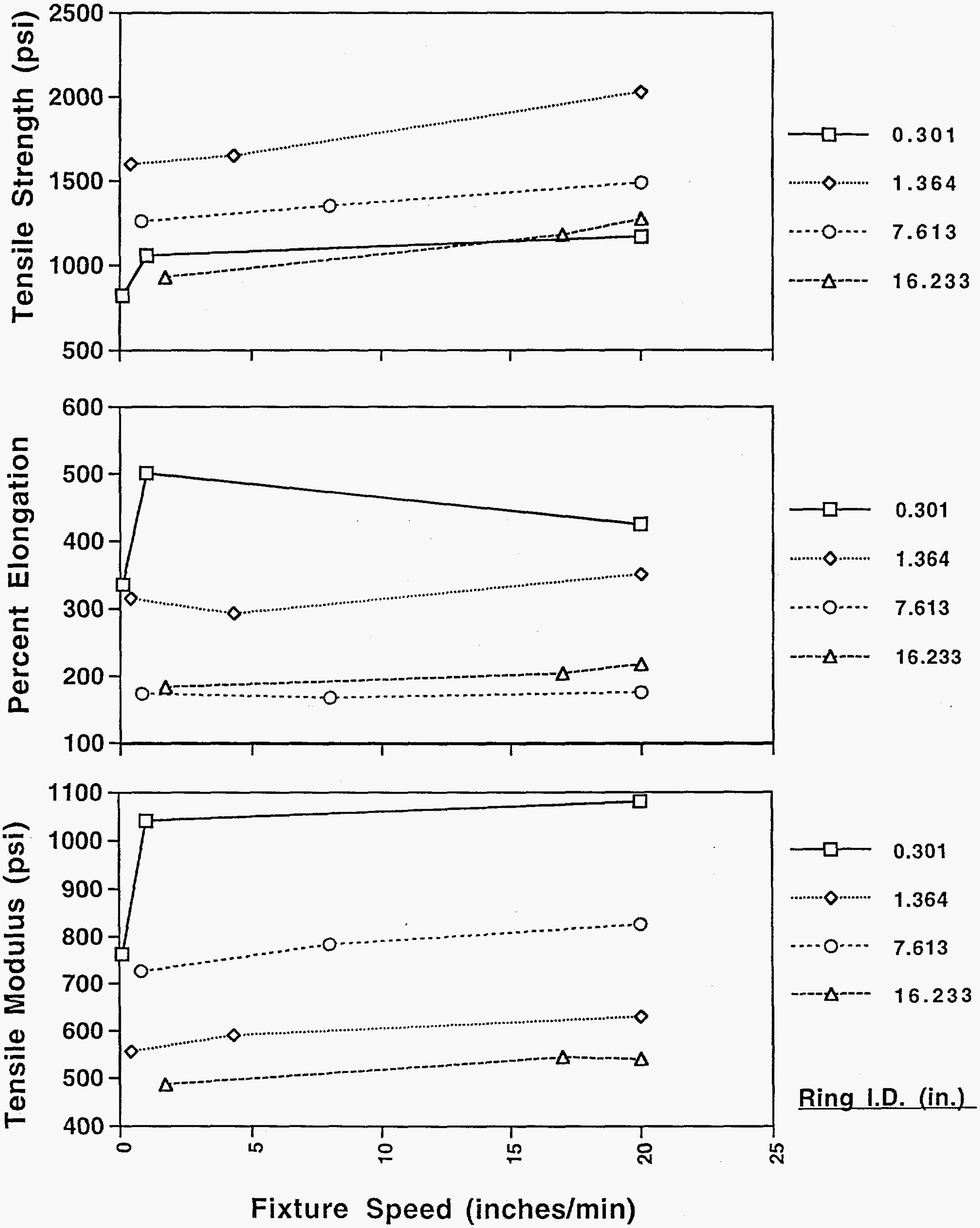
Additional tests being carried out at Kansas City will be using the 5 in./min. fixture speed for smaller rings and 20 in./min. speed for the two larger ring sizes. That data should allow any final adjustments to be made in the target tensile values if needed.

Table 9. Tensile Strength, Elongation and Modulus vs. Test Speed

(All tests carried out on Lutz O-rings.)

Ring size	Fixture Speed (inches/min.)	Ring Elongation Rate (%/min.)	Strength at Break	Percent Elongation at Break	Modulus (10-20% elongation)
0.301 x 0.065	0.09	20	821 ± 414	336 ± 165	763 ± 76
	0.95	200	1058 ± 458	501 ± 94	1041 ± 79
	20	4230	1168 ± 147	425 ± 51	1081 ± 111
1.364 x 0.070	0.43	20	1599 ± 270	315 ± 55	556 ± 30
	4.29	200	1649 ± 405	293 ± 70	590 ± 14
	20	933	2028 ±116	351 ± 19	630 ± 12
7.613 x 0.070	0.80	20	1260 ± 249	174 ± 40	726 ± 7
	7.97	200	1350 ± 377	168 ± 55	783 ± 14
	20	502	1488 ± 211	176 ± 26	825 ± 31
16.233 x 0.139	1.70	20	930 ± 177	184 ± 25	487 ± 6
	17.0	200	1178 ± 381	204 ± 50	544 ± 16
	20	235	1273 ± 278	218 ± 37	540 ± 18

Plot 7. O-Ring Tensile Properties vs. Fixture Speed



O-Ring Properties vs. Cure Cycle (Additional tables and plots in Appendix J & K)

O-ring materials failing the acceptance criteria, whether in the past using test slab samples or in the future using actual ring samples, might do so because of either formulation or processing errors. Lack of anti-oxidant, for example, would impair the material aging performance, poor mixing would affect performance uniformity, and different filler levels and under or over curing would be expected to affect many of the measured properties.

No previous Sandia studies, however, have attempted to actually correlate cure cycle with acceptance test performance. With the cooperation of RD Rubber and the Kansas City personnel, arrangements were made to deliberately undercure multiple lots of rings and slabs using one of the rubber batches already characterized as part of the study. Rheometric curing scans at Kansas City on the uncured rubber suggested that cure times of about 3 min. and 4 min. would produce degrees of cure of 45% and 70% instead of the nominal 95% produced by the current 10 min. cure cycle. All cures were carried out at 150°C. RD Rubber produced 4 lots of O-rings and one lot of test slabs each using these reduced cure times. The smallest O-ring size previously supplied (0.551 x 0.070 in.) was replaced in this series with the small O-ring size supplied by Parker and Precision (0.301 x 0.054 in.). All the rings and slabs in this series were prepared from RD Rubber butyl rubber batch 15107.

Surprisingly, none of the tests of initial material properties demonstrated a strong correlation of performance with cure time. The undercured materials gave more failures upon aging than the fully cured rings, but there was again no strong correlation of aging behavior with cure time. Plots 8 through 13 show the relative hardness, compression set, tensile strength, elongation, and tensile modulus and work for four different ring sizes and the test slabs, each with either 3, 4 or 10 minutes of cure. Corresponding tables in Appendix J provide more details.

None of the materials with reduced cure times would have failed the initial hardness test or the currently allowed change of 10 points after aging. Most of the undercured rings would have failed the proposed maximum aging change of 4 points, however, a finding which prompted that proposed specification modification.

Only two undercured ring lots would have failed the proposed compression set maximum of 10% and none would have failed the current maximum of 15%. The failing ring lots occurred randomly, however, and were not part of any general trend showing increasing compression set with decreasing cure time.

Only one ring lot, cured 4 minutes, would have failed the proposed tensile strength and elongation requirements. Two of the undercured lots would have failed the ±15% maximum aging change in tensile strength and four different lots would have failed the ±15% elongation change. One fully cured lot would also have failed a maximum strength and elongation change of ±15%. Again, these failures were largely random and not part of any clear trend. The undercured test slabs would have also failed the aging elongation change although their tensile strength performance was acceptable.

Both tensile strength and elongation, in some ring sizes, seemed to show trends with cure time, but the same trends would not be observed in other ring sizes. There was overall, no definitive behavior which would insure that undercured materials would be identified via these tensile tests.

Tensile modulus and work measurements also gave no strong correlation with cure time. In some ring sizes the modulus actually decreased with longer cure while in others the values were virtually unchanged with cure. The decreasing modulus with cure time observed in two cases may suggest the cure temperature being used is degrading the rings to some extent. Again, this same trend was not observed in all the rings and was not consistent enough to warrant additional research or vendor efforts.

The lack of substantial changes in ring and slab properties with cure time suggested that, contrary to the rheometrics predictions, the rubber materials were nearly as fully cured after 3 or 4 minutes as they were after 10 minutes. In subsequent discussions with RD Rubber personnel, they indicated that the rubber is typically cured after only one minute in the heated press. Longer cure schedules are used to insure reproducibility.

DSC studies at Sandia on the uncured rubber and on the variously cured ring and slab samples confirmed that the cure is extremely rapid and that no significant differences in degree of cure could be noted in the materials cured 3, 4 or 10 minutes. As shown in the scans in Figure 4, slight trends noted in the rings on examining samples with 3, 4 and 10 minute cure times did not hold up in the slab samples. A DSC scan on an unknown sample would not be able to establish its degree of cure with any certainty. When the uncured rubber was examined (lower right of Fig. 4) a clear early endotherm was noted along with a broad exotherm. When similar samples were first cured in the DSC at 150°C for 2 to 15 minutes and then scanned, the observed initial endotherm had already disappeared and the subsequent exotherm was substantially reduced. The samples cured 2 or 4 minutes still gave slight exotherms, but the remaining samples were largely overlapping and featureless.

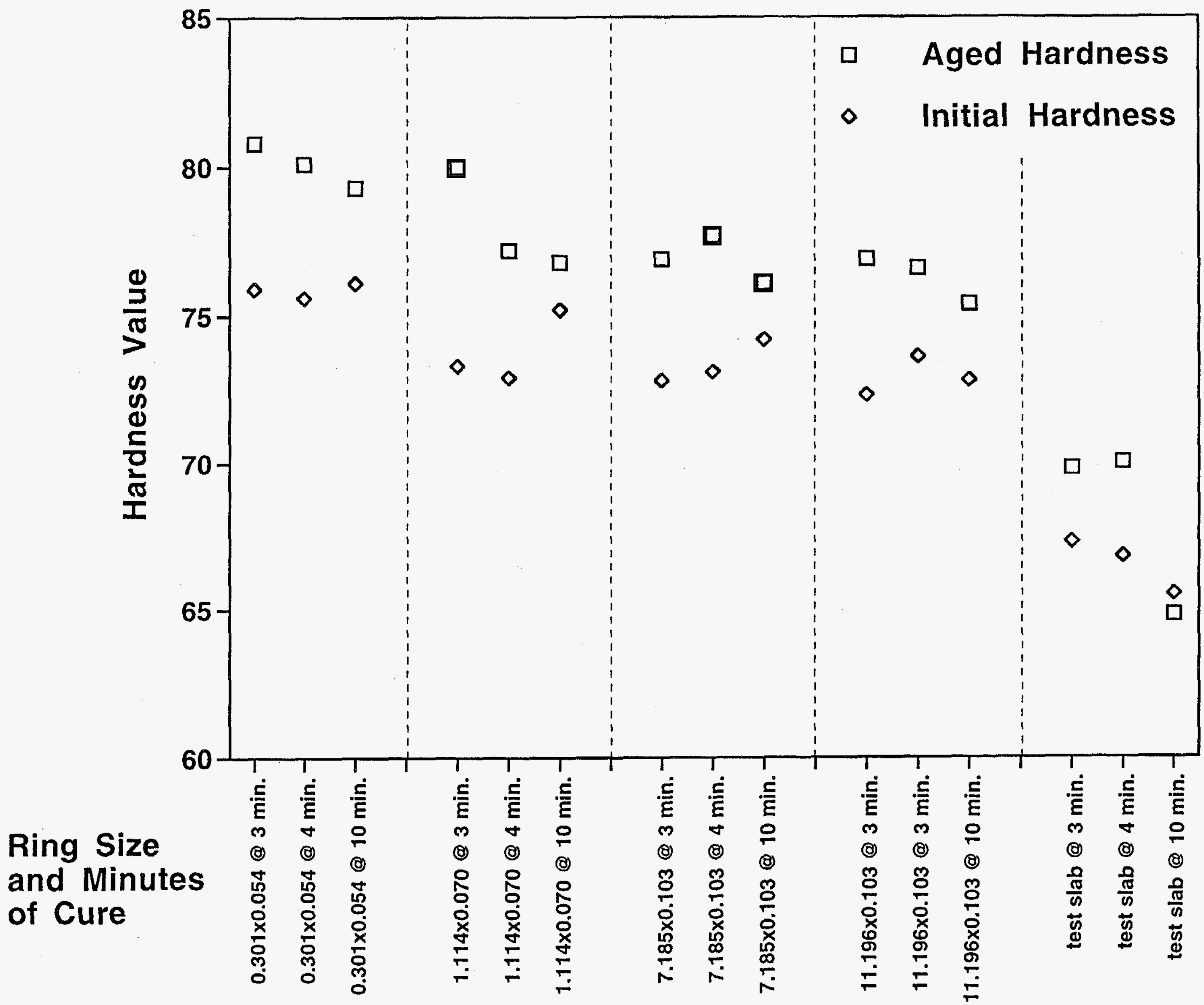
Lower temperature DSC scans were also carried out to measure anticipated increases in Tg as the cure time was increased. Again, all the samples showed similar Tg values and provided no quick and definitive measure of cure level.

Additional DSC scans (see Appendix K) of materials from the different vendors showed general similarities, particularly a broad endotherm starting at about 120°C, between the Parker and RD Rubber materials. This endotherm occurs at higher temperatures than the sharp endotherm observed only in the uncured material. The Precision materials did not show this broader endothermic profile in the one rubber batch examined

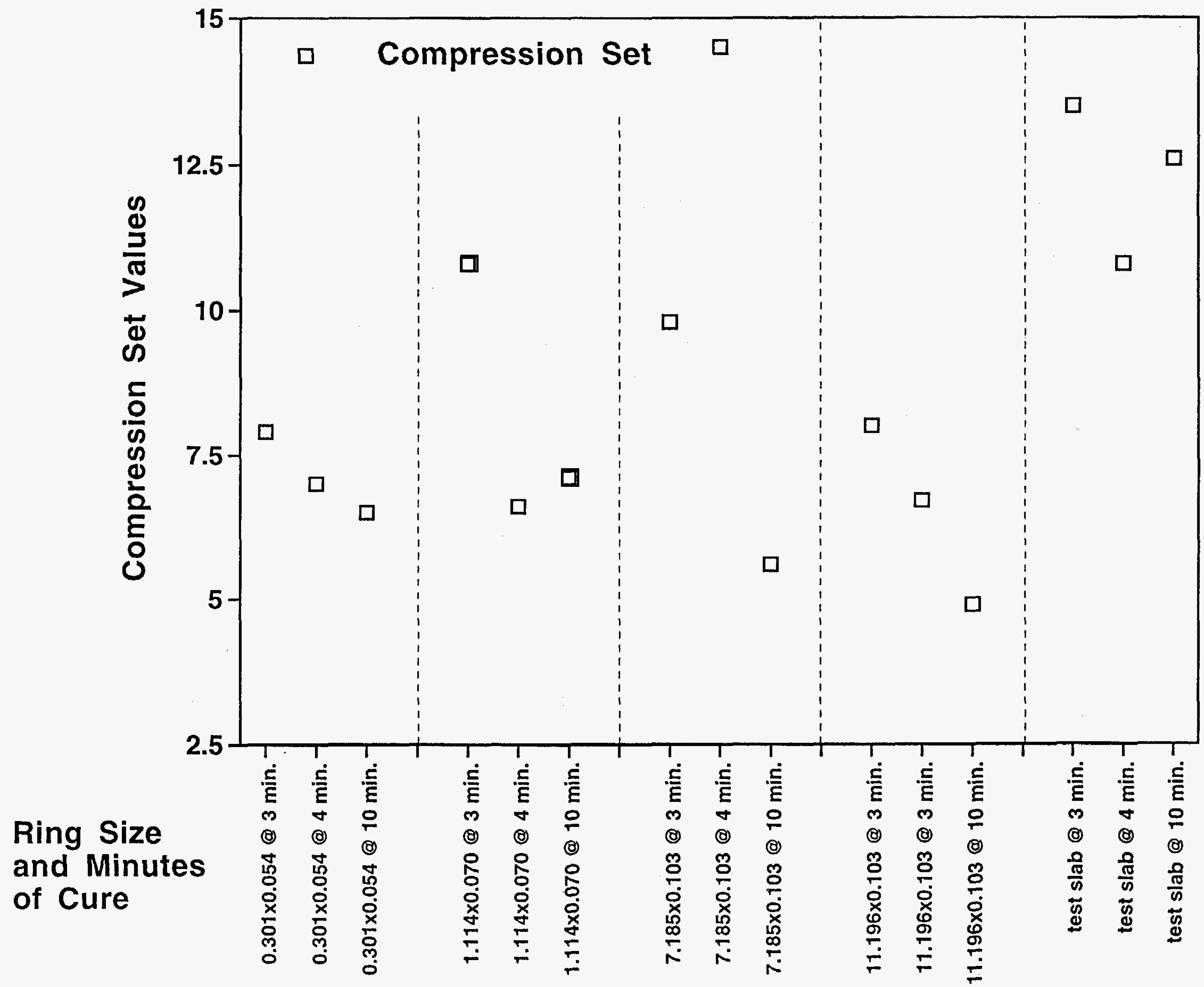
Stockpile aged butyl rubber O-rings from the W76 and W87 were also examined by DSC and showed a general increase in the above broad endotherm peak with aging. In these random samplings, the effect did not appear consistent enough to provide a useful measure of O-ring life, however. For example, three W76 O-rings from different rubber batches showed quite different DSC scans. In the W87 the limited scans available appeared more consistent in behavior, perhaps due to the use of a single O-ring vendor in this weapon. Future aged W87 O-rings should also be examined by DSC to monitor the growth of this endothermic peak and its possible correlation to O-ring performance. It should be noted that the "unaged" W87 Parker O-ring which had been stored in its shipping package and not stockpile aged did not show any endothermic peak such as that noted in more recent Parker and RD Rubber materials. This again reflects the ambiguity of assessing if observed DSC endotherms are due to aging or were present in the as-received materials.

The results of the cure study suggest two major points. First, none of the acceptance tests were able to differentiate the samples having different cure times with any certainty although the reduced maximum on hardness change with aging may be beneficial. Second, the sensitivity of properties to cure cycle is low and suggests that O-ring curing processes are both robust and tolerant of processing excursions. This may further suggest that out-of-spec materials result more from formulation and mixing deviations than from cure cycle deviations.

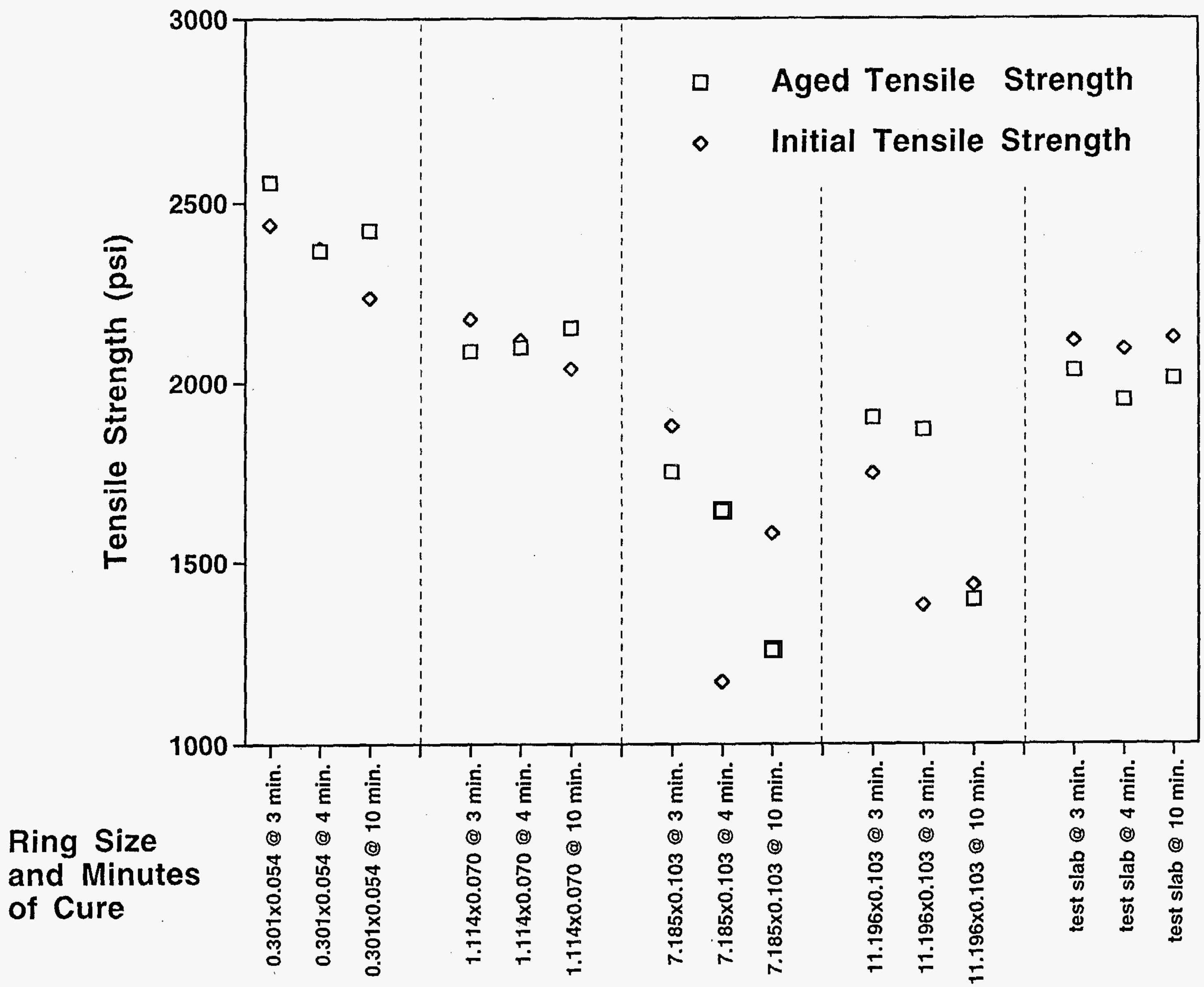
Plot 8. Hardness Values of Aged and Unaged RD Samples with Different Cures



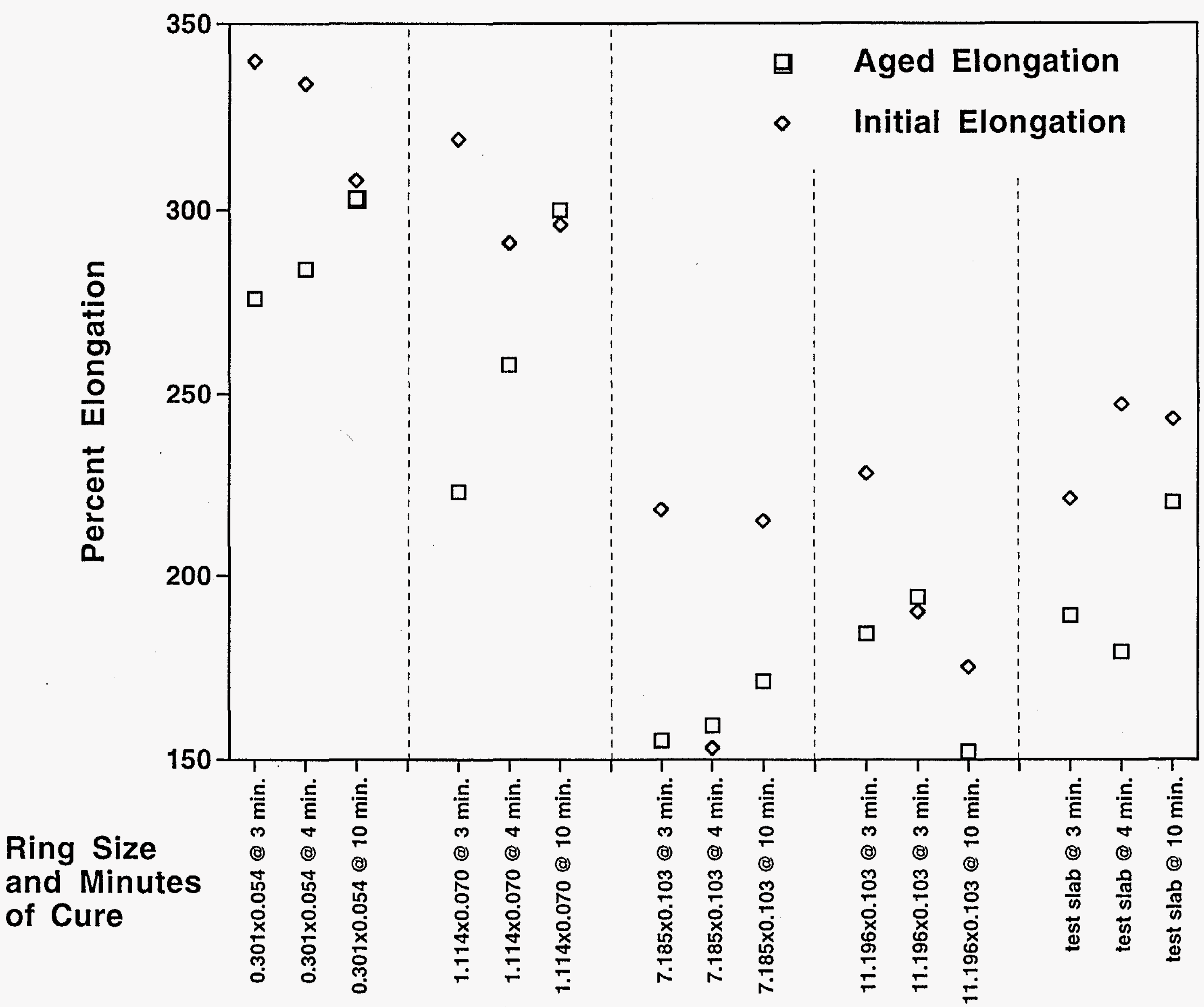
Plot 9. Compression Set of RD Samples with Different Cures



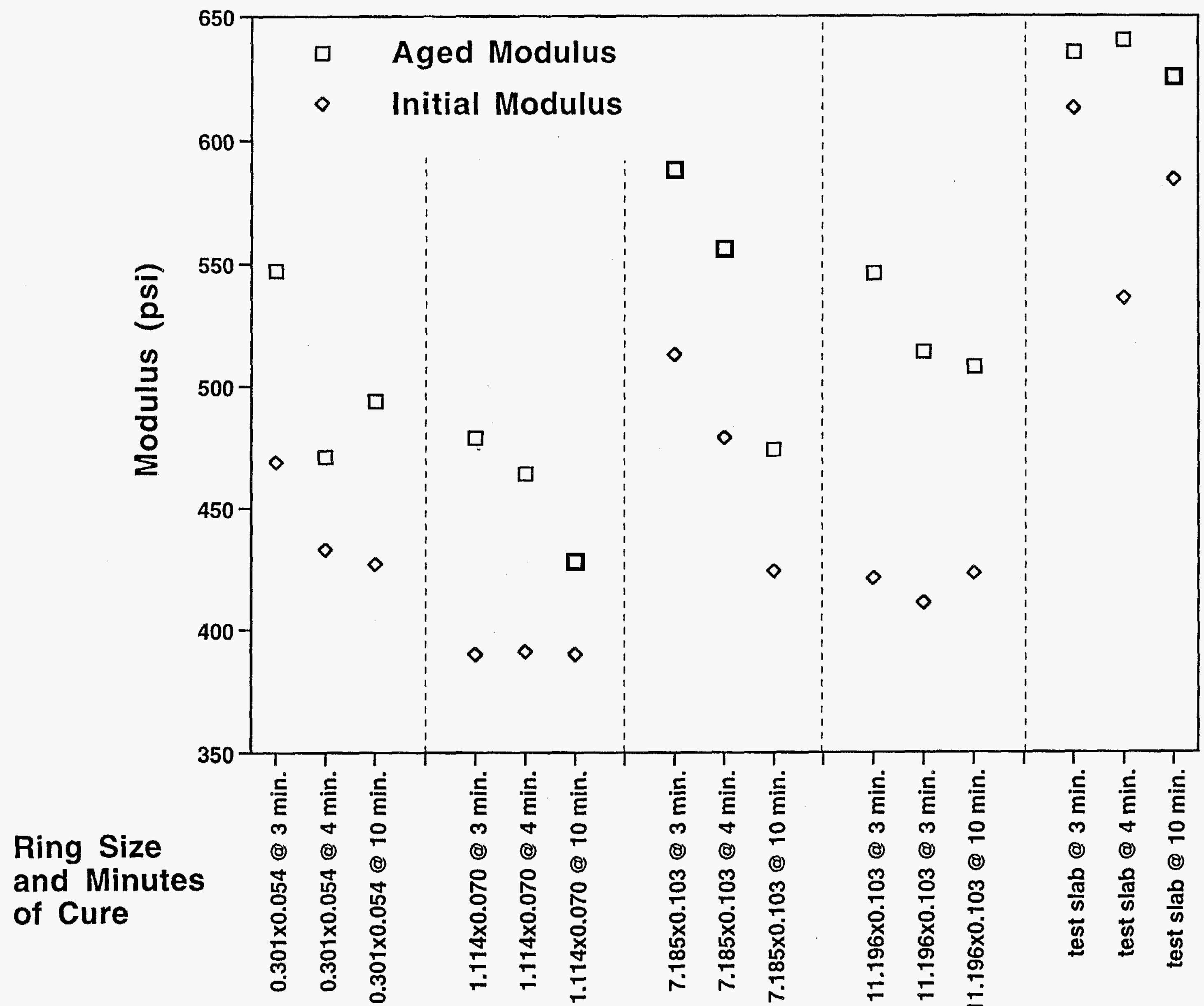
Plot 10. Tensile Strength of Aged and Unaged RD Samples with Different Cures



Plot 11. Tensile Elongation of Aged and Unaged RD Samples with Different Cures



Plot 12. Tensile Modulus (0-25% Elong.) of Aged & Unaged RD Samples with Different Cures



Plot 13. Tensile Work (0-20% Elong.) of Aged & Unaged RD Samples with Different Cures

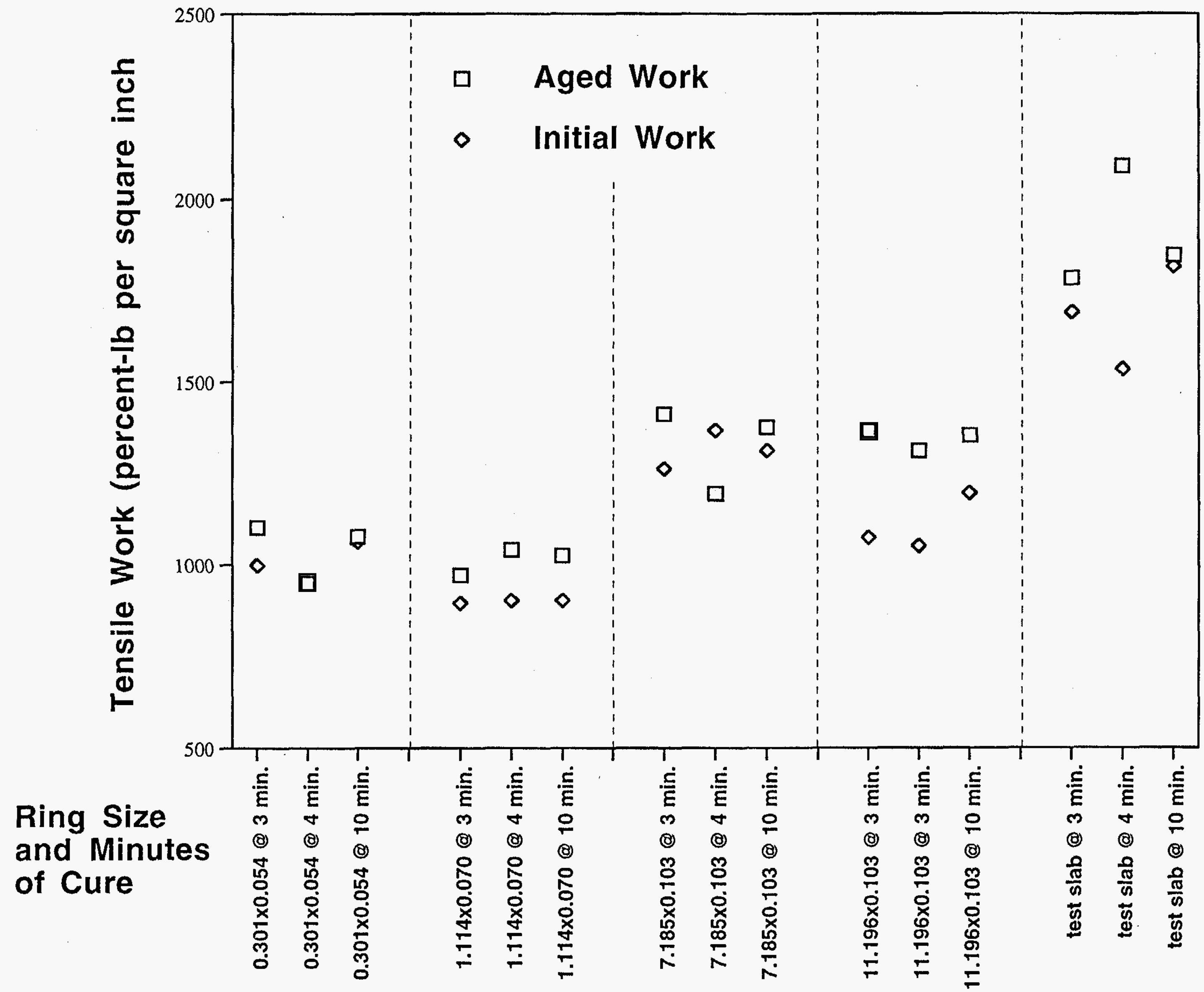
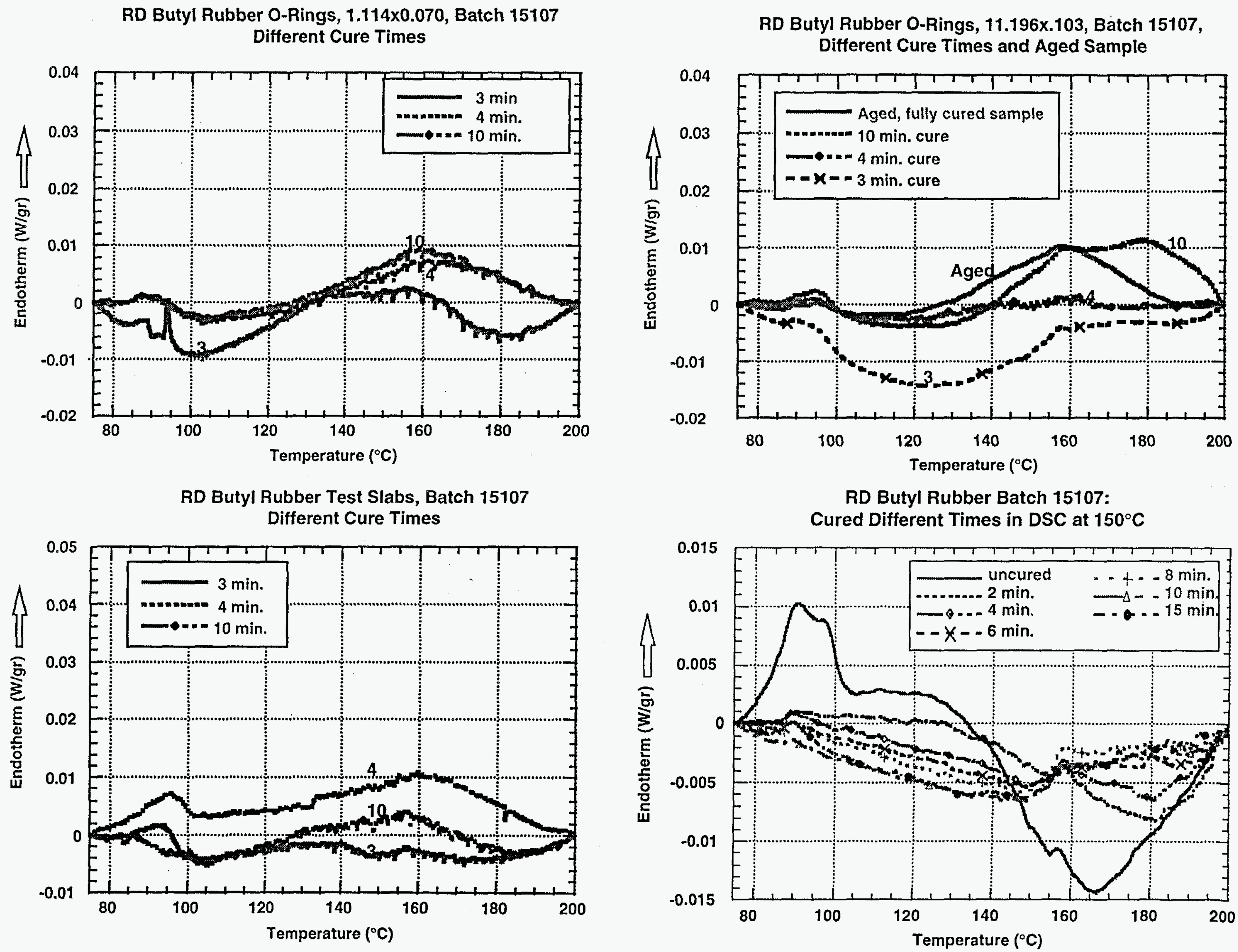


Figure 4. DSC Cure Studies on RD Rubber Materials

(endotherms are positive, exotherms are negative)



Rubber Composition Tests

An unexpected discovery near the end of this program was the finding that two lots of test slabs supplied by Parker Seals and labeled as being prepared from specific batches of butyl rubber were actually prepared from EPDM rubber. Parker has been unable to fully account for how such a substitution could have occurred and whether such errors occur with any regularity.

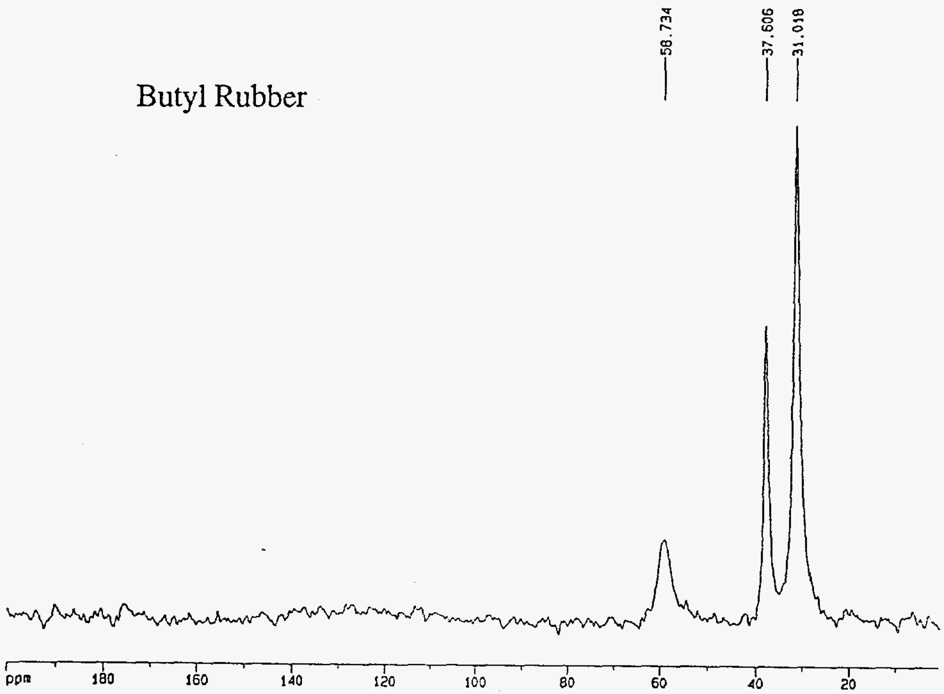
The two Parker test slab lots made from EPDM were those labeled as butyl batches 316710 and 317851. Other assorted Parker and RD materials which were analyzed by solid state NMR and found to be made from the expected butyl rubber included Parker tests slabs from batches 316104 and 317403, Parker O-rings from batch 316710 (16.339 in. and 0.301 in. ID), Parker O-rings from batch 317851 (7.688 in. ID), RD Rubber test slabs from batches 14810 and 15107, and RD Rubber O-rings from batch 15107 (0.551 in. ID). No RD Rubber products and no O-rings from either vendor were found to be made from EPDM rubber. Typical proton NMR spectra for butyl and EPDM rubber are shown in Figure 5.

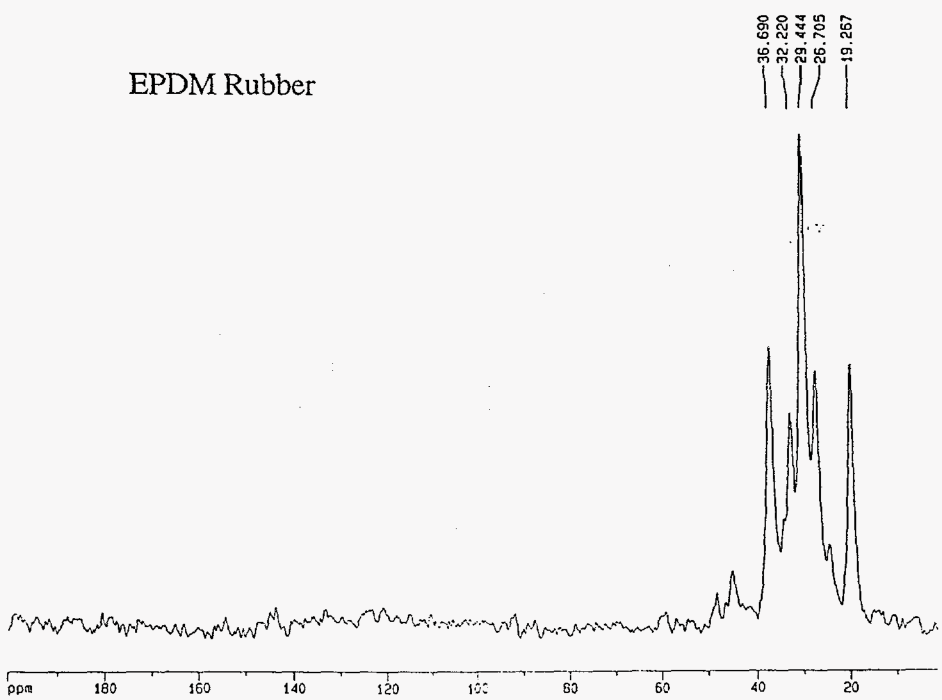
The NMR analyses were prompted by the unusually good aging characteristics, more like EPDM than butyl rubber, found by Mark Wilson for the 316710 test slabs in stress relaxation tests at Kansas City Plant. Subsequent permeation tests by Ken Gillen at Sandia, NM showed also performance similar to that expected from EPDM (much poorer than butyl) and were followed by a solid state NMR analysis confirming the EPDM composition.

None of the normal acceptance tests, including physical properties and density, nor DSC can reliably distinguish butyl and EPDM rubber. Long term aging and permeation tests are more involved and time consuming and are not candidates for qualification testing. The most definitive means, in any case, of identifying a composition as either rubber would be spectroscopic such as NMR or IR and possibly mass spectra. The cost and limited availability of solid state NMR would suggest the use of IR and this method has been used at LLNL to identify rubber samples. SpectraTech ATR (attenuated total reflectance) instruments are available for about $3K or less which are capable of running IR spectra on the as-received slab or ring samples. The IR spectra of the two rubbers, like the NMR spectra, are very distinct.

Inclusion of such an IR test in future rubber material specifications would preclude the inadvertent use of O-ring seals made from the wrong base rubber. EPDM rubber provides very different permeability characteristics and lower levels of environmental protection than butyl rubber. A final decision on the type of spectral test to be used has not yet been made and will largely be determined by equipment availability.

Figure 5. Typical Solid State NMR Spectra for Butyl and EPDM Rubber.





Vendor Comparisons

Of the three vendors participating in this program, only Precision provided O-rings of clearly inadequate quality. Precision is a very low cost vendor and the visual quality of their O-rings reflected their low cost. Most of the O-rings used in the test program were visually inspected at Kansas City to insure comparable quality prior to testing. Precision O-rings were typically coated with talc which had to be removed by washing and the percentage of rings passing visual inspection was low, generally less than 50%. Test results from the Precision O-rings, as noted in the preceding sections, showed higher and sometimes out-of-spec compression set values, a key parameter. Both the poor visual quality and inconsistent compression set performance led to a decision not to include Precision as a future vendor.

Parker rings showed more variability in measured properties and also had large numbers of rings rejected for visual quality. RD Rubber rings were typically lower in hardness and tensile modulus than Parker, but they were also slightly lower, and again more uniform, in compression set, a key criteria. Both vendors appear capable of providing rings which will meet W87 requirements.

Concerns with Parker revolve around the recently discovered mislabeling and shipment of test slabs made from EPDM rubber and general, on-going difficulties noted at Kansas City with product quality and technical service. The small volume of rings required for DOE warhead production and maintenance does not warrant a highly cooperative response from this high volume vendor. RD Rubber, in contrast, is a smaller vendor and has shown a high level of cooperation as exemplified by production of the special materials needed for evaluating cure cycle effects.

Summary

The accumulated test data on rings of various sizes and test slabs from three vendors indicate that hardness, compression set and tensile tests can be readily and reliably performed on O-ring samples in place of the current test slab samples. Tables 10 and 11 and Plots 14 and 15 summarize all of the hardness, compression set and tensile data discussed in the preceding sections.

Procedures and required equipment have been defined and incorporated into the new test methods detailed in Appendices A, B and C. These procedures are currently being reprocessed into the Kansas City format. Modifications have also been made where needed in the target test values and these are shown in Table 12. A comparison of Table 12 with Table 1 in the beginning of the report provides a quick review of the changes made in both procedures and target test values in switching from test slab to O-ring samples. Additional O-ring tests on materials available at Kansas City are in progress and will be evaluated before target test values, especially for the tensile tests, are finalized. An additional test proposed for future O-ring lot acceptance is spectroscopic confirmation of the rubber material used, possibly by IR. A final decision on the use of IR vs. other options has not yet been made.

Difficult remaining issues include the definition of sampling rates from O-ring lots of different ring sizes and ring counts. Appropriate statistical samples for lots with different ring counts, ranging from 100 to 1000 and beyond need to be defined in a manner which is feasible, not overly burdensome or costly, and which yet provides data with acceptable precision. If larger orders are placed to fill both current and future needs, the issue of re-certification of lots in storage will need to be addressed. The definition of the word "lot" even requires clarification as smaller rings are fabricated in molds holding multiple samples while larger rings may be molded one at a time and may require several molding days to fill an order. While a lot of O-rings would clearly need to be fabricated from a single batch of rubber, it is not clear what molding cycle constraints may also be required to insure lot uniformity. The test sampling rates suggested in Table 12 reflect only the rates required to obtain reasonable precision in the test measurements and need to be further reconciled with the sampling rates required for statistically valid sampling of lots with different ring counts.

Table 10. Test Data Summary for Butyl Rubber Materials (Rings and Slabs) from Different Vendors

Vendor	Ring Size	Rubber Batch	Hardness		Comp. Set	Tensile Strength (psi)		Tensile Elongation		0-25% Ten. Modulus		Ten. Work %-lb/sq in.	
			initial	aged		initial	aged	initial	aged	initial	aged	initial	aged
Parker	0.116x0.0038	318466	75	78	10.7	1891	1823	278	264	537	596	1095	1197
Parker	0.301x0.054	316104	81	83	4.6	1959	1964	259	261	768	797	1662	1720
Parker		316710	81	81	9.7	2015	2032	272	271	838	840	1749	1691
Parker	1.364x0.070	316104	80	81	6.1	1591	1573	209	210	669	752	1464	1622
Parker		317403	78	78	10.1	1790	1708	281	269	636	663	1530	1568
Parker	7.688x0.070	316104	81	82	7.7	1447	1561	178	188	875	812	2027	1856
Parker		317851	72	75	8.2	1469	1671	362	341	452	558	1280	1522
Parker	16.339x0.103	316104	80	81	7.8	1309	1430	168	177	826	845	2233	2354
Parker		316710	78	80	8.7	1294	1430	188	203	765	769	2155	2297
Parker	test slabs	316104	72	75	11.0	1563	1458	199	166	613	902	2278	3484
Parker	(*= EPDM)	316710*	69	70	9.9	2503	2282	186	172	948	918	2617	2553
Parker		317403	73	76	10.4	1590	1764	221	221	838	962	2777	3212
Parker		317851*	73	73	15.9	2530	1940	178	152	920	926	2532	2617
Parker		318466	73	74	18.9	1459	1630	535	588	602	716	1387	1265
RD	0.301x0.054	15107	76	79	6.5	2236	2423	308	303	427	494	1061	1076
RD	0.551x0.070	14810	75	76	5.5	2524	2414	402	344	364	395	774	918
RD		15107	75	77	5.7	1965	1864	293	261	372	422	828	900
RD	1.114x0.070	14810	74	76	5.6	2142	2063	314	293	368	385	853	876
RD		15107	75	77	7.1	2039	2153	296	300	390	428	900	1023
RD	7.185x0.103	14810	71	72	5.0	1734	1782	231	220	370	386	1048	1068
RD		15107	74	76	5.6	1579	1255	215	171	424	474	1310	1375
RD	11.196x0.103	14936	73	75	4.5	1334	1458	180	184	416	453	1172	1206
RD		15107	73	75	4.8	1436	1396	175	152	423	508	1194	1352
RD	test slabs	14810	63	69	5.9	2218	2170	273	247	532	545	1674	1627
RD		15107	66	65	12.6	2123	2010	243	220	584	625	1815	1846
Precision	0.301x0.054	19052	75	80	9.5	2218	2162	380	300	570	630	1322	1561
Precision		19895	78	79	10.7	2233	2138	369	289	530	625	1190	1483
Precision	1.364x0.070	17405	77	79	8.8	2078	1971	313	261	553	633	1414	1556
Precision		19895	78	79	10.0	1935	1937	275	247	576	600	1384	1491
Precision	7.739x0.070	19052	78	81	10.7	1578	1653	192	152	732	849	1857	2143
Precision		19895	78	81	11.5	1496	1616	226	181	700	772	1990	2159
Precision	16.955x0.139	19422	76	78	12.0	1129	832	188	114	527	610	1492	1642
Precision		19895	76	79	19.8	1315	1379	223	179	554	654	1686	1934
Precision	test slabs	19052	73	75	24.0	1711	1696	276	208	644	706	2298	2472
Precision		19895	72	76	22.8	1657	1565	229	197	677	705	2336	2405

Aged samples (except compression set) exposed to 70 hours at 212°F plus 24 hours at room temperature. Compression set samples exposed to 22 hours aging at 25% compression and 158°F plus 30 min., uncompressed, at room temperature.

Plot 14. Unaged O-Ring Test Values vs. Ring Size and Vendor

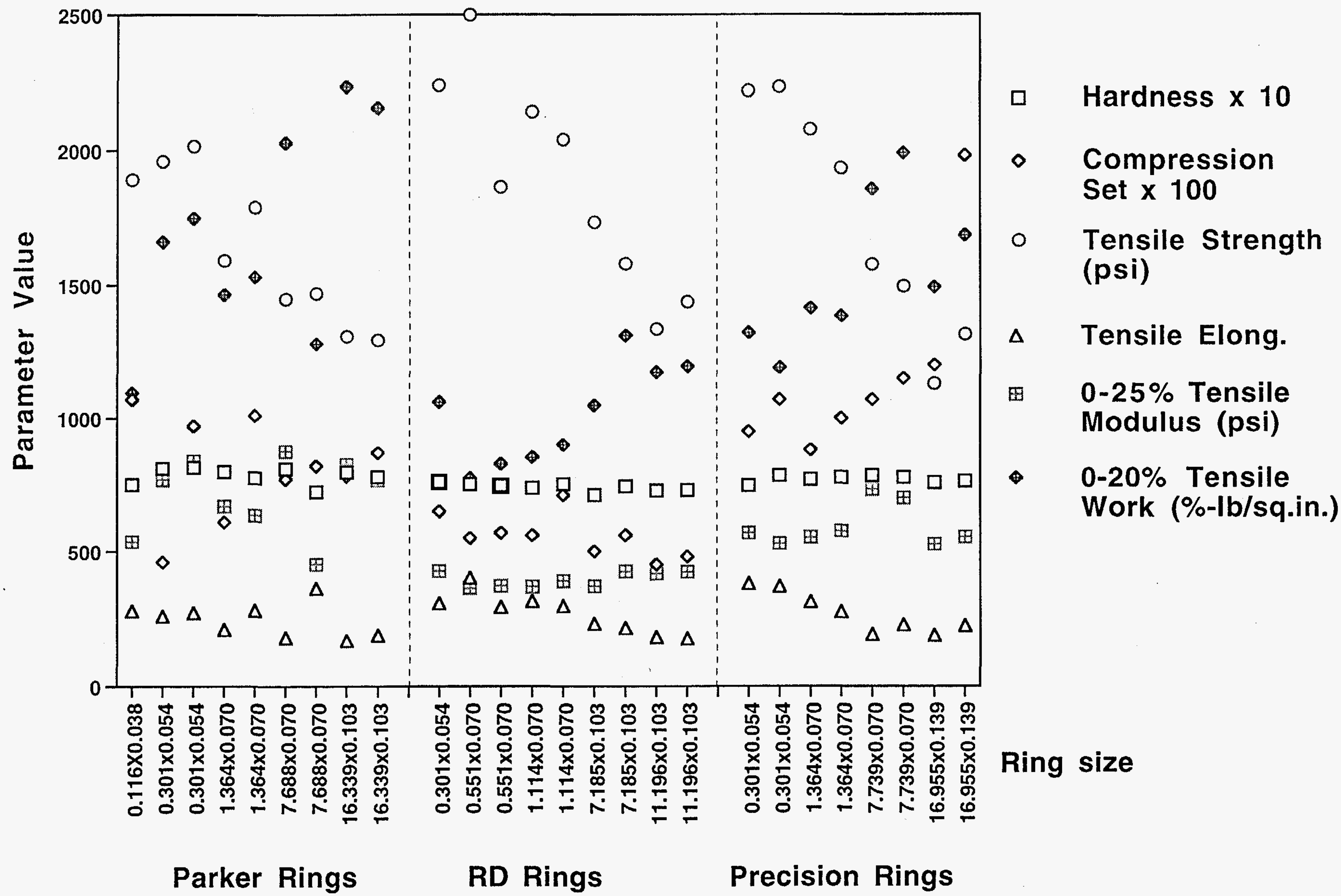


Table 11. Test Data Summary on RD Rubber Materials (Batch 15107) With Differing Cure Schedules

3 min. 12 sec. = 45% cure. 4 min. 18 sec. = 70% cure. 10 min. = 95% cure

Ring Size	Cure Time	Hardness		Comp. Set	Tensile Strength (psi)		Tensile Elongation		0-25% Ten. Modulus		Ten. Work %-lb/sq in.	
		initial	aged		initial	aged	initial	aged	initial	aged	initial	aged
0.301 x 0.054	3 min. 12 sec.	76	81	7.9	2429	2556	340	276	469	547	997	1100
	4 min. 18 sec.	76	80	7.0	2374	2369	334	284	433	471	949	948
	10 min.	76	79	6.5	2236	2423	308	303	427	494	1061	1076
1.114 x 0.070	3 min. 12 sec.	73	80	10.8	2177	2089	319	223	390	479	893	970
	4 min. 18 sec.	73	77	6.6	2119	2099	291	258	391	464	900	1040
	10 min.	75	77	7.1	2039	2153	296	300	390	428	900	1023
7.185 x 0.103	3 min. 12 sec.	73	77	9.8	1879	1751	218	155	513	588	1260	1411
	4 min. 18 sec.	73	78	14.5	1170	1641	153	159	479	556	1366	1192
	10 min.	74	76	5.6	1579	1255	215	171	424	474	1310	1375
11.196 x 0.103	3 min. 12 sec.	72	77	8.0	1746	1902	228	184	421	546	1073	1365
	4 min. 18 sec.	74	77	6.7	1380	1869	190	194	411	514	1050	1310
	10 min.	73	75	4.9	1436	1396	175	152	423	508	1194	1352
Test Slabs	3 min. 12 sec.	67	70	13.5	2116	2034	221	189	613	635	1690	1784
	4 min. 18 sec.	67	70	10.8	2092	1950	247	179	536	640	1534	2090
	10 min.	66	65	12.6	2123	2010	243	220	584	625	1815	1846

1. 70 hours at 212°F plus 24 hours at room temperature.

2. 22 hours compression set aging at 25% compression and 158°F plus 30 min. at room temperature.

Plot 15. Test Values of Unaged RD Samples with Different Cures

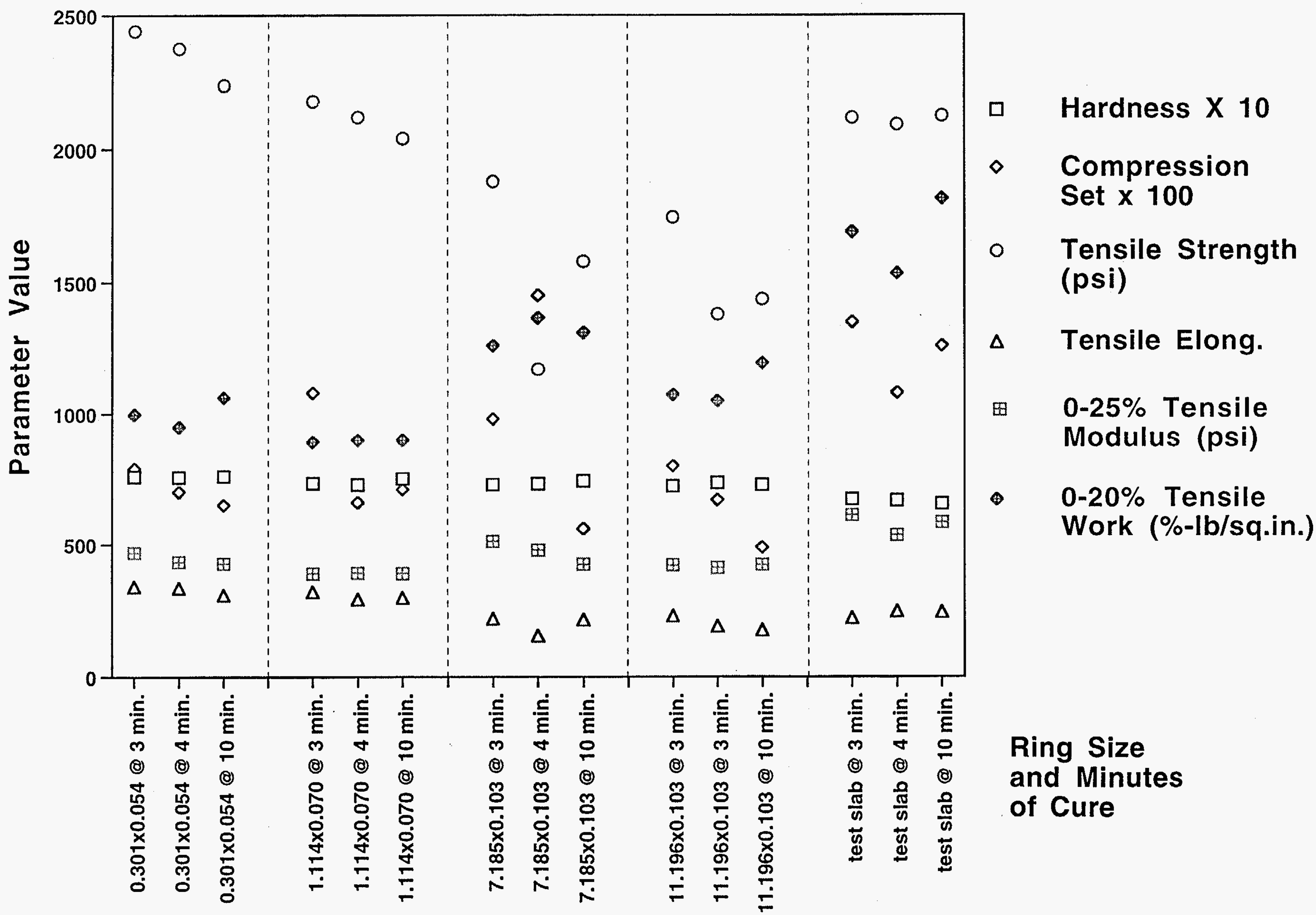


Table 12. Proposed Butyl Rubber O-Ring Physical Testing Requirements

Property	Requirement	Test Method	Test Sample***
Specific gravity	1.14±0.02	ASTM-D-297 (pycnometer or hydrostatic)	any suitable piece of O-ring
Hardness	70-85 Shore M pts before aging. Maximum change of 4 pts after aging*.	Appendix A	5 small O-rings, each tested at 2 sites, or 3 large O-rings, each tested at 4 sites
Compression set**	10% maximum after aging 22 hours at 158 hours under 25% compression.	Appendix B	5 small O-rings, each cut into halves, or 3 large O-rings, each providing 4 slices about 2 in. long
Tensile strength at break	Minimum to be defined and to vary, possibly from 1200 to 1800 psi with decreasing ring size (see Table 6). Maximum ±15% change after aging*.	Appendix C	5 rings before and 5 rings after aging
Tensile elongation at break	Minimum to be defined and to vary, possibly from 150 to 225% with decreasing ring size (see Table 6). Maximum ± 15% change after aging*.	Appendix C	5 rings before and 5 rings after aging
Tensile modulus (from 0-25% elongation)	Minimum to be defined, possibly about 350 psi. Maximum +15% change after aging*.	Appendix C	5 rings before and 5 rings after aging

* Hardness and tensile aging conditions: 70 hours at 212°F.

** 10% compression set maximum corresponds to a maximum reduction in original thickness of 10% x 25% = 2.5%.

*** Test plans in the table are suggestions based on the procedures used in this report. Final sampling plans will need to incorporate statistically valid sampling rates for O-rings lots of different ring counts.

Acknowledgments

This program was initiated by Bob Anderson of the W87 group and benefited heavily from his active involvement. The successful implementation of any revisions to the current test procedures could not have happened without his involvement plus the enthusiastic cooperation of people at Kansas City. Julie Stuckey, Mark Wilson, Tom Snider and Ed Kibalo were all active collaborators as well as discerning customers. All the ring visual inspections were carried out at Kansas City and the materials required for the cure study were procured through KC. Even more important have been the continuous and open discussions regarding the history and issues involved in revising these O-ring test procedures.

The vast majority of the testing, data assembly, vendor contacts, sample exchanges with KC, and any other tasks were all very capably handled by co-author Kevin Wagter.

The tensile test procedures were developed and tests performed by John Totten and the innovative split-spool tensile fixtures were designed and procured by John Korellis. Molly Jacobs made the numerous initial contacts and orders with O-ring and equipment vendors and Ja Lee Yio made many of the very early hardness and ring thickness measurements. DSC characterization of the slabs and rings with different cures and of the various aged samples was carried out by Don Meeker.

Valuable suggestions were made by Craig Henderson and by Ken Gillen who also contributed his long experience in aging studies.

Appendix A: Proposed Test Method for Rubber O-Ring Hardness

(to be reformatted and issued as test specification 9951007A)

Test Method for Rubber O-Ring Hardness

1. Scope

1.1 This test method describes a procedure for measuring the hardness of rubber O-ring samples. The hardness is obtained by the difference in penetration depth of a probe of specified dimensions under two contact conditions: (1) with a small initial force and (2) with a much larger final force. The differential penetration is automatically taken at a specified time and converted to a hardness scale value.

2. Significance and Use

2.1 International Hardness tests are based on measurement of the penetration of a rigid probe into the rubber specimen under specified conditions. The measured penetration is converted into International Rubber Hardness Degrees ranging from zero to 100 where 100 represents a material of infinite elastic modulus.

3. Summary of Method

3.1 O-rings are marked for identification and positioning as test specimens.
3.2 Initial hardness measurements on test specimens are taken and recorded.
3.3 Test specimens are heat aged for 70 hours at 212°F..
3.4 Final hardness measurements on test specimens are taken and recorded approximately 24 hours after removal from the oven.
3.5 The heat aging difference is calculated from the average initial and final hardness measurements.

4. Apparatus

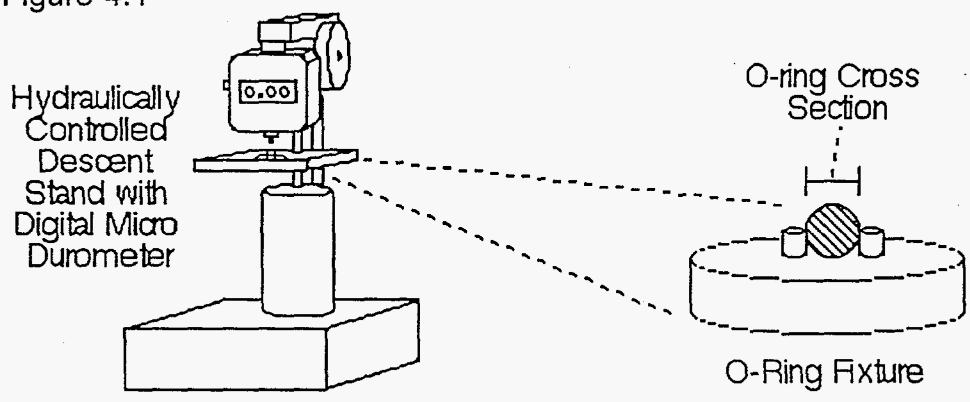
4.1 Micro Durometer- (See Figure 4.1)

4.1.1 A Shore M Digital Micro Durometer with a resolution of ±0.01 points is required. Dial durometers are not suitable. The durometer should automatically record the hardness 1 second after impact.

4.1.2 The durometer must be mounted in a hydraulically controlled stand.

4.1.3 Double pin fixtures are required to hold the ring in place. Fixtures of a standard range are typically provided with the durometer. If the O-rings have a cross section not covered, a custom sized fixture should be ordered.

Figure 4.1



4.2 Oven- A force ventilated or gravity convection oven capable of maintaining a uniform temperatures of 212±10°F should be used. The oven should contain blocks or a fixtured perforated rack at least one inch, preferably several inches, above the oven floor to support the aging rack. An additional verifying temperature chart recorder is desirable.

4.3 Heat Aging Rack-

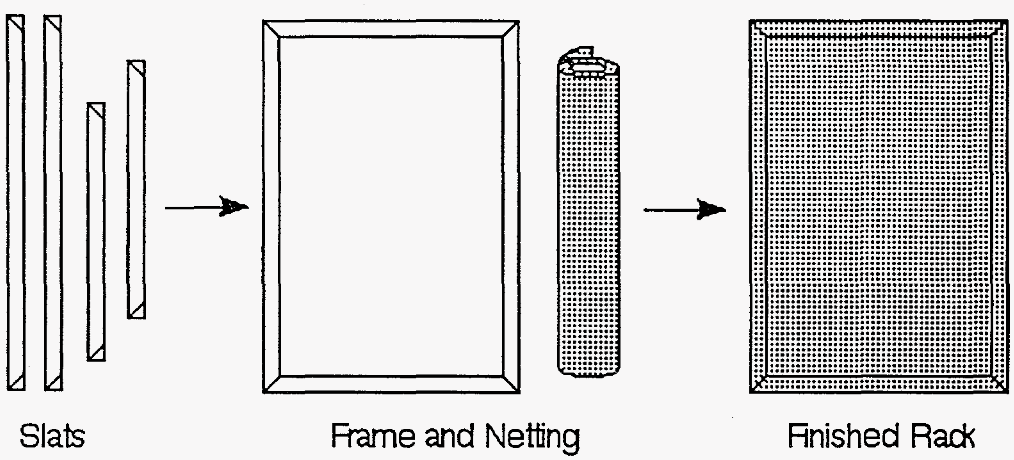
4.3.1 The rack should have a flat, non-heat conducting surface that does not restrict air flow around the O-rings.

4.3.2 The rack frame can be made by assembling custom wood frame segments (used to build frames for painting canvases and available at crafts or art supply stores) or any thin wood slats (available at hardware stores).

4.3.3 The surface can be made out of any natural loose weave material. It needs to be open enough to allow air flow while being tight enough to completely support the O-rings. Needle point netting (available crafts or fabric supply stores) seems to work best, but any equivalent material will do. Avoid synthetic fibers which might contaminate or adhere to the O-rings.

4.3.4 Stretch the fabric over the frame like a canvas and staple it in place.

Figure 4.3



5. Number of Test Specimens

5.1 Sacrificial O-rings must be of the same size and from the same lot as the O-ring they are to represent.

5.2 Sampling plan. (to be determined)

6. Test Specimen Preparation

6.1 Lay out the O-rings on a flat surface. Arrange them in a flat and relaxed state, approximately circular, with no twists or loops.

6.2 Marking test specimens (See Figure 6.2)

6.2.1 Use water based correction fluid to mark target dots on the specimens.

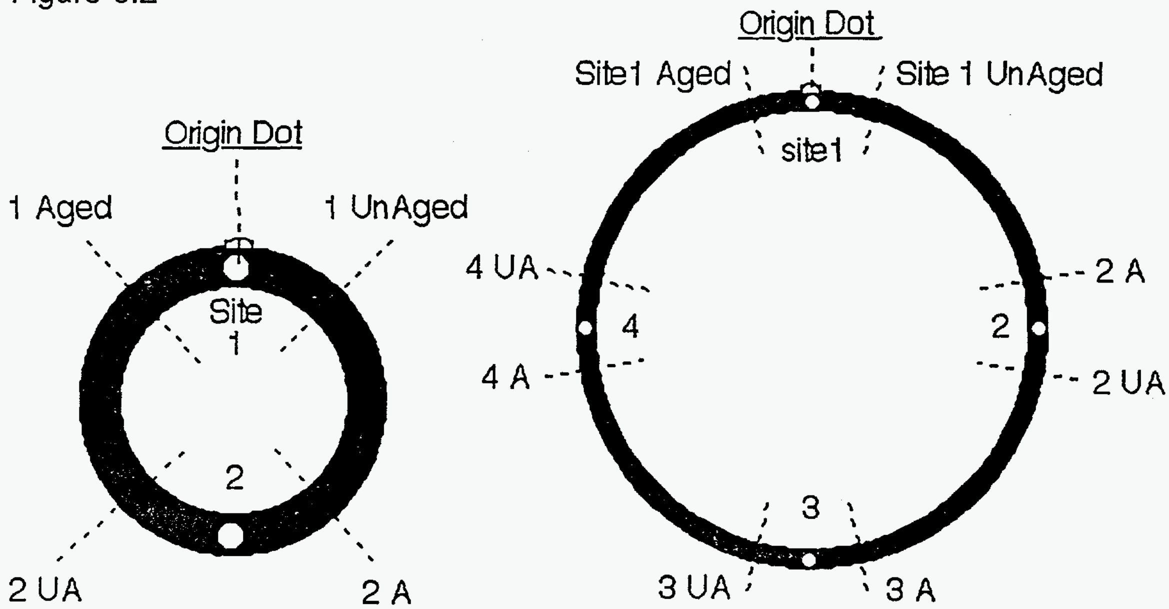
6.2.2a On small O-rings (inside diameter ≤ 2.0 inches) mark two dots approximately 180° apart on the top surface to denote the sampling sites.

6.2.2b On large O-rings (inside diameter > 2.0 inches) mark four dots approximately 90° apart on the top to denote the sampling sites.

6.2.3 The A and UA designations indicate the location of hardness measurements on unaged (UA) and aged (A) samples.

6.2.4 Mark a dot on the outside curve of the O-ring adjacent to a sample dot to denote the "origin".

Figure 6.2



O-Rings ≤ 2.0 inch i.d. O-Rings > 2.0 inch i.d.

7. Test Procedure

7.1 Preparations

7.1.1 Preheat the oven to 212±10°F

7.1.2 With the double pin fixture removed from the durometer platform, raise and drop the durometer assembly ten times to equilibrate the oil in the piston. This will result in a smoother motion over the range of descent, giving more consistent measurements. This should be repeated whenever the durometer has been idle for more than 30 minutes.

7.1.3 Select the appropriate sized double pin fixture for the O-rings being tested and fit it into the durometer platform.

7.1.4 Carefully lower the probe, making sure it does not touch the metal platform. Check to see if the probe is exactly centered between the O-ring pins so that the durometer probe will contact the O-ring at its apex. Realign the platform or the probe if needed until the probe is centered.

7.2 Initial hardness readings

7.2.1 Place the O-rings on the durometer platform in the same orientation as they were marked. For larger O-rings an adjacent flat surface, raised to the height of the durometer with a jack stand, is required to keep the O-ring from being distorted by drooping.

7.2.2 Make sure the O-ring is centered between the two posts of the O-ring fixture with the origin and site 1 dots slightly (about 1/4 inch) to the left of the pins.

7.2.3 There should be no distortions of the O-ring during the measurement. The ring may be held lightly to keep it centered as long as no bending or stretching forces are applied.

7.2.4 Flip the lever that starts the durometer descent. The durometer will take the measurement 1 second after contact with the O-ring. Record the value.

7.2.5 Raise the durometer back to its starting position.

7.2.6 Continue the sampling progression around the O-ring in a clockwise direction. The site dots should always be about 1/4 inch to the left of the pins.

7.2.7 Record vendor, part size, lot number and hardness reading of each site on each O-ring in a log book.

7.3 Heat Aging

7.3.1 Once the initial measurements are taken, place the O-rings on the heat aging rack. Arrange the O-rings so they are flat, relaxed and do not touch one another. The larger rings may have to be doubled over to fit on the rack.

7.3.2 Make a sketch of the layout to keep track of the locations and identity of the O-rings being aged if multiple lots are being tested. If desired, the O-rings may also be identified with tags attached with string.

7.3.3 Place the heat aging rack with O-rings in the preheated oven at 212±10°F for 70.0±0.5 hours.

7.3.4 Use hot gloves to remove the heat aging rack and O-rings from the oven.

7.3.5 Cool the O-rings on the rack for at least 16 and no more than 48 hours.

7.4 Take final hardness readings on the test specimens

7.4.1 Repeat the procedure used above except that all measurements should be made with the dots slightly (about 1/4 inch) to the right of the pins. Measurements may not be made in exactly the same location due to puncturing of the ring surface by the hardness probe.

7.4.2 Record all measurements in a log book.

8. Calculation

8.1 Calculate the change in hardness expressed as difference from the original to final hardness as follows:

$$\Delta H = h_o - h_f$$

where:

where:	ΔH	=	change in hardness
	h_o	=	average original hardness of specimens.
	h_f	=	average final hardness of specimens.

9. Report

The report shall include the following:

9.1 Description of O-ring lot, including vendor, rubber compound and batch number, ring part number, ring size (inside diameter and cross section), lot size (number of O-rings), and date the lot was produced and received.

9.2 Number of O-rings used, date and time of the test, and ambient temperature.

9.3 Test Results

9.3.1 Original average hardness, h_o, of the O-rings.

9.3.2 Final average hardness, h_f of the O-rings.

9.3.3 Change in hardness, expressed as the difference in points between the average initial and average final hardness of the samples.

Appendix B: Proposed Test Method for Rubber O-Ring Compression Set

(to be reformatted and issued as test specification 9951009A)

Test Method for Rubber O-Ring Compression Set

1. Scope

1.1 This test method describes a procedure for measuring the compression set of rubber O-ring samples under constant deflection conditions in air.

2. Significance and Use

2.1 Compression set tests measure the ability of rubber compounds to retain elastic properties after prolonged compressive stresses. The testing involves the maintenance of a fixed deflection at an elevated temperature. Compression set tests are primarily applicable to service conditions involving static stresses.

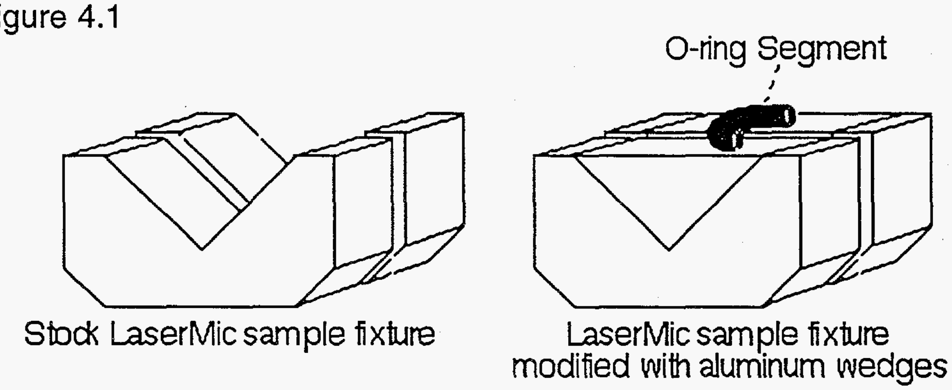
3. Summary of Method

3.1 O-rings are cut and marked for identification and positioning as test specimens.
3.2 Initial cross section thickness measurements on test specimens are taken and recorded.
3.3 Test specimens are compressed to a constant deflection and maintained under this condition for 22 hours at 158°F.
3.4 Final cross section thickness measurements on test specimens are taken and recorded 30±10 minutes after removal from the compression device.
3.5 The compression set value is calculated from the average initial and final thickness measurements.

4. Apparatus

4.1 Laser Micrometer- A laser micrometer capable of measuring sample thickness with a resolution of ±0.0001 in. is required. Fixtures typically provided with such micrometers must be modified (see Figure 4.1) to provide a flat plane on which the O-ring samples can be placed. Use of such flat plane fixtures allows alignment of the compressed plane of the ring segments parallel to the laser reading beam

Figure 4.1



4.2 Compression Device-

4.2.1 Samples are to be compressed in a constant deflection device consisting of two or more parallel compression plates assembled by means of a frame or threaded bolts. The device shall be portable and self-contained after assembly and designed such that the parallelism of the plates can be maintained.

4.2.2 The plates between which the test specimens are compressed shall be made of steel of sufficient thickness (typically 0.5 in.) to withstand the compressive stresses without bending. The surfaces against which the specimens are held shall have a highly polished chrome-plated finish and shall be cleaned thoroughly and wiped dry before each test.

4.3 Spacer Bars- A set of 4 steel spacer bars are required, per layer, to maintain the constant deflection distance of 75% of the nominal Cross Section diameter of the O-rings being tested (± 0.001 inch).

4.4 Oven- A force ventilated or gravity convection oven capable of maintaining a uniform temperature of 158±10°F shall be used. The oven should contain a sturdy rack at least one inch, preferably several inches, above the oven floor to hold the compression set apparatus. An additional verifying temperature chart recorder is desirable

4.5 Cooling surface- A surface with low thermal conductivity, such as wood or cardboard covered with a clean layer of paper, should be used as a cooling surface.

5. Number of Test Specimens

5.1 Sacrificial O-rings must be of the same size and from the same lot as the O-rings they are to represent.

5.2 Sampling plan (to be determined)

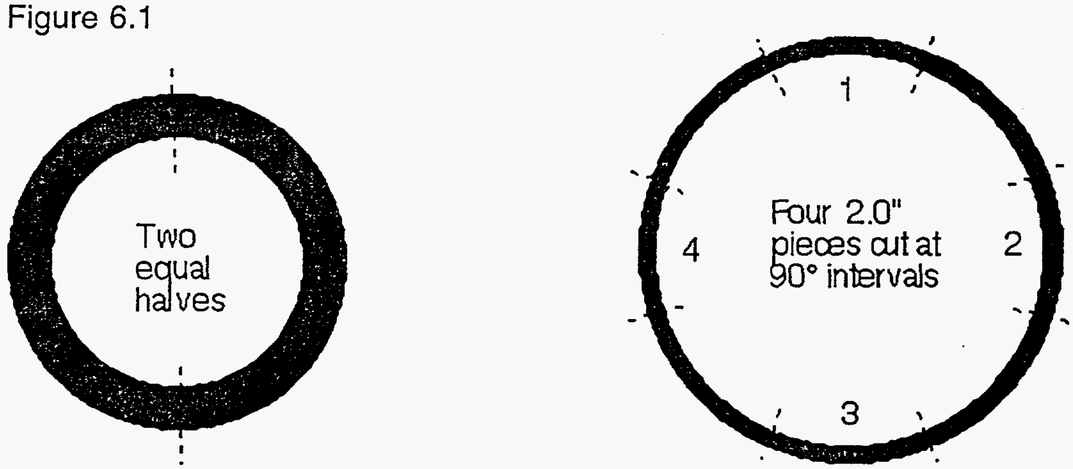
6. Test Specimen Preparation

6.1 Cutting test specimens (See Figure 6.1)

6.1.1 Small O-rings (< 2.0 inch inside diameter) are to be cut in half to give two specimens per O-ring.

6.1.2 Large O-rings (> 2.0 inch inside diameter) are to be cut into quarters, and a 2.0 inch specimen then cut from the end of each quarter. The rest of the O-ring pieces may be discarded or used for other tests.

Figure 6.1



O-Rings ≤ 2.0 in. id

O-Rings > 2.0 in. id

6.2 Lay out the cut test specimens on a flat surface. Roll the specimens gently about until they are flat and stable.

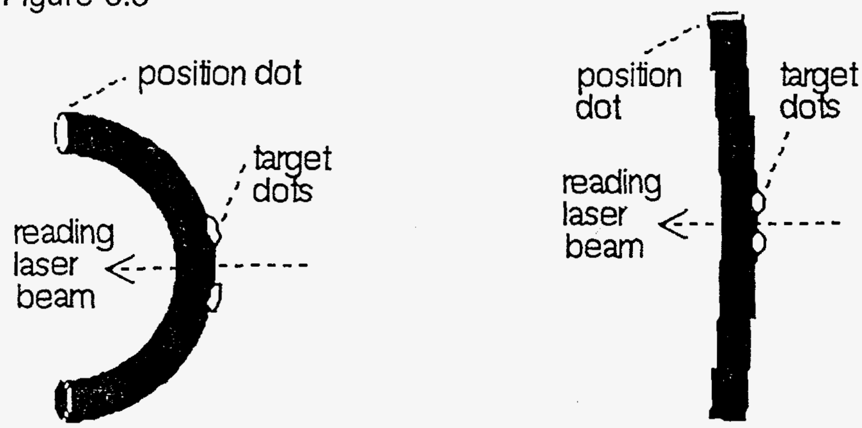
6.3 Marking test specimens (See Figure 6.3)

6.3.1 Use water based correction fluid to mark target dots on the specimens.

6.3.2 Mark two target dots, approximately 5 mm apart, about midway along the outside curve of the O-ring segment to denote the measurement area.

6.3.3 Mark a position dot on the top end of the segment to denote orientation

Figure 6.3



7. Test Procedure

7.1 Preparations

7.1.1 Preheat oven to 158±10°F

7.1.2 Clean the surfaces of the compression plates that will come in contact with the O-rings with alcohol (methanol, ethanol, or isopropanol) and wipe dry with lint free cloth or paper.

7.1.3 Spray the surfaces with a thin coat of dry Teflon mold release and rewipe.

7.1.4 Turn on, calibrate if necessary, and center the laser micrometer.

7.2 Initial thickness readings

7.2.1 Place test segments on the laser micrometer platform in the same orientation as they were marked, with the reading laser centered between the two target dots (See Figures 6.3 & 7.3).

7.2.2 Record vendor, part size, lot number, and thickness reading of each specimen in a log book.

7.3 Compressing test specimens

7.3.1 Place the compression set apparatus on a flat surface and remove the top nuts and top plates, leaving only the bottom plate and compression screws.

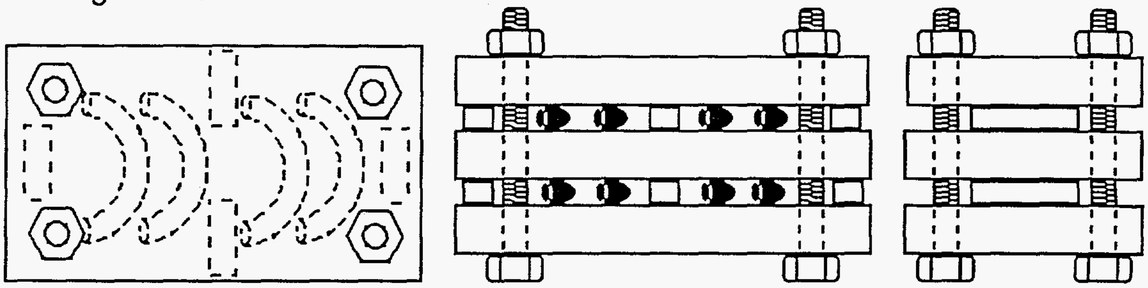
7.3.2 Place the test specimens on the bottom compression plate in the same flat and relaxed manner with the dots to the side as was used in taking the initial thickness reading. Specimens should not touch each other or the screws.

7.3.3 Select spacers that are 75% of the nominal cross section of the O-rings that are being tested (see Table 7.3). Wipe any oil or dirt off the spacers and place them on the plates. Make sure the spacers do not touch the specimens.

Table 7.3

O-ring Cross Section Diameter	Appropriate Spacer Thickness
0.038 inches	0.0285 inches
0.054 inches	0.0405 inches
0.070 inches	0.0525 inches
0.103 inches	0.0772 inches
0.139 inches	0.1042 inches

Figure 7.3



7.3.4 A second layer plate, set of specimens and appropriate spacers may be added if desired.

7.3.5 Replace top plate and nuts, being careful not to disturb the specimens and spacers.

7.3.6 Finger tighten and then use a pair of wrenches to tighten down the plates. Cross tighten the nuts using half turns to keep the pressure as even as possible. Keep tightening the nuts until all the specimens are flattened and the spacers don't slide out when the assembly is tipped sideways. If there are many O-ring pieces this may require a lot of torque.

7.4 Place the assembled compression set apparatus in the preheated oven at 158±10°F for 22.0±0.5 hours.

7.5 Cooling

7.5.1 Use hot gloves to remove the compression apparatus from the oven.

7.5.2 Immediately loosen and remove the nuts in reverse manner of how they were tightened and separate the plates.

7.5.3 Gently scrape the test specimens off the plates with a flat sheet of paper or a blade being careful not to bend or stretch them.

7.5.4 Place the O-ring segments on a clean piece of paper on a flat piece of wood in the same positions as when their initial thickness measurements were taken and let them cool for 30-60 minutes.

7.6 Take final thickness readings on the test specimens

7.6.1 Follow the same procedure used for the initial readings to take the final readings. Measurements should be made as close to the same orientation and location as the initial measurements.

7.6.2 Again record all measurements in a log book.

8. Calculations

8.1 Calculate the actual percent compression of the O-ring speciments as follows: (This value indicates how close the actual compression was to the target 75%.)

$$T\% = [(t_o - t_b) / t_o] \times 100$$

where:

T%	=	actual percent compression of the specimens.
t_o	=	average original thickness of the specimens.
t_b	=	thickness of spacer bar used.

8.2 Calculate the compression set expressed as a percentage of the imposed compression as follows:

$$C = [(t_o - t_f)/(t_o - t_b)] \times 100$$

where:

C = compression set.
t_o = average original thickness of the specimens.
t_f = average final thickness of the specimens.
t_b = thickness of spacer bar used.

9. Report

The report shall include the following:

9.1 Description of O-ring lot, including vendor, rubber compound and batch number, ring part number, ring size (inside diameter and cross section), lot size (number of O-rings), and date the lot was produced and received.

9.2 Number of specimens used, date and time of the test, and ambient temperature.

9.3 Test Results

- 9.3.1 Original average thickness, t_o, of the test specimens.
- 9.3.2 Final average thickness, t_f, of the test specimens.
- 9.3.3 Size of spacers used, t_b.
- 9.3.4 Actual percentage compression of the specimen, $T_{\%}$.
- 9.3.5 Compression set, expressed as a percentage of the original deflection, C.

Appendix C: Proposed Test Method for Rubber O-Ring Tensile Properties

(to be reformatted and issued as test specification 9951008A)

Test Method for Rubber O-Ring Tensile Properties

1. Scope

1.1 This test method describes a procedure for measuring the ultimate strength, ultimate elongation and linear modulus at 25% elongation of rubber O-rings before and after aging in air.

2. Significance and Use

2.1 The tensile properties of intact rubber O-rings reflect the bulk properties, the level of defects, and surface aging effects of the materials. Specific fixtures are used in the test which differ slightly from those used in ASTM tests and which accomodate multiple loops of larger O-rings. Different test elongation speeds are used for single vs. multiple looped rings.

3. Summary of Method

3.1 Two identical sets of O-rings are bagged and labeled as test specimens.

3.2 Initial tensile measurements on the first set of test specimens are taken and recorded.

3.3 The second set of test specimens is heat aged for 70 hours at 212°F.

3.4 Final tensile measurements on the second set of test specimens are taken and recorded approximately 24 hours after removal from the oven.

3.5 The heat aging difference is calculated from the average initial and final tensile measurements.

4. Apparatus

4.1 Testing Machine-

4.1.1 Tensile tests shall be made on a screw driven machine equipped to produce uniform grip separation speeds between 5 and 20 inches/minute for a distance of at least 30 inches. Different speeds are used for smaller and larger O-rings to insure adequate data collection times for the smaller rings and reasonable test times for the larger rings. No significant sensitivity of the tensile data to test speed has been noted within the ranges used.

4.1.2 The testing machine shall have both a suitable load cell and a recording device for measuring the applied force within ±2%. Both chart recorders and computer controlled recorders may be used if they provide suitable resolution.

4.2 Test Fixtures- All tests will be conducted on Sandia furnished fixtures or fixtures designed to Sandia specifications.

4.2.1 The base fixtures are shown in Figure 4.2 and are designed to fit a standard screw driven test machine.

4.2.2 The split spool fixtures are made with a range of groove and spool sizes to accommodate different O-rings and are designed to fit interchangeably on the base fixtures.

4.2.3 The spools required for different O-ring sizes, and the initial spool separation distance for each O-ring size are given in Table 4.2

4.3 Oven- A force ventilated or gravity convection oven capable of maintaining a uniform temperatures of 212±10 °F should be used. The oven should contain blocks or a fixtured perforated rack at least one inch, preferably several inches, above the oven floor to support the aging rack. An additional verifying temperature chart recorder is desirable.

Figure 4.2

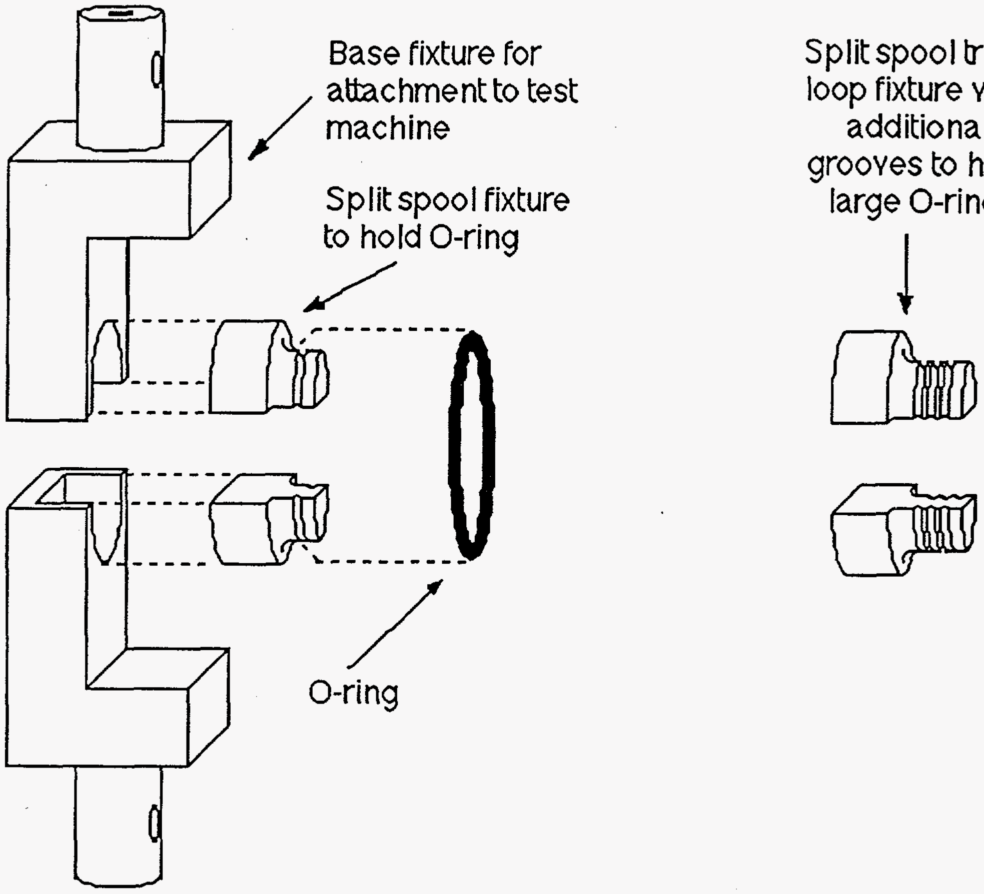


Table 4.2 O-Ring Dimensions and Corresponding Fixture and Test Parameters

O-ring inside diameter (id)	O-ring cross section (cs)	spool diameter (D)	groove diameter	number of loops (#)	initial fixture gap distance (L_i)	fixture speed (in./ min.)
0.116 in.	0.038 in.	0.090 in.	0.038 in.	1	0.041 in.	5.0
0.301 in.	0.054 in.	0.196 in.	0.054 in.	1	0.165 in.	5.0
0.652 in.	0.070 in.	0.250 in.	0.070 in.	1	0.631 in.	5.0
1.239 in.	0.070 in.	0.250 in.	0.070 in.	1	1.554 in.	5.0
1.301 in.	0.070 in.	0.250 in.	0.070 in.	1	1.651 in.	5.0
1.364 in.	0.070 in.	0.250 in.	0.070 in.	1	1.750 in.	5.0
1.487 in.	0.103 in.	1.000 in.	0.103 in.	1	0.765 in.	5.0
1.739 in.	0.070 in.	0.250 in.	0.070 in.	1	2.339 in.	5.0
1.913 in.	0.070 in.	0.250 in.	0.070 in.	1	2.612 in.	5.0
7.688 in.	0.070 in.	1.040 in.	0.070 in.	3	2.392 in.	20.0
16.339 in.	0.103 in.	1.000 in.	0.103 in.	3	6.984 in.	20.0

4.4 Heat Aging Rack- (See Figure 4.4)

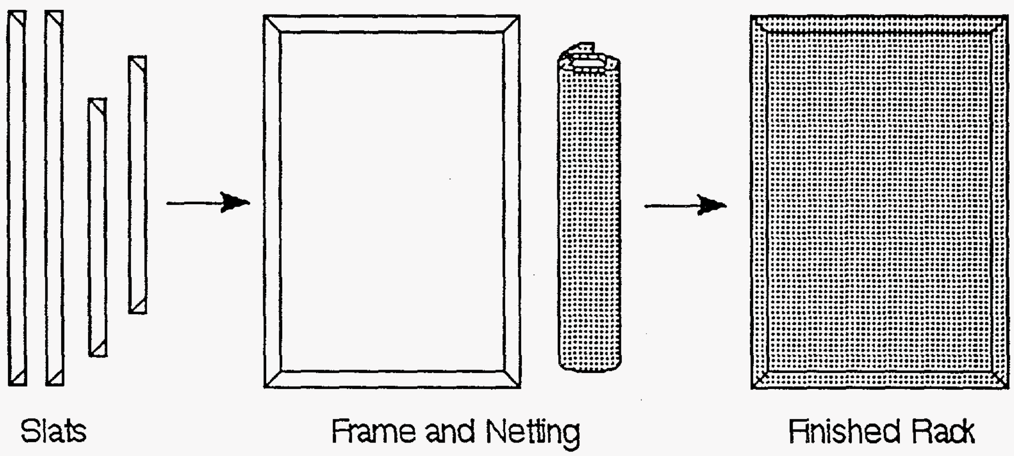
4.4.1 The rack should have a flat, non-heat conducting surface that does not restrict air flow around the O-rings.

4.4.2 The rack frame may be made by assembling custom wood frame segments (used to build frames for painting canvases and available at crafts or art supply stores) or any thin wood slats (available at hardware stores).

4.4.3 The surface can be made out of any natural loose weave material. It needs to be open enough to allow air flow while being tight enough to completely support the O-rings. Needle point netting (available at crafts or fabric supply stores) seems to work best, but any equivalent material will do. Avoid synthetic fibers which might contaminate or adhere to the O-rings.

4.4.4 Stretch the fabric over the frame like a canvas and staple it in place.

Figure 4.4



5. Number of Test Specimens

5.1 Sacrificial O-rings must be of the same size and from the same lot as the O-ring they are to represent.

5.2 Sampling plan (to be determined)

6. Test Specimen Preparation

6.1 Select and label two sets of O-rings, designating one set "non-aged" and the other as "aged". It is convenient to store the O-rings in labeled plastic bags.

7. Test Procedure

7.1 Preparations

7.1.1 Preheat oven to 212±10°F.

7.2 Heat Aging

7.2.1 Place the O-rings which are later to be used to determine "aged" tensile properties on the heat aging rack. Arrange the O-rings so they are flat, relaxed and do not touch one another. Some of the largest O-rings may have to be doubled over to fit on the rack.

7.2.2 Place the heat aging rack with O-rings in the preheated oven at 212±10°F for 70.0±0.5 hours.

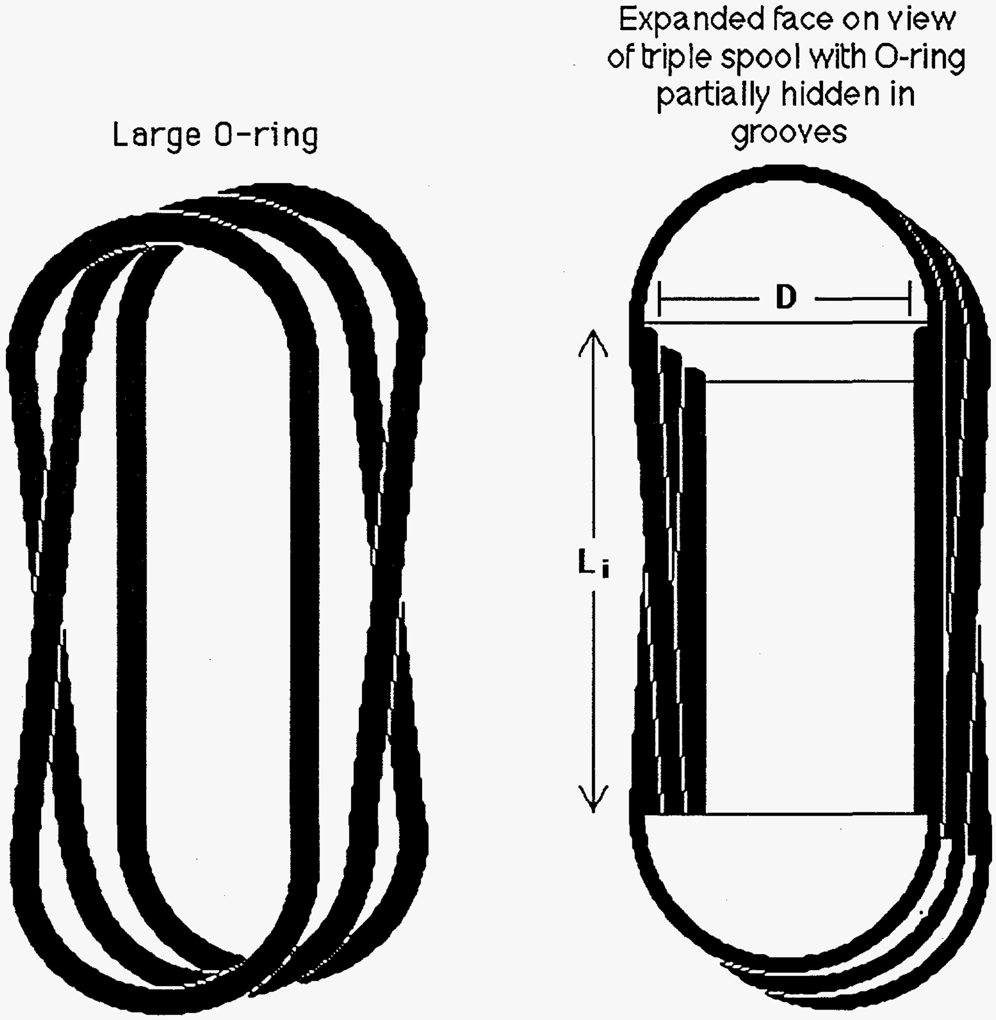
7.2.3 Use hot gloves to remove the heat aging rack and O-rings from the oven.

7.2.4 Cool the O-rings on the rack for at least 16 and no more than 48 hours.

7.3 Initial tensile readings on "non-aged" test specimens

7.3.1 Select the appropriate sized split spool O-ring fixture for the O-rings being tested and fit it into the base fixture (see Table 4.2). O-rings with inner diameters of 7.185 inch or larger shall be tested using the three loop configuration to insure adequate elongation and ring failure. The required crossings in the multi-looped configurations should be arranged such that there is single crossing of strands on each side of the spools (see Figure 7.3).

Figure 7.3



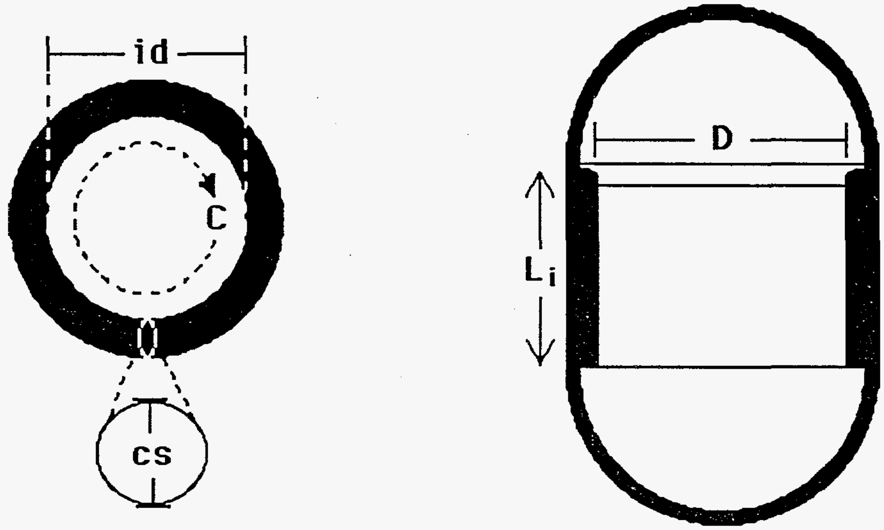
7.3.2 Bring the two halves of the split spool fixture together and reset the gap distance (L) to zero.
7.3.3 Adjust the initial gap distance (L_i) to the value given in Table 4.2 for the O-ring being tested.
7.3.4 Lubricate the O-ring with mineral oil and install the O-ring in the groove(s) of the split spool spindle.
7.3.5 Reset the strain force (F_i) equal to zero.
7.3.6 Set the fixture separation speed at either 5 inches/minute (for single-looped rings) or 20 inches/minute (for larger, triple-looped rings).
7.3.7 Start the stress-strain recording device and begin elongation at the selected speed. Continue elongation until sample failure.
7.3.8 Identify and save data as appropriate to the chart recorder or computer.
7.3.9 Repeat the procedure on the remaining O-rings.

7.4 Tensile measurements on the "aged" test specimens should follow the same procedure used for the initial measurements. The aged O-rings should be tested 16 to 48 hours after removal from the oven, preferably about 24 hours.

8. Data Analysis

8.1 Definitions (see Figure 8.1)

Figure 8.1



i.d. = the nominal **i**nside **d**iameter of the O-ring.
c.s. = the nominal **c**ross **s**ection diameter of the O-ring.
C = the inside **C**ircumference of the O-ring. ($C = id \times \pi$)
D = the **D**iameter of the split spool fixture.
G = the circumference of the split spool fixture. ($G = D \times \pi$)
L_i = the initial fixture gap distance or **L**ength between the split spool fixtures that corresponds to 0% elongation of the O-ring being tested. These values are given in Table 4.2
for the single looped O-rings $L_i = (C - G) / 2$
for the triple looped O-rings $L_i = (C - 3G) / 6$
F_i = the initial Force when the split spool fixtures, with O-ring installed, are set to L_i By definition, $F_i = 0$.
L_x and F_x are the fixture gap distance and corresponding force at any point "x" during the test. $L_{25\%}$ and $F_{25\%}$ are used for the modulus calculations.
L_f and F_f are the final fixture gap distance and corresponding force at the maximum elongation before break.

8.3 Calculations

8.3.1 Maximum Elongation at break ($e\%_{max}$) is calculated as a percentage of the original O-ring circumference:

8.3.1a Elongation for single looped small O-rings

$$e\%_{max} = [(2 \times \Delta L_f) / C] \times 100 \quad \text{where} \quad \Delta L_f = L_f - L_i$$

8.3.1b Elongation for triple looped large O-rings

$$e\%_{max} = [(6 \times \Delta L_f) / C] \times 100 \quad \text{where} \quad \Delta L_f = L_f - L_i$$

8.3.2 Maximum Strength (S_{max}) is calculated as pounds per square inch.

8.3.2a Strength for single looped small O-rings

$$S_{max} = \Delta F_f / [2 X (cs / 2)^2 X \pi] \quad \text{where} \quad \Delta F_f = F_f - F_i$$

8.3.2b Strength for triple looped larger O-rings

$$S_{max} = \Delta F_f / [6 X (cs / 2)^2 X \pi] \quad \text{where} \quad \Delta F_f = F_f - F_i$$

If the recording device has been reset such that F_i is zero, then $\Delta F_f = F_f$ in the above calculations.

8.3.3 Modulus is calculated as pounds per square inch. Use Table 8.3.3 to find the $L_{25\%}$ Distance value corresponding to the O-rings being tested. Convert the $L_{25\%}$ value to a $F_{25\%}$ Force value using the Force vs Distance graph for that O-ring (see the example in Figure 8.3)

8.3.3a Modulus (or stress at 25% elongation) for single looped rings

$$M_{25} = \Delta F_{25\%} / [2 X (cs /2)^2 X \pi] /0.25 \quad \text{where} \quad \Delta F_{25\%} = F_{25\%} - F_i$$

8.3.3b Modulus (or stress at 25% elongation) for triple looped rings

$$M_{25} = \Delta F_{25\%} / [6 X (cs /2)^2 X \pi] /0.25 \quad \text{where} \quad \Delta F_{25\%} = F_{25\%} - F_i$$

If the recording device has been reset such that F_i is zero, then $\Delta F_{25\%} = F_{25\%}$ in the above calculations.

Figure 8.3 Force vs. Elongation Distance Graph

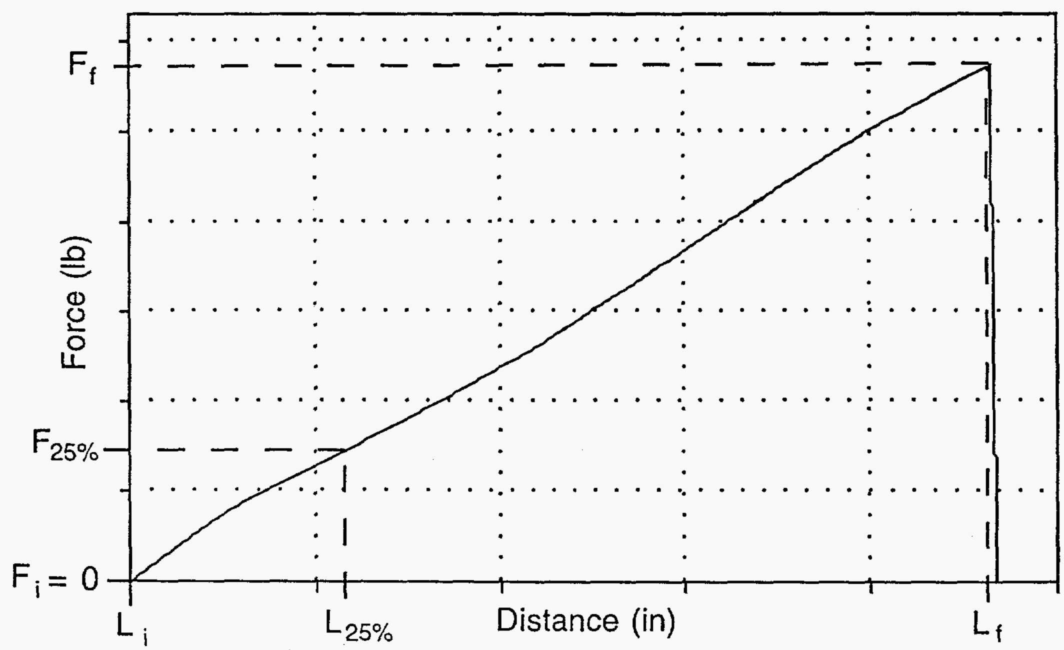


Table 8.3.3 O-Ring and Spool Dimensions and Corresponding Test Parameters

O-Ring Dimensions			Spool Dimensions			Test Parameters				
O-ring inside diameter (inches)	O-ring inside circum. (inches)	O-ring cross section (inches)	spool diameter (inches)	spool circum. (inches)	groove diameter (inches)	no. of loops	initial fixture gap, L_i (inches)	O-ring circum. X125% (inches)	$L_{25\%}$ fixture gap (inches)	$L_{25\%} - L_i$ (inches)
0.116	0.364	0.038	0.090	0.283	0.038	1	0.041	0.455	0.087	0.046
0.301	0.946	0.054	0.196	0.616	0.054	1	0.165	1.181	0.283	0.118
0.652	2.048	0.070	0.250	0.785	0.070	1	0.631	2.559	0.887	0.256
1.239	3.892	0.070	0.250	0.785	0.070	1	1.554	4.863	2.040	0.486
1.301	4.087	0.070	0.250	0.785	0.070	1	1.651	5.106	2.161	0.510
1.364	4.285	0.070	0.250	0.785	0.070	1	1.750	5.354	2.285	0.535
1.487	4.672	0.103	1.000	3.142	0.103	1	0.765	5.836	1.347	0.582
1.739	5.463	0.070	0.250	0.785	0.070	1	2.339	6.826	3.021	0.682
1.913	6.010	0.070	0.250	0.785	0.070	1	2.612	7.509	3.362	0.750
7.688	24.153	0.070	1.040	3.267	0.070	3	2.392	30.175	3.396	1.004
16.339	51.331	0.103	1.000	3.142	0.103	3	6.984	64.131	9.117	2.133

9. Report

The report shall include the following:

9.1 Description of O-ring lot, including vendor, rubber compound and batch number, ring part number, ring size (inside diameter and cross section), lot size (number of O-rings) and date the lot was produced and received.

9.2 Number of O-rings used, date and time of the test, and ambient temperature.

9.3 Test Results

9.3.1 Original average value of $e\%_{max}$ (maximum elongation at break), S_{max} (maximum strength at break) and M_{25} (linear 25% elongation modulus).

9.3.2 Final average value of $e\%_{max}$, S_{max} and M_{25}.

9.3.3 Change in $e\%_{max}$, S_{max} and M_{25} expressed as a percentage of the original values.

Appendix D: Current Butyl Rubber O-Ring Specification (SS453883)

Contents:

1) Table D-1. Current W87 Butyl Rubber O-Rings.

2) Copy of SS453883

Table D-1. Current W87 Butyl Rubber O-Rings (all made from Parker B612-70 per SS453883)

W87 Part No.	Parker No.	Quantity	Application	Size (id x cs in inches)
453907	5-102	13	FSA seal screw/WES deck	0.116 x 0.038
453882	5-710	4	RF conn/mon plug and aft bulkhead	0.301 x 0.054
455915	5-252	1	purge valve cap/valve body (part 458376, Parker 2-112, in Alt 342 list)	0.652 x 0.070
453876	2-026	1	MSAD actuator/WES deck	1.239 x 0.070
453879	2-027	1	MSAD actuator cover/actuator	1.301 x 0.070
453877	2-028	1	FSA/WES deck (det. cable hole)	1.364 x 0.070
453878	2-128	2	CF2703/WES deck & aft bulkhead	1.487 x 0.103
453880	2-031	1	det. conn. cover/FSA	1.739 x 0.070
453881	5-796	1	monitor plug/WES deck	1.913 x 0.070
453875	non-std	1	WES deck/RV body	7.688 x 0.070
453874	non-std	1	aft bulkhead/RV body	16.339 x 0.103
adjusting pin top cover connector cover screws	2-008 2-029 2-017 non-std	1 1 1 2	LLNL parts supplied within actuator assembly	

W87 Non-Butyl Rubber O-Rings

W87 Part No.	Parker Compound	Quantity	Application	Rubber Type
453468	V894-90	1	pit tube/WES deck (SS453864)	Viton
455887	E692-75	1	purge valve/aft bulkhead (SS453414)	EP/EPDM
455888	E692-75	1	purge valve seal (SS453414)	EP/EPDM
452889	E981-50	2	CF2711 & CF2989 conn pad	EP/EPDM
231485-02	E515-80	2	stem seal/valve	EP/EPDM

CAGE CODE 14214

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Released 1-25-96

PREFORMED PACKINGS, ELASTOMERIC REQUIREMENTS FOR W87 (U)

CHANGE HISTORY

CONTROL NUMBER	ISSUE	RELEASE/CHANGE NO.	DATE
SS453883-000	N	951806KC C REV 2	1/96

1. GENERAL

1.1. Scope.

This specification defines the material, design parameters and acceptance requirements for preformed elastomeric packings for the W87.

1.2. Purpose.

The W87 O-rings are intended to maintain a moisture and chemical barrier for a 20 year stockpile life.

1.3. Records.

The Production Agency shall retain records of all tests and certifications indicated in the text for a period of 25 years.

1.4. Definitions.

1.4.1. Design Agency.

Sandia National Laboratories, Livermore, California, Code Ident. 14214.

1.4.2. Production Agency.

AlliedSignal Corporation, Kansas City Division, Code Ident. 14061.

1.4.3. Manufacturer.

R. D. Rubber Technology, Corporation or Parker Hannifin Corporation.

1.4.4. Deleted.

1.4.5. Batch Definition.

A batch shall be that quantity of material compounded at one time either on a mill or in a mixer.

1.4.6. Manufacturer's Cure Date Definition.

The date the preformed packings are manufactured (quarter and year).

1.4.7. Expiration Date.

The first day of the month following the shelf life. Example: Cure date 1Q89 - Shelf life 12 quarters from cure date. Expiration date would be 4/1/92.

2. DOCUMENTS

The following documents form a part of this specification to the extent stated herein.

MIL-STD-413	Visual Inspection Guide for Elastomeric O-rings
MIL-B-131	Barrier Materials, Watervaporproof, Heatsealable
ANSI/ASQC Z1.4	Sampling Procedures and Tables for Inspection by Attributes

3. REQUIREMENTS

3.1. Design.

The preformed packing shall be an O-ring type.

3.2. Raw Material.

The preformed packing shall be made from a non-halogenated, Butyl rubber compound.

Approved Compound	Company/Manufacturer
B612-70	Parker Hannifin Corporation,

3.3. Dimensions and Tolerances.

a. The dimensions and tolerances are given on individual drawings.

b. Maximum allowable flash extension is 0.003 inch and maximum allowable flash thickness is 0.005 inch.

3.4. Physical Properties.

The physical properties of the preformed packings shall meet the requirements listed in Table 1 when tested on ASTM test sheets.

TABLE 1:

Property	Values	Test Method
Original		
Tensile Strength, psi	1600 minimum	ASTM-D-412
Elongation, %	200 minimum	ASTM-D-412
Hardness, Shore A pts.	65-75	ASTM-D-2240
Specific Gravity	1.14 ±0.02	ASTM-D-297
Air Age, 70 ±0.1 hours		
@ 212 ±5°F		3.4.1
Tensile Strength, psi	±15% max change	ASTM-D-412
Elongation	±15% max change	ASTM-D-412
Hardness, Shore A, pts.	10 pts. max change	ASTM-D-2240
Air Age, 22 ±0.1 hours		
@ 158 ±5°F	15% maximum	ASTM-D-395, Method B
Compression Set		

3.4.1. Air Aging.

Air Aging for 70 ±.1 hours at 212 ±5°F. The test specimens shall be aged per ASTM-D-573 and cooled at room temperature for 24 hours ±2 hours prior to testing per Table 1.

3.5. Workmanship.

a. Each preformed packing shall be consistent with requirements established in MIL-STD-413. There must be no defects or foreign materials in the rubber which will alter its ability to form a seal or endanger longevity by chemical interactions. Questionable flaws should be cleared with the KC product engineer for approval or rejection.

b. When an off-resigter (mismatch) condition exists that is acceptable per MIL-STD-413, any cross-section diameter measurements, other than 90° from the parting line, shall be an average of two measurements taken approximately equidistant in opposite directions from the parting line.

3.6. Identification.

Permanent marking is not required on the individual preformed packing. Product shall be identified by markings on unit packages specified in 5.1. Temporary marking of packings for the manufacturer's identification are allowed, but shall in no way affect the properties or function of the packings.

3.7. Shelf Life.

The manufacturer's cure date shall be designated by the quarter and year in which the O-ring was cured (i.e. 1Q96 would designate an O-ring cured during the first quarter of 1996). The shelf life of the O-ring shall be 36 months from the end of the quarter designated as the cure date. The expiration date is the first day of the month following the shelf life (i.e. for a cure date of 1Q96, the expiration date would be 4/1/99).

4. QUALITY PROVISIONS

4.1. Manufacturer's Certification.

The manufacturer shall identify the material content of the product by compound number, batch or lot number, and cure date.

4.2. Production Agency Inspection.

4.2.1. Sampling.

An AQL of 0.25, general inspection level II per ANSI/ASQC Z1.4 is required. If the sample fails, 100% inspection of the entire lot is acceptable for lot disposition. Any portion of the parts returned to the Supplier or scrapped shall not be considered part of the 100% inspection.

4.2.2. Dimensional Inspection.

The Production Agency shall verify conformance with individual drawings.

4.2.3. Physical Properties.

a. The Production Agency shall verify properties on ASTM test sheets molded from the same batch of material and molded within 30 days of the product the test sheets represent. Properties shall meet the requirements and shall be determined per 3.4.

b. Manufacturer's certification shall be verified on each shipment of product. The manufacturer shall certify that the product conforms to 3.4. Actual test data shall be furnished with each lot submitted for acceptance.

c. For the purposes of physical properties verification, the properties for several part numbers may be combined to meet the requirements of this specification provided the requirements of 4.2.3.a are met.

4.2.4. Workmanship.

The Production Agency shall examine the preformed packing per 3.5.

5. PACKAGING AND HANDLING

5.1. Packaging Material.

Heat sealable, foil lined, kraft bag per MIL-B-131, Class 2.

5.1.1. Supplier.

The supplier shall ship preformed packings to KCD sealed in either bulk or individual packaging per 5.1. The supplier must provide KCD with unsealed individual packaging when using bulk packaging. The supplier must package the preformed packings per 5.1 no later than one quarter from the cure date.

5.1.2. KCD.

Packaging per 5.1.1 must remain sealed until time of inspection. The preformed packings in a package opened for inspection shall be reheat sealed within 45 days in individual packaging per 5.1. After inspection, the sealed packages may not be opened until use.

5.2. Marking.

Each unit package shall be marked with the following information.

Design Agency Part Number
Manufacturer's Name
Manufacturer's Compound Number
Manufacturer's Batch or Lot Number
Manufacturer's Cure Date (Quarter and Year)
Expiration Date:

DO NOT OPEN UNTIL READY FOR INSPECTION OR USE.

5.3. Storage Conditions.

Preformed packings covered by this specification shall be stored by the Production Agency at 45°F to 100°F.

6. ENVIRONMENTS

All seals will encounter the following environments:

Temperature Extremes	Tmax = 100°F Tmin = -25°F Short Term (<2 hrs) Tmax = 175°F Tmin = -30°F
Moisture	Dew Point 50°F External to Sealed Zone
Freon 12	220 ppm max
Ozone	0.60 ppm short term 0.23 ppm long term 0.045 ppm average annual
Salt	21300 ppm by mass of air 2700 long term
Molds and Fungi	Any within the Continental US
Expected Life	20 years after assembly
Intrinsic Radiation	Low Level β

Appendix E: Vendor Information

Contents:

Table E-1. Participating Vendors

Vendor and Phone No.	Address	Items Ordered
Parker Seals O Ring Division 606-269-2351	2360 Palumbo Dr. Lexington, KY 50505	0.301 x 0.054 in. 1.364 x 0.070 in. 7.688 x 0.070 in. 16.339 x 0.103 in. test slabs (6 x 6 x 0.072 in.)
RD Rubber 310-802-7888	13230 E. Firestone Blvd. Suite P Santa Fe Springs, CA 90670	0.551 x 0.070 in. 1.114 x 0.070 in. 7.185 x 0.103 in. 11.196 x 0.103 in. test slabs (6 x 6 x 0.072.in.)
Precision 612-333-7464	742 N. Washington Ave. Minneapolis, MN 55401	0.301 x 0.054 in. 1.365 x 0.070 in. 7.354 x 0.070 in. 16.955 x 0.139 in. test slabs (6 x 6 x 0.072 in.)

Table E-2. Non-participating Vendors

Vendor and Phone No.	Address	Reason for not participating
Apple Rubber Products 716-684-656	310 Erie St. Lancaster, NY 14086	Butyl rubber material made by offshore vendor and cannot guarantee it is non-halogenated.
Bryant Rubber 310-530-2530	1112 Lomita Blvd. Harbor City, CA 90710	No butyl rubber
Burke Rubber 209-571-6400	2250 S. 10th St. San Jose, CA 95112	Custom tooling required
Century Rubber 800-364-9541	21609 Parthenia St. Conoga Park, CA 91304	Custom tooling required
GAPI USA 800-442-4274	P.O. Box 90064-T Dayton, OH 45490-0064	No butyl rubber
Hydroseal 909-279-9981	170 Vander Unit A Corona, CA 91720	Distributor for Precision
Kirkhill Rubber Co. 714-529-4901	Cypress Court Brea, CA 92621	Custom tooling required
Kotek America Inc., 714-863-3126	17752 Cowan St. Irvine, CA 92714	Minimum batch size 1,000 pieces
Lutz Sales Co. 708-437-9393	55 North Lively Blvd. Elk Grove Village, IL 60007	Distributor for Precision
Parco Inc. 909-947-2200	2150 Parco Ave Ontario, CA 91761	Halogenated butyl rubber- Distributor for Kirkhill?
Polyseal 800-274-9722	725 Channing Wy Berkeley, CA 95376	No butyl rubber
Price Rubber 209-239-7478	17760 Ideal Pkwy Manteca, CA 95336	Custom tooling required
Ro-Lab 800-726-1009	8830 W. Linne Road Tracy, CA 95376	Halogenated butyl rubber
R.T. Enterprises 800-423-9272	7540 Linder Ave. Skokie, IL 60077	No butyl rubber
Southwest Rubber & Supply 602-252-9524	4007-TS. 20th St. Phoenix, AZ 85040-1400	Minimum batch size 1,000 pieces
Wynn's Precision, Inc. 602-894-2361	708 West 22nd Street Tempe, AZ 85282	Could not meet material requirements.

Table E-3. Equipment Vendors

Vendor Information	Items Ordered
Instron Corp. (Shore Division acquired through purchase) 100 Royal St. Canton, MA 02021 617-575-5856	Shore M Durometers (digital and dial) plus hydraulic stands and O-ring double pin fixtures. cost: $3921 for Model 2000 digital durmometer and stand plus $250 for custom fixtures Shore Model 910 Thickness Gauge (shown to have inadequate resolution for O-ring measurements). cost: $1251
Laser Mike, Inc. 6060 Executive Blvd. Dayton, Ohio 45424 513-233-9935	Laser Micrometer, Model 183B, plus V-block platform and calibration pins. cost: $6863
E.H. Benz Co. 73 Maplehurst Ave. Providence, RI 02908 800-230-8684	Compression set test fixtures, double layer (smaller and poorer design than those from Custom Scientific, but with better surface finish). cost: $2990
Custom Scientific Instruments 13 Wing Drive Cedar Knolls, NJ 07927 800-229-1274	Compression set test fixtures, double layer (more robust design than those from Benz, but plagued with poor surface finishes and unresponsive technical service). cost: $1900
Charles F. Siebenthal 3819 Osuna, N.E. Albuquerque, NM 87109 505-344-3467	Gauge blocks used as spacers in compression set tests. 8 each of 5 sizes (0.02850, 0.04050, 0.05200, 0.07725, and 0.10425 inches) cost: $1490

Appendix F: Hardness Test Data

Contents:

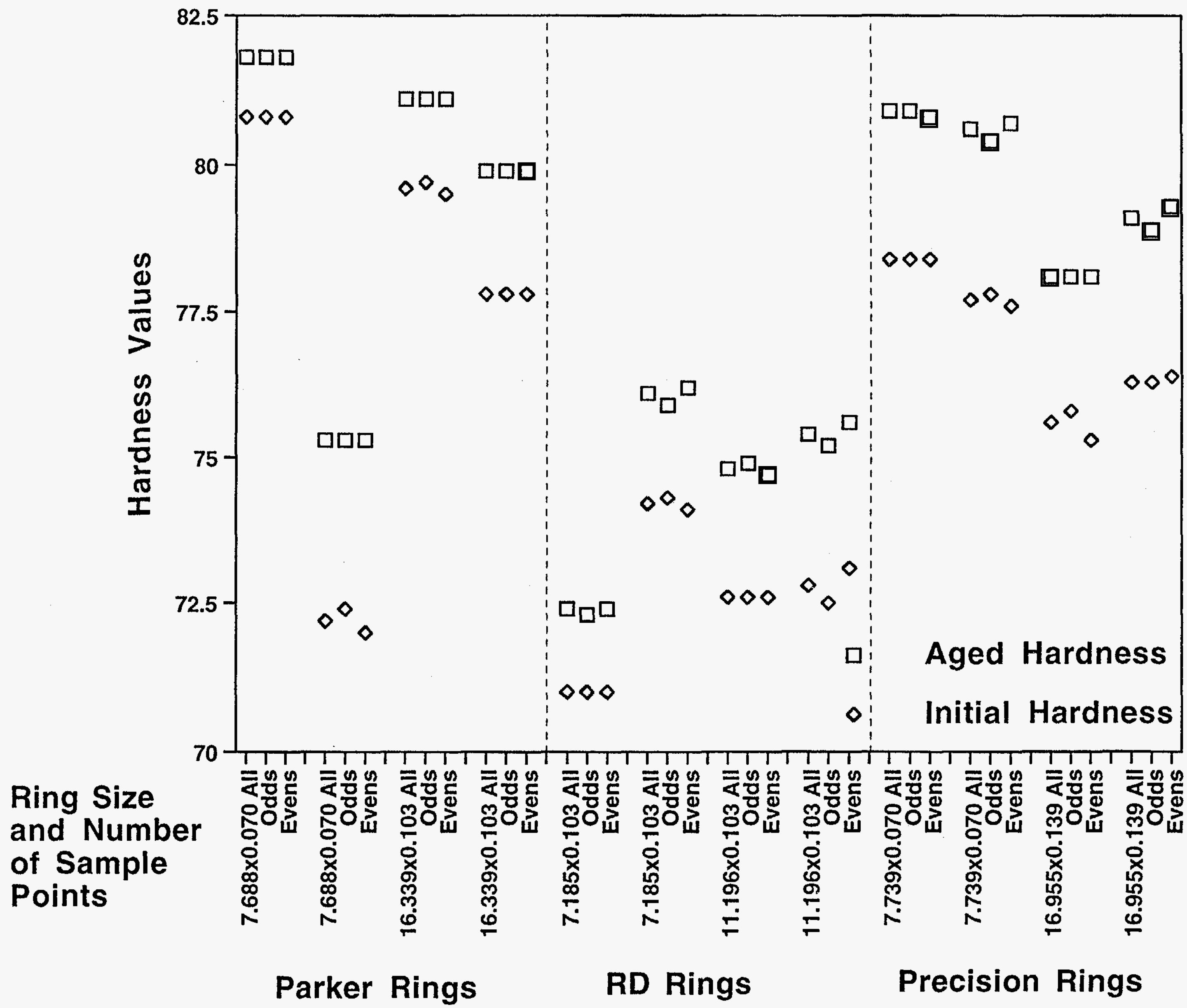
Table F-1. Hardness and Compression Set Data on Butyl Rubber O-Rings

Vendor	Ring size	Rubber Batch	Hardness, Shore M data pts.	unaged	aged	Δ	Compression set data pts.	orig. thick	aged thick	change	comp. set
Parker	0.116 x 0.038	318466	5 x 2	74.9 ± 1.8	78.1 ±1.8	+3.2	5 x 2	0.03958±0.00053	0.03840±0.00046	0.00118	10.7
Parker	0.301 x 0.054	316104	3 x 2	81.1 ± 0.3	82.5 ± 0.3	+1.4	2 x 4	0.05441±0.00068	0.05377±0.00083	0.00064	4.6
Parker		316710	5 x 2	81.3 ± 0.6	80.8 ± 0.4*	-0.5	5 x 2	0.05494±0.00071	0.05354±0.00057	0.00140	9.7
Parker	1.364 x 0.070	316104	3 x 2	79.7 ± 0.3	80.9 ± 0.3	+1.2	3 x 4	0.07190±0.00031	0.07072±0.00021	0.00118	6.1
Parker		317403	5 x 2	77.5 ± 0.7	77.9 ± 0.8	+0.4	5 x 2	0.07054±0.00066	0.06871±0.00075	0.00183	10.1
Parker	7.688 x 0.070	316104	3 x 8	80.8 ± 0.7	81.8 ± 0.6	+1.0	3 x 8	0.07177±0.00043	0.07029±0.00042	0.00148	7.7
Parker		317851	3 x 8	72.2 ± 1.0	75.3 ± 0.9	+3.1	3 x 8	0.07160±0.00064	0.07004±0.00068	0.00156	8.2
Parker	16.339 x 0.103	316104	3 x 8	79.6 ± 0.7	81.1 ± 0.7	+1.5	3 x 8	0.10336±0.00092	0.10131±0.00103	0.00205	7.8
Parker		316710	3 x 8	77.8 ± 1.0	79.9 ± 0.6	+2.1	3 x 8	0.10271±0.00072	0.10048±0.00080	0.00223	8.7
RD	0.301 x 0.054	15107	5 x 2	76.1 ± 0.4	79.3 ± 0.6	+3.2	5 x 2	0.05524±0.00044	0.05429±0.00041	0.00095	6.5
RD	0.551 x 0.070	14810	5 x 2	75.1 ± 0.3	76.2 ± 0.7	+1.1	5 x 2	0.07096±0.00022	0.06995±0.00031	0.00101	5.5
RD		15107	5 x 2	74.6 ± 0.8	76.8 ± 0.7	+2.2	5 x 2	0.07109±0.00034	0.07004±0.00026	0.00105	5.7
RD	1.114 x 0.070	14810	5 x 2	73.7 ± 0.3	75.7 ± 0.4	+2.0	5 x 2	0.06937±0.00030	0.06842±0.00028	0.00095	5.6
RD		15107	5 x 2	75.2 ± 0.8	76.8 ± 0.6	+1.6	5 x 2	0.06930±0.00022	0.06811±0.00019	0.00119	7.1
RD	7.185 x 0.103	14810	3 x 8	71.0 ± 0.4	72.4 ± 0.5	+1.4	3 x 8	0.10453±0.00067	0.10316±0.00071	0.00137	5.0
RD		15107	3 x 8	74.2 ± 0.8	76.1 ± 0.7	+1.9	3 x 8	0.10473±0.00064	0.10318±0.00058	0.00155	5.6
RD	11.196 x 0.103	14936	3 x 8	72.6 ± 1.0	74.8 ± 0.9	+2.2	2 x 8	0.10680±0.00067	0.10545±0.00076	0.00135	4.5
RD		15107	3 x 8	72.8 ± 0.9	75.4 ± 1.4	+2.6	3 x 8	0.10685±0.00078	0.10540±0.00069	0.00145	4.8
Precision	0.301 x 0.054	19052	5 x 2	74.6 ± 1.1	80.0 ± 0.7	+5.4	5 x 2	0.05644±0.00108	0.05494±0.00033	0.00150	9.5
Precision		19895	5 x 2	78.3 ± 1.0	79.4 ± 1.1	+1.1	5 x 2	0.05626±0.00050	0.05457±0.00041	0.00169	10.7
Precision	1.364 x 0.070	17405	5 x 2	76.9 ± 1.1	79.0 ± 0.5	+2.1	5 x 2	0.06968±0.00048	0.06816±0.00040	0.00152	8.8
Precision		19895	5 x 2	77.6 ± 0.6	79.2 ± 0.6	+1.6	5 x 2	0.06932±0.00086	0.06764±0.00087	0.00168	10.0
Precision	7.739 x 0.070	19052	3 x 8	78.4 ± 0.9	80.9 ± 0.7	+2.5	3 x 8	0.07129±0.00096	0.06927±0.00084	0.00202	10.7
Precision		19895	3 x 8	77.7 ± 0.9	80.6 ± 0.9	+2.9	3 x 8	0.07105±0.00061	0.06893±0.00048	0.00212	11.5
Precision	16.955 x 0.139	19422	3 x 8	75.6 ± 0.5	78.1 ± 0.6	+2.5	3 x 8	0.14120±0.00101	0.13677±0.00101	0.00425	12.0
Precision		19895	3 x 8	76.3 ± 0.9	79.1 ± 0.6	+2.8	3 x 8	0.14048±0.00099	0.13327±0.00218	0.00721	19.8

Table F-2. Effect of Sampling Rate (4 vs. 8 points per ring) on Hardness and Compression Set Data

Vendor	Ring size	Rubber Batch	Hardness, Shore M data pts.	Hardness, Shore M unaged	Hardness, Shore M aged	Δ	Compression Set data pts.	Compression Set orig. thick	Compression Set aged thick	change	comp. set
Parker	7.688 x 0.070	316104	3 x 8	80.8 ± 0.7	81.8 ± 0.6	+1.0	3 x 8	0.07177±0.00043	0.07029±0.00042	0.00148	7.7
		ODDS	3 x 4	80.8 ± 0.7	81.8 ± 0.5	+1.0	3 x 4	0.07173±0.00044	0.07028±0.00046	0.00145	7.5
		EVENS	3 x 4	80.8 ± 0.7	81.8 ± 0.7	+1.0	3 x 4	0.07182±0.00042	0.07030±0.00037	0.00152	7.8
Parker		317851	3 x 8	72.2 ± 1.0	75.3 ± 0.9	+3.1	3 x 8	0.07160±0.00064	0.07004±0.00068	0.00156	8.2
		ODDS	3 x 4	72.4 ± 1.0	75.3 ± 0.7	+2.9	3 x 4	0.07155±0.00073	0.07016±0.00068	0.00139	7.3
		EVENS	3 x 4	72.0 ± 0.9	75.3 ± 1.0	+3.3	3 x 4	0.07165±0.00053	0.06993±0.00066	0.00172	9.0
Parker	16.339 x 0.103	316104	3 x 8	79.6 ± 0.7	81.1 ± 0.7	+1.5	3 x 8	0.10336±0.00092	0.10131±0.00103	0.00205	7.8
		ODDS	3 x 4	79.7 ± 0.5	81.1 ± 0.8	+1.4	3 x 4	0.10339±0.00085	0.10132±0.00092	0.00207	7.8
		EVENS	3 x 4	79.5 ± 0.9	81.1 ± 0.6	+1.6	3 x 4	0.10332±0.00099	0.10130±0.00112	0.00202	7.7
Parker		316710	3 x 8	77.8 ± 1.0	79.9 ± 0.6	+2.1	3 x 8	0.10271±0.00072	0.10048±0.00080	0.00223	8.7
		ODDS	3 x 4	77.8 ± 0.9	79.9 ± 0.8	+2.1	3 x 4	0.10262±0.00062	0.10039±0.00059	0.00223	8.7
		EVENS	3 x 4	77.8 ± 1.0	79.9 ± 0.3	+2.1	3 x 4	0.10280±0.00079	0.10057±0.00096	0.00223	8.6
RD	7.185 x 0.103	14810	3 x 8	71.0 ± 0.4	72.4 ± 0.5	+1.4	3 x 8	0.10453±0.00067	0.10316±0.00071	0.00137	5.0
		ODDS	3 x 4	71.0 ± 0.5	72.3 ± 0.5	+1.3	3 x 4	0.10478±0.00075	0.10329±0.00069	0.00149	5.4
		EVENS	3 x 4	71.0 ± 0.4	72.4 ± 0.5	+1.4	3 x 4	0.10428±0.00045	0.10303±0.00071	0.00125	4.6
RD		15107	3 x 8	74.2 ± 0.8	76.1 ± 0.7	+1.9	3 x 8	0.10473±0.00064	0.10318±0.00058	0.00155	5.6
		ODDS	3 x 4	74.3 ± 0.7	75.9 ± 0.6	+1.6	3 x 4	0.10495±0.00053	0.10344±0.00050	0.00151	5.4
		EVENS	3 x 4	74.1 ± 0.8	76.2 ± 0.7	+2.1	3 x 4	0.10451±0.00067	0.10292±0.00053	0.00159	5.8
RD	11.196 x 0.103	14936	3 x 8	72.6 ± 1.0	74.8 ± 0.9	+2.2	2 x 8	0.10680±0.00067	0.10545±0.00076	0.00135	4.5
		ODDS	3 x 4	72.6 ± 1.1	74.9 ± 1.0	+2.3	2 x 4	0.10685±0.00075	0.10550±0.00087	0.00135	4.6
		EVENS	3 x 4	72.6 ± 0.8	74.7 ± 0.7	+2.1	2 x 4	0.10674±0.00058	0.10540±0.00063	0.00134	4.5
RD		15107	3 x 8	72.8 ± 0.9	75.4 ± 1.4	+2.6	3 x 8	0.10685±0.00078	0.10540±0.00069	0.00145	4.9
		ODDS	3 x 4	72.5 ± 0.6	75.2 ± 1.2	+2.7	3 x 4	0.10698±0.00094	0.10547±0.00083	0.00151	5.1
		EVENS	3 x 4	73.1 ± 1.0	75.6 ± 1.5	+2.5	3 x 4	0.10673±0.00055	0.10534±0.00049	0.00139	4.7
Precision	7.739 x 0.070	19052	3 x 8	78.4 ± 0.9	80.9 ± 0.7	+2.5	3 x 8	0.07129±0.00096	0.06927±0.00084	0.00202	10.7
		ODDS	3 x 4	78.4 ± 1.0	80.9 ± 0.6	+2.5	3 x 4	0.07122±0.00082	0.06912±0.00081	0.00210	11.2
		EVENS	3 x 4	78.4 ± 0.7	80.8 ± 0.8	+2.4	3 x 4	0.07135±0.00107	0.06942±0.00085	0.00193	10.2
Precision		19895	3 x 8	77.7 ± 0.9	80.6 ± 0.9	+2.8	3 x 8	0.07105±0.00061	0.06893±0.00048	0.00212	11.5
		ODDS	3 x 4	77.8 ± 0.8	80.4 ± 1.1	+2.6	3 x 4	0.07123±0.00073	0.06918±0.00055	0.00205	11.0
		EVENS	3 x 4	77.6 ± 1.0	80.7 ± 0.7	+3.1	3 x 4	0.07088±0.00037	0.06867±0.00016	0.00221	12.0
Precision	16.955 x 0.139	19422	3 x 8	75.6 ± 0.5	78.1 ± 0.6	+2.5	3 x 8	0.14120±0.00101	0.13677±0.00101	0.00425	11.9
		ODDS	3 x 4	75.8 ±0.4	78.1 ± 0.5	+2.3	3 x 4	0.14113±0.00090	0.13667±0.00077	0.00446	12.0
		EVENS	3 x 4	75.3 ±0.5	78.1 ± 0.7	+2.8	3 x 4	0.14127±0.00111	0.13687±0.00120	0.00440	11.8
Precision		19895	3 x 8	76.3 ± 0.9	79.1 ± 0.6	+2.8	3 x 8	0.14048±0.00099	0.13327±0.00218	0.00721	19.8
		ODDS	3 x 4	76.3 ± 0.9	78.9 ± 0.7	+2.6	3 x 4	0.14097±0.00095	0.13336±0.00163	0.00761	20.6
		EVENS	3 x 4	76.4 ± 1.0	79.3 ± 0.5	+3.0	3 x 4	0.14000±0.00078	0.13319±0.00261	0.00681	18.9

Plot F-3. Effect of Sample Rate on O-Ring Hardness Values (4 vs. 8 points/ring)



Plot F-4. Standard Deviations of Hardness Measurements vs. Sample Rate (4 vs. 8 points/ring)

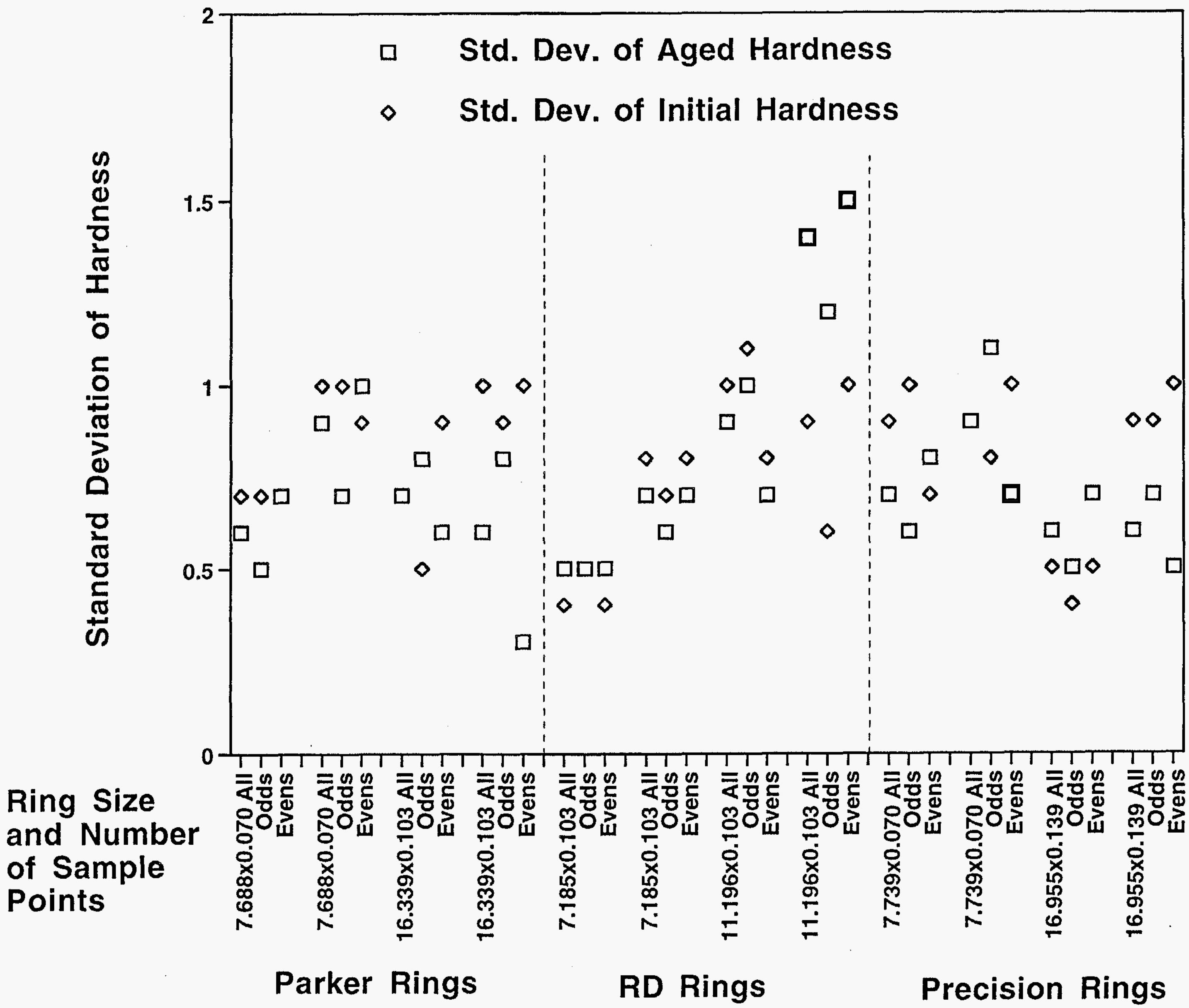


Table F-5. Hardness Data from Single O-Rings Compared to Stacked O-Rings

Ring dimensions	Hardness Values on Single Rings			Hardness Values on Stacked Rings		
	Ring #1	Ring #2	Average	Ring #1 on top	Ring #2 on top	Average
0.301 x 0.065	78.3 ± 1.1	78.9 ± 1.1	78.6	77.9 ± 0.7	77.6 ± 1.7	77.8
1.364 x 0.070	78.0 ± 0.5	78.2 ± 0.3	78.1	76.2 ± 0.2	76.3 ± 0.3	76.3
7.688 x 0.070	79.5 ± 0.4	78.8 ± 0.3	79.2	76.9 ± 0.5	77.1 ± 0.8	77.0
16.339 x 0.140	74.2 ± 0.9	73.2 ± 0.7	73.7	71.5 ± 1.2	71.8 ± 1.4	71.7

All measurements carried out on Lutz O-rings. Each value in the table is the average of five measurements. Rings with a cross section of 0.065 inches were tested in the double pin fixture with a gap of 0.070 inches.

Table F-6. Operator Sensitivity of Hardness Testing...(**BOLD** = high reading, *italics* = low reading)

using Shore M Digital Durometer with automatic 1 second readings:

Ring dimensions	Readings/ring x no. of rings	Initial Hardness Operator #1	Initial Hardness Operator #2	Initial Hardness Operator #3	Range	Hardness after Aging Operator #1	Hardness after Aging Operator #2	Hardness after Aging Operator #3	Range
0.301 x 0.054	2 x 5	79.3 ± 0.7	**79.4 ± 0.6**	*78.1 ± 0.8*	78.1-79.4	**81.1 ± 0.3**	*80.3 ± 1.3*	**81.1 ± 0.8**	80.3-81.1
1.364 x 0.070	2 x 5	*75.6 ± 0.6*	77.4 ± 0.4	**77.5 ± 0.9**	75.6-77.5	**80.5 ± 0.6**	*79.6 ± 0.6*	80.1 ± 0.5	79.6-80.5
7.688 x 0.070	2 x 5	*77.3 ± 1.0*	78.6 ± 1.1	**79.0 ± 0.8**	77.3-79.0	81.1 ± 0.6	*80.9 ± 0.6*	**81.2 ± 0.6**	80.9-81.2
16.339 x 0.103	2 x 5	*77.1 ± 0.8*	77.4 ± 0.9	**77.9 ± 1.5**	77.1-77.9	80.2 ± 0.5	*79.6 ± 0.7*	**80.7 ± 0.9**	79.6-80.7

using Shore M Dial Durometer with estimated 1 second readings:

Ring dimensions	Readings/ring x no. of rings	Initial Hardness Operator #1	Initial Hardness Operator #2	Initial Hardness Operator #3	Range	Hardness after Aging Operator #1	Hardness after Aging Operator #2	Hardness after Aging Operator #3	Range
0.301 x 0.054	4 x 1	**76.9 ± 0.6**	75.9 ± 1.9	*74.3 ± 1.2*	74.3-76.9				
1.364 x 0.070	8 x 1	**74.8 ± 0.7**	74.6 ± 0.9	*73.5 ± 0.7*	73.5-74.8				
7.688 x 0.070	72 x 1	**76.2 ± 1.1**	75.8 ± 1.2	*74.7 ± 1.0*	74.7-76.2				
16.339 x 0.103	72 x 1	**77.6 ± 0.9**	77.4 ± 1.0	*76.6 ± 0.9*	76.6-77.6				

using Shore M Dial Durometer with estimated 10 second readings:

Ring dimensions	Readings/ring x no. of rings	Initial Hardness Operator #1	Initial Hardness Operator #2	Initial Hardness Operator #3	Range	Hardness after Aging Operator #1	Hardness after Aging Operator #2	Hardness after Aging Operator #3	Range
0.301 x 0.054	4 x 1	**78.3 ± 0.6**	77.0 ± 2.0	*75.1 ± 1.1*	75.1-78.3				
1.364 x 0.070	8 x 1	75.2 ± 0.9	**75.3 ± 1.1**	*74.0 ± 0.7*	74.0-75.3				
7.688 x 0.070	72 x 1	**76.7 ± 0.9**	76.5 ± 1.1	*75.0 ± 1.0*	75.0-76.7				
16.339 x 0.103	72 x 1	77.3 ± 0.7	**77.4 ± 1.0**	*76.4 ± 0.9*	76.4-77.4				

All tests used Parker Batch 316104 O-rings. Readings were taken on the same durometer and on the same face of the O-ring. Readings were grouped to measure similar ring areas but offset to avoid re-puncturing of the ring. Operator code: #1 = JY, #2 = KW, #3 = LD.

Table F-7. Round-Robin Hardness Testing with Shore M Digital Durometers

(**Bold** = high reading and *italics* = low reading)

Durometer No.	SN 3217	SN 3225	SN 3224
Sample:			
Green std. block (63.1 hardness)	**64.4 ± 0.2**	63.3 ± 0.3	*62.5 ± 0.7*
Red std. block (71.2 hardness)	**73.4 ± 0.6**	72.8 ± 0.4	*71.2 ± 0.5*
Brown std. block (79.7 hardness)	**80.8 ± 0.5**	80.1 ± 0.5	*78.5 ± 1.2*
Parker 0.301 x 0.054 (316710)	**82.1 ± 0.4**	81.0 ± 0.6	*80.6 ± 0.8*
Parker 7.688 x 0.070 (317851)	**73.0 ± 0.9**	72.6 ± 0.7	*71.7 ± 1.1*
Parker 16.399 x 0.103 (316710)	*76.6 ± 1.1*	**78.2 ± 0.7**	**78.2 ± 0.9**

Hardness standard blocks: 5 readings taken

O-Rings: 5 rings x 2 readings = 10 readings taken

Durometers SN 3217 and 3225 are located at Sandia, CA and tests were run by Kevin Wagter.

Durometer SN 3224 is located at Kansas City Plant and tests were run by Julie Stuckey.

Table F-8. Shore A vs. Shore M Dial Durometer Hardness Data (1 vs. 10 sec. readings)

Sample	Type A Dial Durometer		Type M Dial Durometer	
Read time:	~ 1 sec.	~ 10 sec.	~ 1 sec.	~ 10 sec.
Test Blocks (given value)				
White (31.9)	29.6 ± 0.4 (5)	27.5 ± 0.5 (5)	29.6 ± 0.5 (5)	29.5 ± 0.5 (5)
Yellow (47.0)	44.1 ± 0.2 (5)	41.9 ± 0.2 (5)	46.2 ± 0.3 (5)	46.2 ± 0.3 (5)
Blue(56.2)	50.6 ± 0.7 (5)	49.2 ± 0.4 (5)	54.0 ± 0.0 (5)	54.0 ± 0.0 (5)
Breen (64.0)	59.4 ± 0.5 (5)	57.0 ± 0.0 (5)	62.0 ± 0.5 (5)	61.5 ± 0.5 (5)
Red (74.5)	70.0 ± 0.0 (5)	67.8 ± 0.4 (5)	73.0 ± 0.0 (5)	72.0 ± 0.0 (5)
Brown (83.3)	81.2 ± 0.4 (5)	79.2 ± 0.4 (5)	81.6 ± 0.5 (5)	81.0 ± 0.6 (5)
Black (90.9)	88.4 ± 0.9 (5)	87.0 ± 0.9 (5)	89.3 ± 0.7 (5)	89.0 ± 0.7 (5)
Test Slabs (batch number)				
Parker single (316104)	75.2 ± 1.4 (30)	71.0 ± 1.5 (30)	74.0 ± 0.3 (30)	72.6 ± 0.9 (30)
Parker stack (316104)	72.4 ± 0.7 (30)	67.6 ± 0.7 (30)	73.5 ± 0.7 (30)	72.1 ± 0.9 (30)
RD Rubber single (14810)	68.0 ± 1.0 (30)	62.6 ± 1.0 (30)	66.4 ± 0.4 (30)	64.8 ± 0.4 (30)
RD Rubber stack (14810)	63.3 ± 0.7 (30)	56.3 ± 0.7 (30)	65.5 ±0.5 (30)	64.3 ± 0.5 (30)
Precision single (19052A)	74.1 ± 2.1 (30)	69.5 ± 1.8 (30)	74.0 ± 0.3 (30)	71.1 ± 0.9 (30)
Precision stack (19052A)	69.8 ±2.9 (30)	64.8 ± 2.7 (30)	72.4 ± 0.9 (30)	70.7 ± 1.0 (30)
O-Rings, I.D. X C.S. (Parker 316104, RD 14810)				
Parker 0.301 x 0.054	NA	NA	74.6 ± 2.2 (4)	75.8 ± 2.6 (4)
Parker 1.364 x 0.070	NA	NA	75.4 ± 0.7 (9)	75.8 ± 0.7 (9)
Parker 7.688 x 0.070	NA	NA	73.7 ± 1.4 (37)	73.6 ± 1.5 (37)
Parker 16.339 x 0.103	NA	NA	76.8 ± 1.4 (37)	75.9 ± 1.3 (37)
RD Rubber 0.551 x 0.070	NA	NA	69.3 ± 0.7 (9)	70.6 ± 0.8 (9)
RD Rubber 1.114 x 0.070	NA	NA	68.1 ± 0.6 (9)	69.1 ± 0.8 (9)

Numbers in parentheses indicate the number of individual readings taken.

Table F-9. Hardness of Small RD Rubber O-Rings (0.301x0.054, 0.551x0.070 and 1.114x0.054)

0.301 x 0.054			RD 15107
Ring	Site	Initial Hardness	Aged Hardness
1	1	76.1	79.8
	2	75.8	79.4
2	1	75.9	79.7
	2	76.6	79.5
3	1	76.4	79.0
	2	75.9	78.9
4	1	76.2	79.3
	2	76.6	79.1
5	1	75.0	78.1
	2	76.0	80.5
Avg ± S.D.:		76.1±0.5	79.3±0.6
Hardness Change			3.2

0.301 x 0.054 (4 min. cure)			RD 15107
Ring	Site	Initial Hardness	Aged Hardness
1	1	74.8	79.4
	2	75.5	80.3
2	1	74.6	79.1
	2	73.7	81.0
3	1	75.7	80.4
	2	76.4	79.4
4	1	76.1	80.8
	2	75.5	80.5
5	1	76.4	80.4
	2	77.2	80.1
Avg ± S.D.:		75.6±1.0	80.1±0.6
Hardness Change			4.5

0.301 x 0.054 (3 min. cure)			RD 15107
Ring	Site	Initial Hardness	Aged Hardness
1	1	75.0	79.6
	2	75.4	80.4
2	1	76.6	81.2
	2	75.6	81.6
3	1	75.6	80.0
	2	76.3	81.4
4	1	74.7	79.7
	2	74.5	80.8
5	1	77.8	82.3
	2	77.7	81.3
Avg ± S.D.:		75.9±1.2	80.8±0.9
Hardness Change			4.9

1.114 x 0.070			RD 15107
Ring	Site	Initial Hardness	Aged Hardness
1	1	75.6	77.5
	2	76.0	76.6
2	1	75.1	75.6
	2	73.9	77.2
3	1	76.0	77.0
	2	74.6	76.9
4	1	76.3	76.8
	2	75.1	76.7
5	1	75.9	76.2
	2	73.8	77.8
Avg ± S.D.:		75.2±0.9	76.8±0.6
Hardness Change			1.6

1.114 x 0.070 (4 min. cure)			RD 15107
Ring	Site	Initial Hardness	Aged Hardness
1	1	73.0	78.2
	2	73.9	77.1
2	1	73.8	76.7
	2	71.9	76.4
3	1	72.8	77.0
	2	73.3	77.9
4	1	71.5	77.5
	2	73.5	77.0
5	1	73.2	77.2
	2	72.3	77.0
Avg ± S.D.:		72.9±0.8	77.2±0.5
Hardness Change			4.3

1.114 x 0.070 (3 min. cure)			RD 15107
Ring	Site	Initial Hardness	Aged Hardness
1	1	73.4	80.1
	2	70.8	80.1
2	1	74.6	79.9
	2	71.9	79.6
3	1	72.3	80.2
	2	74.2	80.1
4	1	74.7	80.1
	2	73.9	80.4
5	1	73.5	79.4
	2	73.7	80.0
Avg ± S.D.:		73.3±1.3	80.0±0.3
Hardness Change			6.7

0.551 x 0.070			RD 14810
Ring	Site	Initial Hardness	Aged Hardness
1	1	75.2	74.7
	2	75.4	76.4
2	1	75.1	76.7
	2	75.1	77.1
3	1	74.6	75.6
	2	75.6	76.4
4	1	75.7	76.1
	2	74.9	76.6
5	1	74.9	75.6
	2	74.8	77.2
Avg ± S.D.:		75.1±0.4	76.2±0.8
Hardness Change			1.1

0.551 x 0.070			RD 15107
Ring	Site	Initial Hardness	Aged Hardness
1	1	76.0	77.8
	2	75.9	77.8
2	1	74.1	76.3
	2	73.8	76.4
3	1	74.8	76.2
	2	74.3	75.7
4	1	73.9	77.7
	2	74.1	77.2
5	1	75.3	76.8
	2	74.1	76.5
Avg ± S.D.:		74.6±0.8	76.8±0.7
Hardness Change			2.2

1.114 x 0.070			RD 14810
Ring	Site	Initial Hardness	Aged Hardness
1	1	73.7	75.9
	2	73.4	75.6
2	1	74.1	75.5
	2	73.8	74.9
3	1	74.2	76.3
	2	73.2	75.5
4	1	73.9	76.1
	2	73.9	76.1
5	1	73.8	75.7
	2	73.1	75.2
Avg ± S.D.:		73.7±0.4	75.7±0.4
Hardness Change			2.0

Table F-10. Hardness of Medium RD Rubber O-Rings (7.185x0.103)

7.185 x 0.103 RD 15107

Ring	Site	Initial Hard.	Aged Hard.
1	1	74.2	75.1
	2	73.1	76.3
	3	73.5	75.3
	4	72.8	76.0
	5	74.9	75.7
	6	73.7	76.2
	7	74.6	76.6
	8	73.7	76.7
2	1	74.7	77.0
	2	74.5	75.8
	3	73.5	75.3
	4	73.7	77.0
	5	75.6	75.1
	6	75.6	74.8
	7	74.9	76.2
	8	75.2	75.3
3	1	74.3	76.8
	2	73.7	77.3
	3	73.7	75.9
	4	74.1	76.6
	5	73.0	75.6
	6	74.1	76.2
	7	74.2	76.2
	8	74.9	76.7
Avg ± S.D.:		74.2±0.8	76.1±0.7
Hardness Change			1.9
Odd No. Values Only			
Avg ± S.D.:		74.3±0.7	75.9±0.7
Hardness Change			1.6
Even No. Values Only			
Avg ± S.D.:		74.1±0.8	76.2±0.7
Hardness Change			2.1

7.185 x 0.103 RD 15107
4 minute cure

Ring	Site	Initial Hard.	Aged Hard.
1	1	73.4	77.5
	2	73.0	77.6
	3	72.7	78.1
	4	73.0	77.9
	5	72.2	77.9
	6	73.1	78.5
	7	73.0	78.0
	8	73.1	77.6
2	1	72.5	77.5
	2	73.9	77.7
	3	73.2	77.2
	4	72.8	77.0
	5	72.8	78.1
	6	73.3	77.5
	7	73.2	77.4
	8	73.5	77.6
3	1	73.7	77.5
	2	73.2	77.2
	3	74.3	77.7
	4	73.9	77.6
	5	72.9	78.1
	6	73.0	77.5
	7	72.6	77.5
	8	73.0	77.4
Avg ± S.D.:		73.1±0.5	77.7±0.3
Hardness Change			4.5
Odd No. Values Only			
Avg ± S.D.:		73.0±0.6	77.7±0.3
Hardness Change			4.7
Even No. Values Only			
Avg ± S.D.:		73.2±0.4	77.6±0.4
Hardness Change			4.4

7.185 x 0.103 RD 15107
3 minute cure

Ring	Site	Initial Hard.	Aged Hard.
1	1	73.7	77.0
	2	73.1	77.8
	3	72.2	77.4
	4	73.3	77.1
	5	74.3	77.5
	6	72.0	77.6
	7	70.5	76.7
	8	73.3	75.4
2	1	73.0	78.7
	2	74.5	77.1
	3	71.2	76.7
	4	74.3	76.8
	5	74.3	77.1
	6	74.6	78.9
	7	74.1	76.8
	8	74.5	76.7
3	1	70.8	76.5
	2	72.5	76.0
	3	69.3	76.6
	4	72.8	75.4
	5	70.4	76.4
	6	73.1	77.0
	7	70.9	75.7
	8	73.8	77.8
Avg ± S.D.:		72.8±1.5	76.9±0.9
Hardness Change			4.2
Odd No. Values Only			
Avg ± S.D.:		72.1±1.8	76.9±0.7
Hardness Change			4.9
Even No. Values Only			
Avg ± S.D.:		73.5±0.9	77.0±1.0
Hardness Change			3.5

7.185 x 0.103 RD 14810

Ring	Site	Initial Hard.	Aged Hard.
1	1	72.3	73.3
	2	71.4	72.5
	3	70.9	72.2
	4	71.3	72.4
	5	70.6	73.2
	6	71.4	73.7
	7	71.4	71.4
	8	71.3	72.9
2	1	71.0	72.1
	2	71.7	72.4
	3	71.4	72.6
	4	70.6	72.3
	5	70.2	72.2
	6	70.5	72.7
	7	70.9	72.1
	8	70.5	72.2
3	1	70.9	72.4
	2	71.1	72.3
	3	71.0	71.9
	4	70.9	72.0
	5	70.8	72.1
	6	70.8	71.7
	7	70.8	72.0
	8	70.7	72.2
Avg ± S.D.:		71.0±0.5	72.4±0.5
Hardness Change			1.4
Odd No. Values Only			
Avg ± S.D.:		71.0±0.5	72.3±0.5
Hardness Change			1.3
Even No. Values Only			
Avg ± S.D.:		71.0±0.4	72.4±0.5
Hardness Change			1.4

Table F-11. Hardness of Large RD Rubber O-Rings (11.196x0.103)

11.196 x 0.103 RD 15107

Ring	Site	Initial Hard.	Aged Hard.
1	1	71.9	77.4
	2	73.1	74.0
	3	72.4	75.0
	4	73.2	74.8
	5	72.6	75.6
	6	71.6	75.8
	7	72.9	74.2
	8	72.1	74.1
2	1	72.8	75.2
	2	74.5	78.0
	3	73.2	75.6
	4	73.4	78.0
	5	73.0	76.0
	6	73.9	76.2
	7	73.2	75.7
	8	74.7	77.1
3	1	71.4	73.8
	2	71.3	73.3
	3	71.6	72.6
	4	72.7	74.6
	5	72.5	75.8
	6	73.2	76.6
	7	72.5	75.5
	8	73.6	75.2
Avg ± S.D.:		72.8±0.9	75.4±1.4
Hardness Change			2.6
Odd No. Values Only			
Avg ± S.D.:		72.5±0.6	75.2±1.2
Hardness Change			2.7
Even No. Values Only			
Avg ± S.D.:		73.1±1.1	75.6±1.6
Hardness Change			2.5

11.196 x 0.103 RD 15107
4 minute cure

Ring	Site	Initial Hard.	Aged Hard.
1	1	72.3	77.4
	2	73.3	77.8
	3	73.8	77.2
	4	73.1	76.6
	5	73.4	77.0
	6	72.5	76.6
	7	73.5	76.3
	8	73.7	78.0
2	1	73.6	74.6
	2	73.8	76.0
	3	74.2	76.0
	4	73.7	76.5
	5	73.8	76.9
	6	73.8	75.8
	7	73.0	76.2
	8	74.4	77.5
3	1	73.5	76.0
	2	73.0	76.8
	3	73.5	76.6
	4	73.9	76.7
	5	73.8	76.7
	6	75.1	76.0
	7	73.8	76.5
	8	73.4	77.3
Avg ± S.D.:		73.6±0.6	76.6±0.7
Hardness Change			3.0
Odd No. Values Only			
Avg ± S.D.:		73.5±0.5	76.5±0.7
Hardness Change			2.9
Even No. Values Only			
Avg ± S.D.:		73.6±0.7	76.8±0.7
Hardness Change			3.2

11.196 x 0.103 RD 15107
3 minute cure

Ring	Site	Initial Hard.	Aged Hard.
1	1	70.3	77.5
	2	72.8	77.4
	3	69.4	76.7
	4	70.0	75.7
	5	69.7	76.7
	6	70.6	77.2
	7	69.4	74.2
	8	70.2	75.3
2	1	71.7	77.0
	2	73.5	76.4
	3	72.7	77.6
	4	72.6	77.3
	5	73.8	77.8
	6	74.2	77.8
	7	72.0	77.5
	8	74.1	78.0
3	1	74.3	77.5
	2	74.1	77.0
	3	73.1	76.6
	4	74.1	76.5
	5	73.6	77.7
	6	73.2	76.9
	7	73.0	76.4
	8	74.0	76.4
Avg ± S.D.:		72.4±1.7	76.9±0.9
Hardness Change			4.5
Odd No. Values Only			
Avg ± S.D.:		71.9±1.8	76.9±1.0
Hardness Change			5.0
Even No. Values Only			
Avg ± S.D.:		72.8±1.6	76.8±0.8
Hardness Change			4.0

11.196 x 0.103 RD 14936

Ring	Site	Initial Hard.	Aged Hard.
1	1	72.5	74.6
	2	73.2	75.4
	3	72.2	74.8
	4	71.6	74.5
	5	71.0	74.5
	6	71.2	74.6
	7	70.4	72.7
	8	71.9	73.9
2	1	72.9	74.7
	2	72.8	75.2
	3	74.2	75.9
	4	73.6	76.1
	5	72.3	75.5
	6	73.6	75.3
	7	73.3	76.0
	8	71.8	73.9
3	1	74.1	75.5
	2	73.4	75.7
	3	73.0	76.3
	4	73.0	73.9
	5	72.2	73.3
	6	72.0	74.0
	7	73.4	75.4
	8	73.5	74.3
Avg ± S.D.:		72.6±1.0	74.8±0.9
Hardness Change			2.2
Odd No. Values Only			
Avg ± S.D.:		72.6±1.1	74.9±1.1
Hardness Change			2.3
Even No. Values Only			
Avg ± S.D.:		72.6±0.9	74.7±0.8
Hardness Change			2.1

Table F-12. Hardness of Small Parker and Precision O-Rings (0.116x0.038, 0.301x0.054 and 1.364x0.070)

0.116 x 0.038 — Parker 318466

Ring	Site	Initial Hardness	Aged Hardness
1	1	77.9	79.5
	2	77.1	80.5
2	1	76.2	78.6
	2	76.0	79.9
3	1	74.2	75.7
	2	74.4	76.8
4	1	72.4	77.1
	2	75.0	79.5
5	1	72.6	75.0
	2	73.2	78.4
Avg ± S.D.:		74.9±1.8	78.1±1.8
Hardness Change			3.2

0.301 x 0.054 — Parker 316104

Ring	Site	Initial Hardness	Aged Hardness
1	1	81.5	82.9
	2	80.9	82.4
2	1	80.9	82.0
	2	81.0	82.6
3	1	80.8	82.5
	2	81.4	82.3
Avg ± S.D.:		81.1±0.3	82.5±0.3
Hardness Change			1.4

0.301 x 0.054 — Parker 316710

Ring	Site	Initial Hardness	Aged Hardness
1	1	82.1	80.6
	2	80.3	80.9
2	1	80.5	79.8
	2	81.2	81.3
3	1	80.6	80.7
	2	81.5	81.2
4	1	81.3	80.7
	2	81.5	80.9
5	1	81.8	81.1
	2	82.0	80.8
Avg ± S.D.:		81.3±0.6	80.8±0.4
Hardness Change			-0.5

1.364 x 0.070 — Parker 316104

Ring	Site	Initial Hardness	Aged Hardness
1	1	79.8	80.8
	2	79.5	80.6
2	1	79.9	81.0
	2	79.2	81.4
3	1	79.6	80.6
	2	80.2	80.7
Avg ± S.D.:		79.7±0.3	80.9±0.3
Hardness Change			1.2

1.364 x 0.070 — Parker 317403

Ring	Site	Initial Hardness	Aged Hardness
1	1	76.2	77.8
	2	77.3	76.4
2	1	77.1	77.9
	2	78.2	77.3
3	1	77.5	78.1
	2	78.9	78.6
4	1	76.6	78.7
	2	77.7	79.0
5	1	78.1	77.1
	2	77.7	78.3
Avg ± S.D.:		77.5±0.8	77.9±0.8
Hardness Change			0.4

0.301 x 0.054 — Precision 19052

Ring	Site	Initial Hardness	Aged Hardness
1	1	75.7	80.6
	2	73.0	79.7
2	1	73.4	79.7
	2	73.1	80.1
3	1	74.6	79.8
	2	73.8	79.9
4	1	75.6	78.6
	2	75.6	80.1
5	1	75.4	80.0
	2	76.1	81.3
Avg ± S.D.:		74.6±1.2	80.0±0.7
Hardness Change			5.4

0.301 x 0.054 — Precision 19895

Ring	Site	Initial Hardness	Aged Hardness
1	1	77.6	79.0
	2	78.9	78.0
2	1	78.6	79.7
	2	78.4	80.1
3	1	76.3	77.6
	2	78.7	80.0
4	1	79.8	80.3
	2	78.6	81.5
5	1	78.9	79.3
	2	77.1	78.4
Avg ± S.D.:		78.3±1.0	79.4±1.2
Hardness Change			1.1

1.364 x 0.070 — Precision 17405

Ring	Site	Initial Hardness	Aged Hardness
1	1	76.7	78.9
	2	75.5	79.3
2	1	76.5	78.3
	2	77.4	79.0
3	1	77.2	78.4
	2	74.4	78.7
4	1	77.3	79.9
	2	78.8	79.8
5	1	77.3	78.8
	2	77.6	79.3
Avg ± S.D.:		76.9±1.2	79.0±0.5
Hardness Change			2.1

1.364 x 0.070 — Precision 19895

Ring	Site	Initial Hardness	Aged Hardness
1	1	78.3	80.2
	2	76.9	78.2
2	1	77.1	79.0
	2	76.8	79.2
3	1	77.3	79.3
	2	78.8	79.5
4	1	77.6	79.7
	2	78.2	79..7
5	1	78.0	78.3
	2	77.1	79.4
Avg ± S.D.:		77.6±0.7	79.2±0.6
Hardness Change			1.6

Table F-13. Hardness of Medium and Large Parker O-Rings (7.688x0.070 and 16.339x0.103)

7.688 x 0.070 Parker 316104

Ring	Site	Initial Hard.	Aged Hard.
1	1	81.6	82.5
	2	80.8	82.4
	3	80.7	82.0
	4	81.7	82.0
	5	81.7	82.0
	6	80.8	83.1
	7	81.6	82.6
	8	81.8	82.4
2	1	81.1	82.0
	2	80.4	81.6
	3	81.2	82.2
	4	81.9	81.3
	5	81.0	82.2
	6	81.2	82.5
	7	79.5	81.6
	8	80.0	80.9
3	1	80.7	81.3
	2	79.4	80.5
	3	80.6	81.1
	4	80.6	81.9
	5	80.6	81.1
	6	80.3	81.6
	7	79.3	81.5
	8	80.8	81.3
Avg ± S.D.:		80.8±0.7	81.8±0.6
Hardness Change			1.0
Odd No. Values Only			
Avg ± S.D.:		80.8±0.8	81.8±0.5
Hardness Change			1.0
Even No. Values Only			
Avg ± S.D.:		80.8±0.8	81.8±0.7
Hardness Change			1.0

7.688 x 0.070 Parker 317851

Ring	Site	Initial Hard.	Aged Hard.
1	1	73.2	74.8
	2	71.7	74.2
	3	70.8	75.1
	4	71.3	75.7
	5	72.8	75.1
	6	73.6	76.8
	7	74.3	76.9
	8	72.9	77.2
2	1	72.4	75.6
	2	72.9	75.6
	3	73.5	75.4
	4	71.2	76.2
	5	72.4	76.2
	6	72.2	75.7
	7	73.1	74.9
	8	72.6	74.9
3	1	70.5	75.3
	2	70.8	74.5
	3	72.2	74.2
	4	72.2	74.2
	5	72.1	75.3
	6	72.2	74.3
	7	71.5	74.4
	8	70.6	74.8
Avg ± S.D.:		72.2±1.0	75.3±0.9
Hardness Change			3.1
Odd No. Values Only			
Avg ± S.D.:		72.4±1.1	75.3±0.7
Hardness Change			2.9
Even No. Values Only			
Avg ± S.D.:		72.0±0.9	75.3±1.0
Hardness Change			3.3

16.339 x 0.103 Parker 316104

Ring	Site	Initial Hard.	Aged Hard.
1	1	80.5	82.0
	2	80.0	82.0
	3	80.0	81.6
	4	79.4	80.5
	5	79.8	80.5
	6	79.8	81.1
	7	80.0	81.2
	8	79.4	80.5
2	1	79.9	81.5
	2	79.5	81.5
	3	79.0	81.6
	4	79.5	81.6
	5	79.1	81.0
	6	78.2	80.7
	7	80.2	81.0
	8	80.9	81.4
3	1	79.9	81.2
	2	78.0	80.1
	3	79.4	79.1
	4	80.1	81.1
	5	79.5	82.0
	6	80.6	82.1
	7	78.9	80.4
	8	78.1	80.7
Avg ± S.D.:		79.6±0.7	81.1±0.7
Hardness Change			1.5
Odd No. Values Only			
Avg ± S.D.:		79.7±0.5	81.1±0.8
Hardness Change			1.4
Even No. Values Only			
Avg ± S.D.:		79.5±0.9	81.1±0.6
Hardness Change			1.7

16.339 x 0.103 Parker 316710

Ring	Site	Initial Hard.	Aged Hard.
1	1	78.8	81.4
	2	76.4	79.9
	3	76.7	78.0
	4	78.4	79.9
	5	77.6	79.9
	6	77.9	79.9
	7	78.4	79.9
	8	78.5	80.2
2	1	78.8	79.7
	2	77.6	79.6
	3	78.2	79.9
	4	78.2	79.1
	5	77.6	79.7
	6	79.0	79.8
	7	78.3	80.4
	8	78.1	80.0
3	1	78.5	80.9
	2	78.8	80.5
	3	76.0	80.4
	4	75.2	79.7
	5	78.0	79.1
	6	77.8	80.3
	7	76.2	80.0
	8	77.4	80.1
Avg ± S.D.:		77.8±1.0	79.9±0.6
Hardness Change			2.2
Odd No. Values Only			
Avg ± S.D.:		77.8±1.0	79.9±0.9
Hardness Change			2.2
Even No. Values Only			
Avg ± S.D.:		77.8±1.1	79.9±0.4
Hardness Change			2.1

Table F-14. Hardness of Medium and Large Precision O-Rings (7.739x0.070 and 16.955x0.139)

7.739 x 0.070 Precision 19052

Ring	Site	Initial Hard.	Aged Hard.
1	1	77.0	80.1
	2	77.0	80.3
	3	77.5	81.3
	4	78.2	79.3
	5	78.7	80.4
	6	79.3	81.2
	7	76.8	80.1
	8	77.9	80.4
2	1	77.8	81.1
	2	78.3	81.9
	3	80.0	81.8
	4	79.5	81.6
	5	78.4	81.1
	6	77.3	81.0
	7	77.9	80.6
	8	78.6	81.2
3	1	79.9	81.4
	2	78.9	80.9
	3	79.3	81.7
	4	79.1	82.0
	5	78.9	80.3
	6	78.1	79.3
	7	78.9	81.3
	8	78.8	80.6
Avg ± S.D.:		78.4±0.9	80.9±0.7
Hardness Change			2.4
Odd No. Values Only			
Avg ± S.D.:		78.4±1.1	80.9±0.6
Hardness Change			2.5
Even No. Values Only			
Avg ± S.D.:		78.4±0.8	80.8±0.9
Hardness Change			2.4

7.739 x 0.070 Precision 19895

Ring	Site	Initial Hard.	Aged Hard.
1	1	78.8	77.4
	2	78.1	79.9
	3	77.1	80.5
	4	77.2	81.2
	5	77.5	81.3
	6	76.1	80.5
	7	76.6	81.4
	8	78.5	81.4
2	1	76.5	79.5
	2	76.2	81.4
	3	78.0	79.9
	4	79.2	81.4
	5	77.9	81.2
	6	76.9	80.9
	7	78.2	81.0
	8	77.9	81.9
3	1	78.3	80.5
	2	78.4	79.7
	3	77.3	80.5
	4	76.7	80.0
	5	79.3	80.3
	6	78.6	80.2
	7	78.3	81.5
	8	77.5	79.8
Avg ± S.D.:		77.7±0.9	80.6±1.0
Hardness Change			2.8
Odd No. Values Only			
Avg ± S.D.:		77.8±0.8	80.4±1.1
Hardness Change			2.6
Even No. Values Only			
Avg ± S.D.:		77.6±1.0	80.7±0.8
Hardness Change			3.1

16.955 x 0.139 Precision 19422

Ring	Site	Initial Hard.	Aged Hard.
1	1	75.5	77.8
	2	75.2	78.1
	3	75.6	77.9
	4	75.3	77.5
	5	76.0	78.4
	6	75.4	77.9
	7	75.8	78.0
	8	76.0	78.2
2	1	75.9	77.1
	2	75.7	78.4
	3	75.3	78.5
	4	74.9	78.9
	5	76.5	79.1
	6	75.9	77.9
	7	76.6	78.9
	8	75.4	78.0
3	1	75.4	78.1
	2	75.3	79.6
	3	75.4	77.6
	4	74.4	76.9
	5	75.8	78.2
	6	74.7	78.1
	7	75.5	77.6
	8	75.7	77.4
Avg ± S.D.:		75.6±0.5	78.1±0.6
Hardness Change			2.5
Odd No. Values Only			
Avg ± S.D.:		75.8±0.4	78.1±0.6
Hardness Change			2.3
Even No. Values Only			
Avg ± S.D.:		75.3±0.5	78.1±0.7
Hardness Change			2.8

16.955 x 0.139 Precision 19895

Ring	Site	Initial Hard.	Aged Hard.
1	1	75.7	79.0
	2	76.1	79.6
	3	76.1	79.2
	4	77.3	79.1
	5	75.9	78.0
	6	76.4	78.8
	7	75.0	78.0
	8	75.3	79.3
2	1	75.2	78.4
	2	76.0	79.0
	3	76.9	79.5
	4	74.2	78.6
	5	75.9	79.4
	6	76.7	80.2
	7	76.3	78.8
	8	76.6	79.6
3	1	76.8	78.4
	2	75.2	78.5
	3	77.6	78.0
	4	77.3	79.7
	5	78.0	80.0
	6	77.7	79.6
	7	76.3	79.8
	8	77.6	79.8
Avg ± S.D.:		76.3±1.0	79.1±0.7
Hardness Change			2.8
Odd No. Values Only			
Avg ± S.D.:		76.3±0.9	78.9±0.7
Hardness Change			2.6
Even No. Values Only			
Avg ± S.D.:		76.4±1.1	79.3±0.5
Hardness Change			3.1

Table F-15. Hardness Data for Test Slabs

Parker 316104

Site	Initial	Aged
1	71	74
2	72	74
3	73	75
4	73	75
Avg:	72.3±1.0	74.5±0.6
Hardness Change:		2.2

Parker 316710

Site	Initial	Aged
1	68	70
2	69	70
3	69	71
4	70	70
Avg:	69.0±0.8	70.3±0.5
Hardness Change:		1.3

Parker 317403

Site	Initial	Aged
1	72	76
2	73	75
3	72	76
4	74	76
Avg:	72.8±1.0	75.8±0.5
Hardness Change:		3.0

Parker 317851

Site	Initial	Aged
1	73	74
2	72	73
3	73	73
4	74	73
Avg:	73.0±0.8	73.3±0.5
Hardness Change:		0.3

Parker 318466

Site	Initial	Aged
1	73	74
2	73	75
3	72	74
4	73	73
Avg:	72.8±0.4	74.0±0.7
Hardness Change:		1.2

RD 14810

Site	Initial	Aged
1	63	67
2	63	68
3	63	69
4	64	70
Avg:	63.3±0.5	68.5±1.3
Hardness Change:		5.2

RD 15107

Site	Initial	Aged
1	65	64
2	65	65
3	66	65
4	66	65
Avg:	65.5±0.6	64.8±0.5
Hardness Change:		-0.7

RD 15107 (4 min. cure)

Site	Initial	Aged
1	67	69
2	66	69
3	66	70
4	68	72
Avg:	66.8±1.0	70.0±1.4
Hardness Change:		3.2

RD 15107 (3 min. cure)

Site	Initial	Aged
1	68	69
2	66	69
3	67	70
4	68	71
Avg:	67.3±1.0	69.8±1.0
Hardness Change:		2.5

Precision 19052A

Site	Initial	Aged
1	73	76
2	73	75
3	73	74
4	72	74
Avg:	72.8±0.5	74.8±1.0
Hardness Change:		2.0

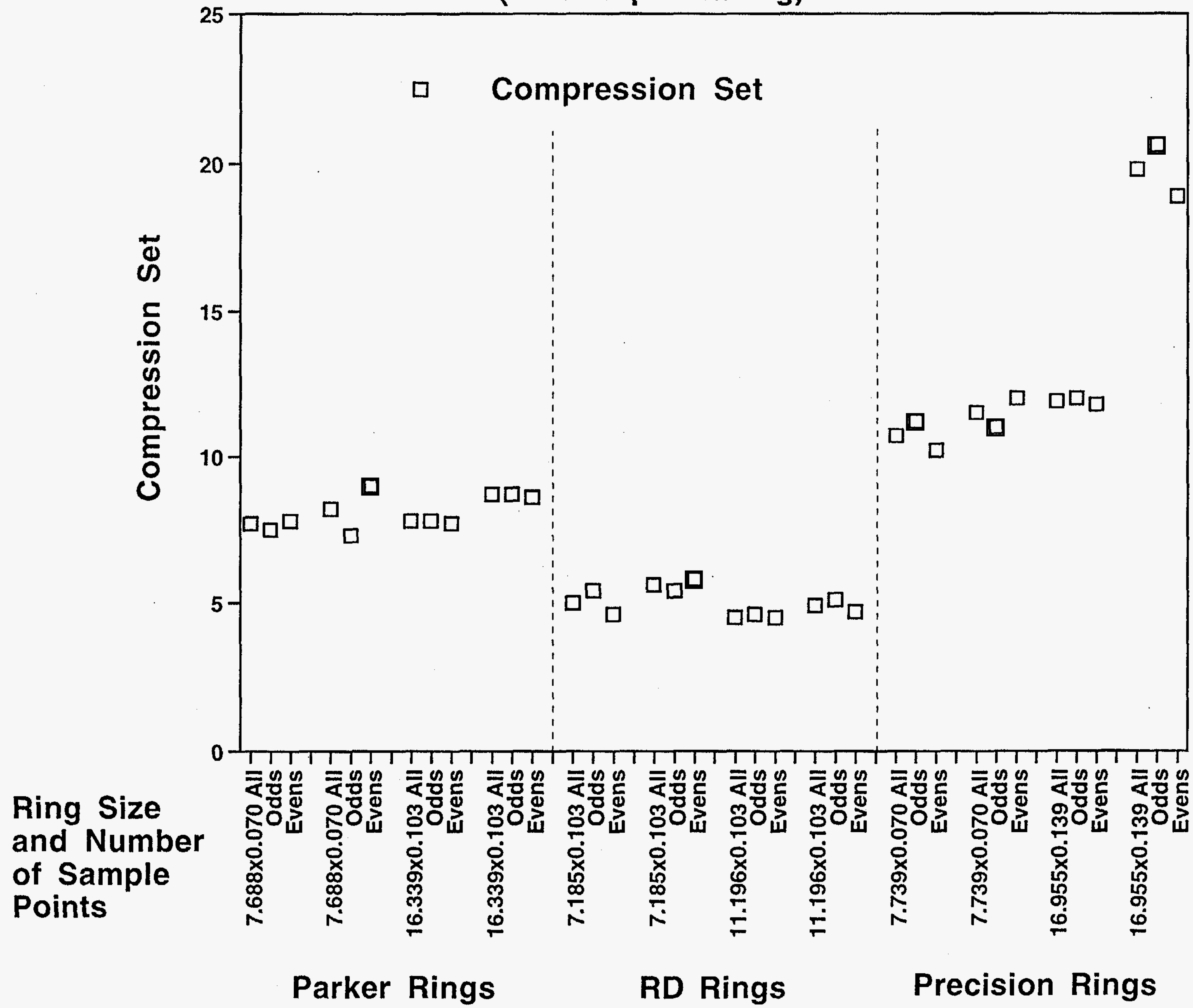
Precision 19895A

Site	Initial	Aged
1	71	76
2	71	75
3	72	75
4	72	76
Avg:	71.5±0.6	75.5±0.6
Hardness Change:		4.0

Appendix G: Compression Set Test Data

Contents:

Plot G-3. Effect of Sample Rate on Compression Set Values (4 vs. 8 points/ring)



Plot G-4. Standard Deviations of Thickness Measurements vs. Sample Rate (4 vs. 8 points/ring)

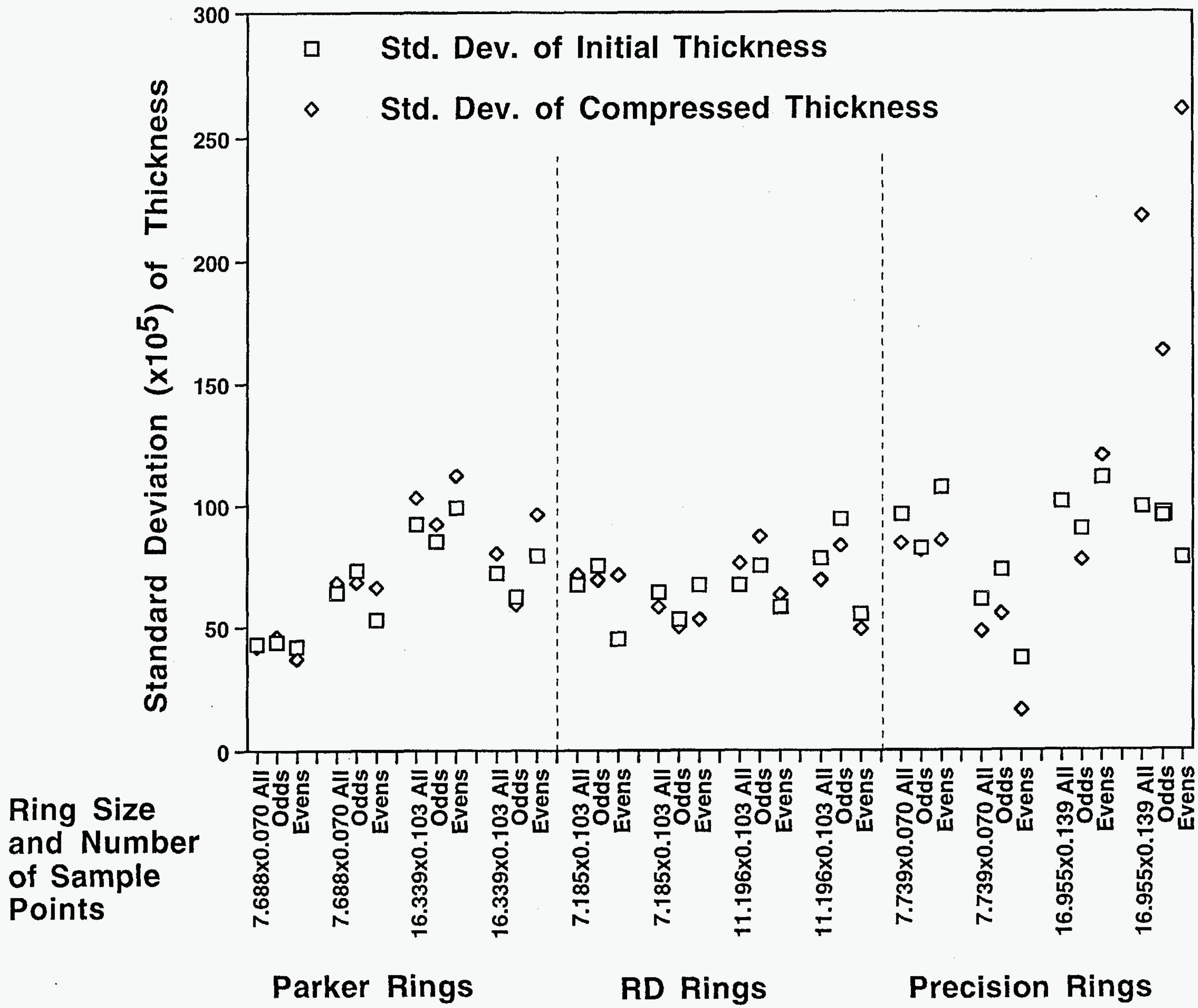


Table G-5. Compression Set Thickness Measurements and Standard Deviations

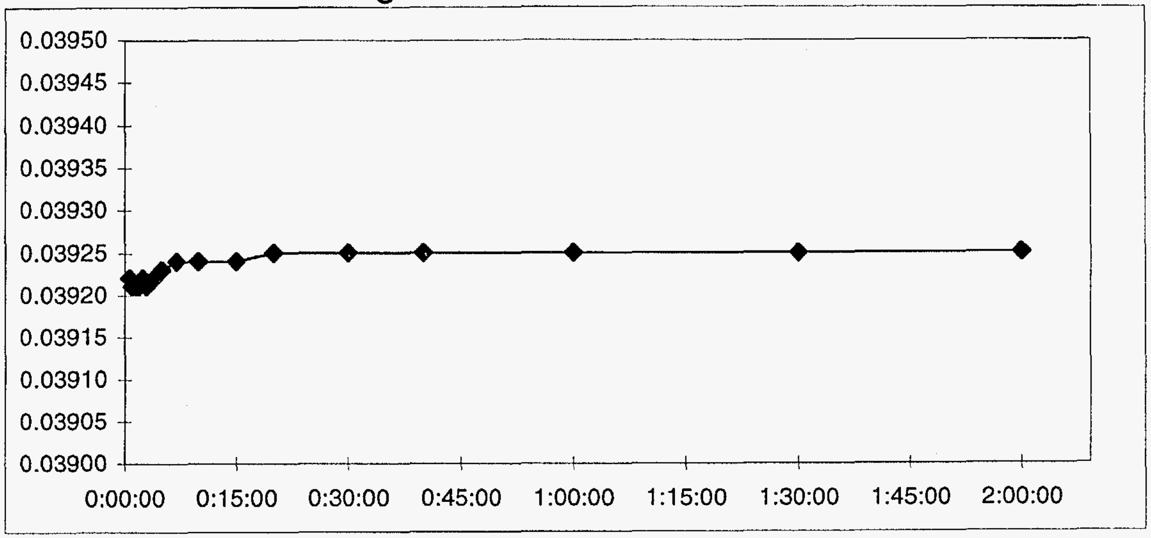
Nominal ring thickness	Range of thickness measurements (before and after compression set)	Range of Standard Deviations	Average Standard Deviation	Range of thickness changes observed during compression set	Average observed thickness change
0.038	0.03840 - 0.03958	0.00046 - 0.00053	0.00050	0.00118	0.00118
0.054	0.05354 - 0.05644	0.00033 - 0.00108	0.00060	0.00064 - 0.00169	0.00124
0.070	0.06764 - 0.07190	0.00019 - 0.00096	0.00049	0.00095 - 0.00212	0.00147
0.103	0.10685 - 0.10048	0.00058 - 0.00103	0.00075	0.00135 - 0.00223	0.00167
ALL*		0.00019 - 0.00108	0.00058		

* Precision rings with a thickness of 0.139 excluded.

Table G-6. O-Ring Thickness vs. Time After Compression Aging

Time @ Ambient (hr:min:sec)	Cross Section (Inches)
0:00:40	0.03922
0:01:00	0.03921
0:01:30	0.03921
0:02:00	0.03921
0:02:30	0.03922
0:03:00	0.03921
0:04:00	0.03922
0:05:00	0.03923
0:07:00	0.03924
0:10:00	0.03924
0:15:00	0.03924
0:20:00	0.03925
0:30:00	0.03925
0:40:00	0.03925
1:00:00	0.03925
1:30:00	0.03925
2:00:00	0.03925

Parker .116"x.038" O-ring Batch 318466



Time @ Ambient (hr:min:sec)	Cross Section (Inches)
0:00:51	0.06858
0:00:58	0.06852
0:01:02	0.06845
0:01:40	0.06838
0:02:20	0.06833
0:03:00	0.06833
0:04:00	0.06830
0:05:00	0.06829
0:07:00	0.06829
0:10:00	0.06829
0:15:00	0.06830
0:20:00	0.06831
0:30:00	0.06832
0:40:00	0.06833
1:00:00	0.06835
1:30:00	0.06837
2:00:00	0.06837

Parker 1.364"x.070" O-ring Batch 317403

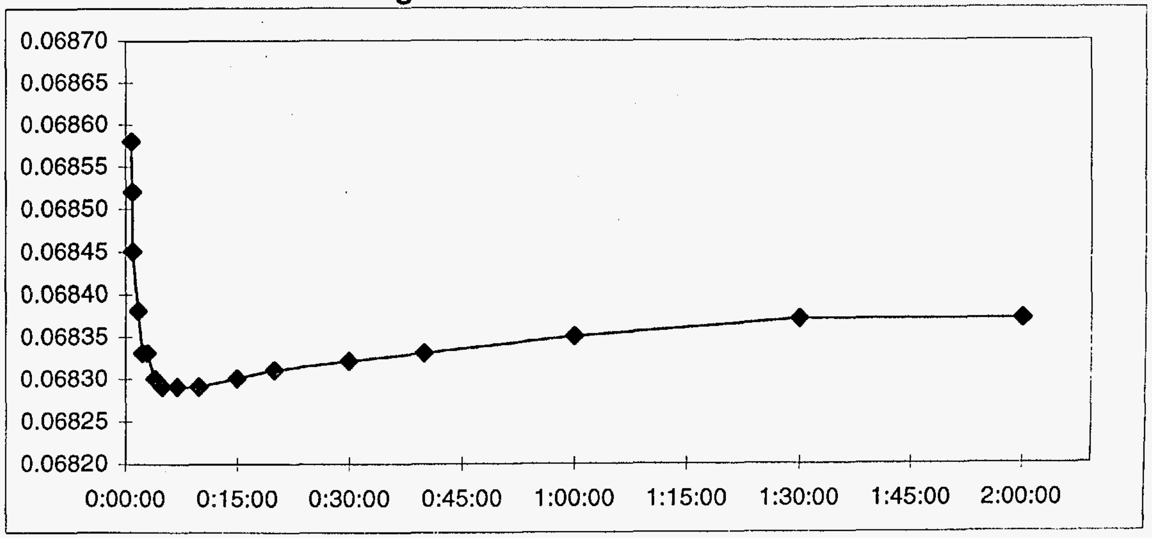


Table G-7. Compression Set of Small RD O-Rings (0.301x0.054, 0.551x0.070 and 1.114x0.070)

0.301 x 0.054 — RD 15107

Ring	Site	Initial Thickness	Aged Thickness
1	1	.05542	.05446
	2	.05590	.05486
2	1	.05490	.05380
	2	.05474	.05380
3	1	.05574	.05476
	2	.05578	.05476
4	1	.05532	.05440
	2	.05514	.05428
5	1	.05476	.05394
	2	.05466	.05380
Avg ± S.D.:		0.05524±0.00047	0.05429±0.00043
Compression Set:			6.5

0.301 x 0.054 (4 min. cure) — RD 15107

Ring	Site	Initial Thickness	Aged Thickness
1	1	.05534	.05422
	2	.05530	.05428
2	1	.05474	.05370
	2	.05428	.05328
3	1	.05468	.05364
	2	.05466	.05372
4	1	.05536	.05428
	2	.05484	.05388
5	1	.05478	.05384
	2	.05499	.05408
Avg ± S.D.:		0.05490±0.00035	0.05389±0.00033
Compression Set:			7.0

0.301 x 0.054 (3 min. cure) — RD 15107

Ring	Site	Initial Thickness	Aged Thickness
1	1	.05474	.05362
	2	.05590	.05348
2	1	.05564	.05468
	2	.05572	.05472
3	1	.05498	.05370
	2	.05466	.05350
4	1	.05616	.05520
	2	.05650	.05546
5	1	.05558	.05464
	2	.05532	.05434
Avg ± S.D.:		0.05552±0.00060	0.05433±0.00072
Compression Set:			7.9

1.114 x 0.070 — RD 15107

Ring	Site	Initial Thickness	Aged Thickness
1	1	.06950	.06820
	2	.06914	.06800
2	1	.06936	.06824
	2	.06882	.06768
3	1	.06910	.06792
	2	.06948	.06828
4	1	.06950	.06832
	2	.06922	.06818
5	1	.06944	.06824
	2	.06948	.06802
Avg ± S.D.:		0.06930±0.00023	0.06811±0.00020
Compression Set:			7.1

1.114 x 0.070 (4 min. cure) — RD 15107

Ring	Site	Initial Thickness	Aged Thickness
1	1	.06922	.06808
	2	.06930	.06810
2	1	.06990	.06864
	2	.06938	.06820
3	1	.06944	.06824
	2	.06914	.06798
4	1	.06948	.06852
	2	.06976	.06876
5	1	.06978	.06866
	2	.06972	.06868
Avg ± S.D.:		0.06951±0.00026	0.06839±0.00029
Compression Set:			6.6

1.114 x 0.070 (3 min. cure) — RD 15107

Ring	Site	Initial Thickness	Aged Thickness
1	1	.06954	.06790
	2	.06974	.06800
2	1	.06952	.06780
	2	.06966	.06792
3	1	.07056	.06794
	2	.06926	.06756
4	1	.06936	.06784
	2	.06966	.06784
5	1	.06972	.06766
	2	.06966	.06772
Avg ± S.D.:		0.06967±0.00035	0.06782±0.00014
Compression Set:			10.8

0.551 x 0.070 — RD 14810

Ring	Site	Initial Thickness	Aged Thickness
1	1	.07086	.06992
	2	.07064	.06984
2	1	.07124	.07014
	2	.07062	.06966
3	1	.07084	.06976
	2	.07110	.07008
4	1	.07112	.06958
	2	.07128	.07000
5	1	.07106	.07072
	2	.07088	.06984
Avg ± S.D.:		0.07096±0.00023	0.06995±0.00032
Compression Set:			5.5

0.551 x 0.070 — RD 15107

Ring	Site	Initial Thickness	Aged Thickness
1	1	.07074	.06990
	2	.07132	.07020
2	1	.07138	.07024
	2	.07130	.07014
3	1	.07104	.07014
	2	.07158	.07028
4	1	.07138	.07028
	2	.07072	.06964
5	1	.07050	.06950
	2	.07090	.07004
Avg ± S.D.:		0.07109±0.00036	0.07004±0.00027
Compression Set:			5.7

1.114 x 0.070 — RD 14810

Ring	Site	Initial Thickness	Aged Thickness
1	1	.06984	.06806
	2	.06912	.06850
2	1	.06964	.06852
	2	.06948	.06868
3	1	.06898	.06800
	2	.06892	.06818
4	1	.06928	.06840
	2	.06972	.06828
5	1	.06944	.06860
	2	.06924	.06896
Avg ± S.D.:		0.06937±0.00031	0.06842±0.00030
Compression Set:			5.6

Table G-8. Compression Set of Medium RD Rubber O-Rings (7.185x0.103)

7.185 x 0.103 RD 15107

Ring	Site	Initial Thick.	Aged Thick.
1	1	.10486	.10342
	2	.10372	.10234
	3	.10448	.10298
	4	.10486	.10316
	5	.10410	.10268
	6	.10382	.10236
	7	.10418	.10290
	8	.10434	.10320
2	1	.10476	.10330
	2	.10456	.10288
	3	.10482	.10308
	4	.10368	.10230
	5	.10462	.10320
	6	.10430	.10262
	7	.10542	.10376
	8	.10382	.10222
3	1	.10536	.10386
	2	.10466	.10330
	3	.10548	.10380
	4	.10542	.10392
	5	.10548	.10386
	6	.10514	.10350
	7	.10578	.10449
	8	.10580	.10328
Avg ± S.D.:		0.10473 ±0.00065	0.10318 ±0.00059
Compression Set:			5.6
Odd No. Values Only			
Avg ± S.D.:		0.10495 ±0.00055	0.10344 ±0.00052
Compression Set:			5.4
Even No. Values Only			
Avg ± S.D.:		0.10451 ±0.00070	0.10292 ±0.00055
Compression Set:			5.8

7.185 x 0.103 RD 15107
4 minute cure

Ring	Site	Initial Thick.	Aged Thick.
1	1	.10514	.10050
	2	.10504	.10058
	3	.10482	.10018
	4	.10502	.10076
	5	.10516	.10112
	6	.10476	.10042
	7	.10544	.10094
	8	.10472	.10102
2	1	.10476	.10060
	2	.10606	.10206
	3	.10418	.10032
	4	.10500	.10119
	5	.10448	.10049
	6	.10576	.10138
	7	.10438	.10048
	8	.10510	.10082
3	1	.10644	.10264
	2	.10590	.10232
	3	.10618	.10236
	4	.10578	.10208
	5	.10686	.10314
	6	.10552	.10184
	7	.10596	.10206
	8	.10674	.10272
Avg ± S.D.:		0.10538 ±0.00074	0.10133 ±0.00089
Compression Set:			14.7
Odd No. Values Only			
Avg ± S.D.:		0.10532 ±0.00087	0.10124 ±0.00103
Compression Set:			15.2
Even No. Values Only			
Avg ± S.D.:		0.10545 ±0.00061	0.10143 ±0.00075
Compression Set:			14.3

7.185 x 0.103 RD 15107
3 minute cure

Ring	Site	Initial Thick.	Aged Thick.
1	1	.10422	.10146
	2	.10400	.10158
	3	.10422	.10158
	4	.10450	.10212
	5	.10410	.10138
	6	.10424	.10150
	7	.10458	.10172
	8	.10380	.10114
2	1	.10422	.10150
	2	.10350	.10098
	3	.10434	.10160
	4	.10446	.10168
	5	.10418	.10136
	6	.10484	.10204
	7	.10526	.10206
	8	.10440	.10164
3	1	.10454	.10196
	2	.10422	.10154
	3	.10398	.10140
	4	.10426	.10184
	5	.10474	.10204
	6	.10488	.10216
	7	.10436	.10170
	8	.10378	.10144
Avg ± S.D.:		0.10432 ±0.00038	0.10164 ±0.00031
Compression Set:			9.9
Odd No. Values Only			
Avg ± S.D.:		0.1044 ±0.00035	0.10165 ±0.00025
Compression Set:			10.1
Even No. Values Only			
Avg ± S.D.:		0.10424 ±0.00042	0.10164 ±0.00036
Compression Set:			9.6

7.185 x 0.103 RD 14810

Ring	Site	Initial Thick.	Aged Thick.
1	1	0.10632	0.10456
	2	0.10448	0.10290
	3	0.10352	0.10210
	4	0.10410	0.10262
	5	0.10460	0.10300
	6	0.10500	0.10440
	7	0.10458	0.10318
	8	0.10436	0.10370
2	1	0.10474	0.10334
	2	0.10358	0.10224
	3	0.10550	0.10418
	4	0.10446	0.10306
	5	0.10422	0.10274
	6	0.10380	0.10252
	7	0.10432	0.10298
	8	0.10450	0.10416
3	1	0.10596	0.10434
	2	0.10356	0.10194
	3	0.10434	0.10290
	4	0.10420	0.10316
	5	0.10452	0.10290
	6	0.10440	0.10294
	7	0.10476	0.10326
	8	0.10496	0.10272
Avg ± S.D.:		0.10453 ±0.00068	0.10316 ±0.00073
Compression Set:			5.0
Odd No. Values Only			
Avg ± S.D.:		0.10478 ±0.00078	0.10329 ±0.00072
Compression Set:			5.4
Even No. Values Only			
Avg ± S.D.:		0.10428 ±0.00047	0.10303 ±0.00074
Compression Set:			4.6

Table G-9. Compression Set of Large RD Rubber O-Rings (11.196x0.103)

11.196 x 0.103 RD 15107

Ring	Site	Initial Thick.	Aged Thick.
1	1	.10590	.10454
	2	.10588	.10466
	3	.10794	.10624
	4	.10690	.10580
	5	.10672	.10546
	6	.10662	.10554
	7	.10788	.10670
	8	.10684	.10538
2	1	.10746	.10594
	2	.10704	.10568
	3	.10616	.10496
	4	.10652	.10550
	5	.10842	.10686
	6	.10684	.10584
	7	.10642	.10510
	8	.10640	.10502
3	1	.10810	.10604
	2	.10664	.10440
	3	.10688	.10460
	4	.10754	.10598
	5	.10652	.10496
	6	.10579	.10476
	7	.10530	.10426
	8	.10774	.10546
Avg ± S.D.:		0.10685 ±0.00079	0.10540 ±0.00070
Compression Set:			4.9

Odd No. Values Only

Avg ± S.D.:	0.10698 ±0.00098	0.10547 ±0.00087
Compression Set:		5.1

Even No. Values Only

Avg ± S.D.:	0.10673 ±0.00057	0.10534 ±0.00051
Compression Set:		4.7

11.196 x 0.103 RD 15107
4 minute cure

Ring	Site	Initial Thick.	Aged Thick.
1	1	.10394	.10192
	2	.10442	.10188
	3	.10328	.10144
	4	.10462	.10226
	5	.10430	.10212
	6	.10442	.10230
	7	.10354	.10162
	8	.10376	.10210
2	1	.10454	.10246
	2	.10308	.10142
	3	.10388	.10250
	4	.10382	.10232
	5	.10358	.10250
	6	.10332	.10224
	7	.10418	.10216
	8	.10358	.10178
3	1	.10374	.10182
	2	.10356	.10172
	3	..10466	.10226
	4	.10366	.10200
	5	.10368	.10184
	6	.10392	.10268
	7	.10444	.10226
	8	.10350	.10192
Avg ± S.D.:		0.10386 ±0.00043	0.10206 ±0.00034
Compression Set:			6.8

Odd No. Values Only

Avg ± S.D.:	0.10392 ±0.00040	0.10208 ±0.00035
Compression Set:		6.9

Even No. Values Only

Avg ± S.D.:	0.10381 ±0.00047	0.10205 ±0.00034
Compression Set:		6.6

11.196 x 0.103 RD 15107
3 minute cure

Ring	Site	Initial Thick.	Aged Thick.
1	1	.10552	.10276
	2	.10500	.10236
	3	.10542	.10270
	4	.10466	.10204
	5	.10522	.10242
	6	.10522	.10328
	7	.10464	.10188
	8	.10422	.10270
2	1	.10480	.10280
	2	.10430	.10230
	3	.10484	.10276
	4	.10512	.10292
	5	.10332	.10198
	6	.10426	.10220
	7	.10464	.10240
	8	.10460	.10224
3	1	.10434	.10222
	2	.10400	.10210
	3	.10478	.10262
	4	.10514	.10262
	5	.10504	.10260
	6	.10464	.10249
	7	.10480	.10274
	8	.10382	.10196
Avg ± S.D.:		0.10468 ±0.00052	0.10246 ±0.00035
Compression Set:			8.1

Odd No. Values Only

Avg ± S.D.:	0.10478 ±0.00057	0.10249 ±0.00032
Compression Set:		8.3

Even No. Values Only

Avg ± S.D.:	0.10458 ±0.00047	0.10243 ±0.00039
Compression Set:		7.9

11.196 x 0.103 RD 14936

Ring	Site	Initial Thick.	Aged Thick.
1	1	.10618	.10496
	2	.10738	.10574
	3	.10692	.10512
	4	.10634	.10482
	5	.10706	.10578
	6	.10696	.10572
	7	.10678	.10542
	8	.10600	.10456
2	1	.10572	.10446
	2	.10604	.10496
	3	.10674	.10504
	4	.10638	.10492
	5	.10850	.10754
	6	.10744	.10606
	7	.10688	.10568
	8	.10740	.10644
Avg ± S.D.:		0.10680 ±0.00070	0.10545 ±0.00079
Compression Set:			4.6

Odd No. Values Only

Avg ± S.D.:	0.10685 ±0.00080	0.10550 ±0.00093
Compression Set:		4.6

Even No. Values Only

Avg ± S.D.:	0.10674 ±0.00062	0.10540 ±0.00068
Compression Set:		4.5

Table G-10. Compression Set of Small Parker and Precision O-Rings (0.116x0.038, 0.301x0.054 and 1.114x0.070)

0.116 x 0.038 — Parker 318466

Ring	Site	Initial Thickness	Aged Thickness
1	1	0.03917	0.03883
	2	0.03933	0.03836
2	1	0.03878	0.03805
	2	0.03949	0.03796
3	1	0.04026	0.03905
	2	0.04024	0.03925
4	1	0.03933	0.03826
	2	0.03903	0.03785
5	1	0.03978	0.03800
	2	0.04036	0.03835
Avg ± S.D.:		0.03958±0.00053	0.03840±0.00046
Compression Set:			10.7

1.364 x 0.070 — Parker 317403

Ring	Site	Initial Thickness	Aged Thickness
1	1	.06996	.06844
	2	.07004	.06880
2	1	.07142	.06976
	2	.06966	.06832
3	1	.07062	.06904
	2	.07128	.06970
4	1	.07160	.06702
	2	.07074	.06910
5	1	.07018	.06868
	2	.06990	.06826
Avg ± S.D.:		0.07054±0.00070	0.06871±0.00079
Compression Set:			10.1

0.301 x 0.054 — Precision 19895

Ring	Site	Initial Thickness	Aged Thickness
1	1	.05638	.05526
	2	.05570	.05426
2	1	.05582	.05420
	2	.05572	.05404
3	1	.05678	.05500
	2	.05582	.05426
4	1	.05672	.05502
	2	.05712	.05454
5	1	.05660	.05488
	2	.05590	.05420
Avg ± S.D.:		0.05626±0.00052	0.05457±0.00044
Compression Set:			10.7

0.301 x 0.054 — Parker 316104

Ring	Site	Initial Thickness	Aged Thickness
1	1	.05460	.05438
	2	.05510	.05466
	3	.05472	.05410
	4	.05530	.05466
2	1	.05368	.05278
	2	.05312	.05224
	3	.05462	.05392
	4	.05412	.05338
Avg ± S.D.:		0.05441±0.00073	0.05377±0.00089
Compression Set:			4.6

1.364 x 0.070 — Parker 316104

Ring	Site	Initial Thickness	Aged Thickness
1	1	.07164	.07062
	2	.07146	.07060
	3	.07188	.07086
	4	.07206	.07114
2	1	.07162	.07060
	2	.07188	.07070
	3	.07184	.07074
	4	.07254	.07042
3	1	.07232	.07098
	2	.07178	.07052
	3	.07214	.07102
	4	.07180	.07078
Avg ± S.D.:		0.07191±0.00031	0.07075±0.00022
Compression Set:			6.1

1.364 x 0.070 — Precision 17405

Ring	Site	Initial Thickness	Aged Thickness
1	1	.07028	.06860
	2	.06960	.06828
2	1	.06946	.06780
	2	.06968	.06822
3	1	.06972	.06822
	2	.06939	.06800
4	1	.07078	.06774
	2	.06908	.06906
5	1	.06946	.06768
	2	.06930	.06802
Avg ± S.D.:		0.06968±0.00050	0.06816±0.00042
Compression Set:			8.8

0.301 x 0.054 — Parker 316710

Ring	Site	Initial Thickness	Aged Thickness
1	1	0.05440	0.05298
	2	0.05616	0.05388
2	1	0.05504	0.05380
	2	0.05496	0.05378
3	1	0.05536	0.05378
	2	0.05494	0.05368
4	1	0.05528	0.05376
	2	0.05338	0.05214
5	1	0.05444	0.05326
	2	0.05542	0.05430
Avg ± S.D.:		0.05494±0.00075	0.05354±0.00061
Compression Set:			9.7

0.301 x 0.054 — Precision 19052

Ring	Site	Initial Thickness	Aged Thickness
1	1	.05636	.05426
	2	.05324	.05456
2	1	.05666	.05480
	2	.05690	.05494
3	1	.05680	.05552
	2	.05698	.05516
4	1	.05682	.05490
	2	.05678	.05502
5	1	.05692	.05510
	2	.05698	.05510
Avg ± S.D.:		0.05644±0.00114	0.05494±0.00034
Compression Set:			9.5

1.364 x 0.070 — Precision 19895

Ring	Site	Initial Thickness	Aged Thickness
1	1	.06828	.06676
	2	.06924	.06730
2	1	.06868	.06708
	2	.07086	.06928
3	1	.06872	.06686
	2	.06928	.06760
4	1	.06864	.06699
	2	.06874	.06722
5	1	.07068	.06904
	2	.07004	.06830
Avg ± S.D.:		0.06932±0.00091	0.06764±0.00091
Compression Set:			10.0

Table G-11. Compression Set of Medium and Large Parker O-Rings (7.688x0.070 and 16.339x0.103)

7.688 x 0.070 Parker 316104

Ring	Site	Initial Thick.	Aged Thick.
1	1	.07124	.06992
	2	.07222	.07046
	3	.07140	.07000
	4	.07114	.06972
	5	.07162	.07024
	6	.07140	.07014
	7	.07242	.07084
	8	.07160	.07040
2	1	.07190	.07044
	2	.07218	.07066
	3	.07124	.07000
	4	.07222	.07072
	5	.07172	.06980
	6	.07240	.07048
	7	.07196	.07030
	8	.07126	.06966
3	1	.07170	.07032
	2	.07146	.06998
	3	.07110	.06954
	4	.07208	.07056
	5	.07260	.07126
	6	.07210	.07080
	7	.07188	.07072
	8	.07174	.07006
Avg ± S.D.:		0.07177 ±0.00044	0.07029 ±0.00043
Compression Set:			7.7
Odd No. Values Only			
Avg ± S.D.:		0.07173 ±0.00046	0.07028 ±0.00048
Compression Set:			7.5
Even No. Values Only			
Avg ± S.D.:		0.07182 ±0.00043	0.0703 ±0.00038
Compression Set:			7.8

7.688 x 0.070 Parker 317851

Ring	Site	Initial Thick.	Aged Thick.
1	1	.07124	.07038
	2	.07146	.06930
	3	.07150	.06999
	4	.07176	.06966
	5	.07074	.07020
	6	.07162	.07058
	7	.07062	.07036
	8	.07130	.07020
2	1	.07306	.07172
	2	.07158	.06944
	3	.07146	.06982
	4	.07146	.07006
	5	.07174	.06904
	6	.07170	.07020
	7	.07074	.07022
	8	.07188	.06956
3	1	.07220	.07052
	2	.07108	.06984
	3	.07230	.07024
	4	.07304	.07166
	5	.07084	.06894
	6	.07084	.06924
	7	.07216	.07044
	8	.07202	.06938
Avg ± S.D.:		0.07160 ±0.00065	0.07004 ±0.00070
Compression Set:			8.2
Odd No. Values Only			
Avg ± S.D.:		0.07155 ±0.00077	0.07016 ±0.00072
Compression Set:			7.3
Even No. Values Only			
Avg ± S.D.:		0.07165 ±0.00055	0.06993 ±0.00069
Compression Set:			9.0

16.339 x 0.103 Parker 316104

Ring	Site	Initial Thick.	Aged Thick.
1	1	.10294	.09994
	2	.10310	.10059
	3	.10464	.10228
	4	.10360	.10100
	5	.10342	.10180
	6	.10176	.09978
	7	.10218	.10094
	8	.10380	.10146
2	1	.10386	.10186
	2	.10356	.10138
	3	.10348	.10152
	4	.10238	.10000
	5	.10362	.10140
	6	.10296	.10106
	7	.10338	.10124
	8	.10334	.10188
3	1	.10426	.10182
	2	.10278	.10034
	3	.10140	.09932
	4	.10436	.10364
	5	.10404	.10284
	6	.10250	.10126
	7	.10346	.10092
	8	.10572	.10322
Avg ± S.D.:		0.10336 ±0.00094	0.10131 ±0.00105
Compression Set:			7.8
Odd No. Values Only			
Avg ± S.D.:		0.10339 ±0.00089	0.10132 ±0.00097
Compression Set:			7.8
Even No. Values Only			
Avg ± S.D.:		0.10332 ±0.00103	0.10130 ±0.00117
Compression Set:			7.7

16.339 x 0.103 Parker 316710

Ring	Site	Initial Thick.	Aged Thick.
1	1	0.10308	0.10080
	2	0.10392	0.10220
	3	0.10260	0.10082
	4	0.10198	0.10024
	5	0.10188	0.10028
	6	0.10260	0.10034
	7	0.10244	0.10000
	8	0.10152	0.09940
2	1	0.10262	0.10026
	2	0.10374	0.10106
	3	0.10288	0.10032
	4	0.10314	0.10028
	5	0.10240	0.10008
	6	0.10408	0.10272
	7	0.10298	0.10066
	8	0.10220	0.10000
3	1	0.10330	0.10066
	2	0.10204	0.09936
	3	0.10350	0.10152
	4	0.10278	0.10054
	5	0.10110	0.09896
	6	0.10236	0.10028
	7	0.10266	0.10032
	8	0.10322	0.10046
Avg ± S.D.:		0.10271 ±0.00073	0.10048 ±0.00082
Compression Set:			8.7
Odd No. Values Only			
Avg ± S.D.:		0.10262 ±0.00065	0.10039 ±0.00061
Compression Set:			8.7
Even No. Values Only			
Avg ± S.D.:		0.10280 ±0.00083	0.10057 ±0.00100
Compression Set:			8.6

Table G-12. Compression Set of Medium and Large Precision O-Rings (7.739x0.070 and 16.955x0.139)

7.739 x 0.070 Precision 19052

Ring	Site	Initial Thick.	Aged Thick.
1	1	.07118	.06882
	2	.07262	.07002
	3	.07204	.06886
	4	.07076	.06866
	5	.07082	.06866
	6	.07138	.06978
	7	.07306	.07134
	8	.07020	.06862
2	1	.07002	.06876
	2	.07120	.06980
	3	.07204	.07008
	4	.07028	.06870
	5	.07190	.06958
	6	.07166	.06886
	7	.07058	.06848
	8	.07420	.07180
3	1	.07100	.06908
	2	.07068	.06944
	3	.07054	.06846
	4	.07132	.06912
	5	.07068	.06878
	6	.07056	.06916
	7	.07082	.06856
	8	.07130	.06910
Avg ± S.D.:		0.07129 ±0.00098	0.06927 ±0.00086
Compression Set:			10.7
Odd No. Values Only			
Avg ± S.D.:		0.07122 ±0.00086	0.06912 ±0.00084
Compression Set:			11.2
Even No. Values Only			
Avg ± S.D.:		0.07135 ±0.00112	0.06942 ±0.00088
Compression Set:			10.2

7.739 x 0.070 Precision 19895

Ring	Site	Initial Thick.	Aged Thick.
1	1	.07192	.06898
	2	.07064	.06874
	3	.07082	.06940
	4	.07058	.06860
	5	.07170	.06982
	6	.07182	.06902
	7	.07128	.06944
	8	.07068	.06854
2	1	.07206	.06938
	2	.07100	.06859
	3	.07056	.06886
	4	.07078	.06846
	5	.07096	.06888
	6	.07066	.06870
	7	.07036	.06886
	8	.07116	.06864
3	1	.07212	.06924
	2	.07130	.06870
	3	.07020	.06806
	4	.07064	.06854
	5	.07234	.07036
	6	.07072	.06894
	7	.07048	.06886
	8	.07052	.06860
Avg ± S.D.:		0.07105 ±0.00062	0.06893 ±0.00049
Compression Set:			11.5
Odd No. Values Only			
Avg ± S.D.:		0.07123 ±0.00077	0.06918 ±0.00058
Compression Set:			10.5
Even No. Values Only			
Avg ± S.D.:		0.07088 ±0.00038	0.06867 ±0.00016
Compression Set			12.0

16.955 x 0.139 Precision 19422

Ring	Site	Initial Thick.	Aged Thick.
1	1	0.14172	0.13664
	2	0.13966	0.13594
	3	0.14124	0.13616
	4	0.14072	0.13590
	5	0.14058	0.13582
	6	0.14084	0.13604
	7	0.14084	0.13694
	8	0.14046	0.13634
2	1	0.14216	0.13726
	2	0.14268	0.13764
	3	0.14278	0.13794
	4	0.14318	0.13870
	5	0.14116	0.13692
	6	0.14230	0.13876
	7	0.14186	0.13772
	8	0.14246	0.13888
3	1	0.14118	0.13626
	2	0.14034	0.13624
	3	0.14050	0.13728
	4	0.14006	0.13560
	5	0.14028	0.13558
	6	0.14076	0.13598
	7	0.13924	0.13556
	8	0.14178	0.13646
Avg ± S.D.:		0.14120 ±0.00103	0.13677 ±0.00104
Compression Set:			12.0
Odd No. Values Only			
Avg ± S.D.:		0.14113 ±0.00094	0.13667 ±0.00081
Compression Set:			12.0
Even No. Values Only			
Avg ± S.D.:		0.14127 ±0.00116	0.13687 ±0.00125
Compression Set:			11.8

16.955 x 0.139 Precision 19895

Ring	Site	Initial Thick.	Aged Thick.
1	1	0.14224	0.13176
	2	0.14012	0.13332
	3	0.14086	0.13429
	4	0.13872	0.12884
	5	0.14172	0.13156
	6	0.14048	0.12978
	7	0.14054	0.13112
	8	0.14076	0.12988
2	1	0.14236	0.13672
	2	0.13948	0.13830
	3	0.14126	0.13490
	4	0.13988	0.13368
	5	0.14120	0.13510
	6	0.14126	0.13466
	7	0.14010	0.13240
	8	0.13958	0.13254
3	1	0.14010	0.13189
	2	0.13866	0.13268
	3	0.13886	0.13312
	4	0.13976	0.13400
	5	0.14078	0.13340
	6	0.14040	0.13612
	7	0.14156	0.13402
	8	0.14086	0.13448
Avg ± S.D.:		0.14048 ±0.00101	0.13327 ±0.00222
Compression Set:			19.8
Odd No. Values Only			
Avg ± S.D.:		0.14097 ±0.00099	0.13336 ±0.00170
Compression Set:			20.6
Even No. Values Only			
Avg ± S.D.:		0.14000 ±0.00081	0.13319 ±0.00272
Compression Set:			18.9

Table G-13. Compression Set Data for Test Slabs

Parker 316104

Site	Initial	Aged
1	.3190	.3093
2	.3199	.3102
3	.3199	.3115
4	.3196	.3103
Avg:	.3196	.3103
Compression Set:		11.0

Parker 316710

Site	Initial	Aged
1	.3164	.3085
2	.3170	.3087
3	.3173	.3089
4	.3165	.3088
Avg:	.3168	.3087
Compression Set:		9.9

Parker 317403

Site	Initial	Aged
1	.3178	.3090
2	.3174	.3095
3	.3181	.3094
4	.3180	.3092
Avg:	.3178	.3093
Compression Set:		10.4

Parker 317851

Site	Initial	Aged
1	.3110	.2976
2	.3110	.2989
3	.3103	.2990
4	.3093	.2984
Avg:	.3104	.2985
Compression Set:		15.9

Parker 318466

Site	Initial	Aged
1	.3100	.2988
2	.3092	.2945
3	.3099	.2936
4	.3100	.2962
Avg:	.3098	.2958
Compression Set:		18.9

RD 14810

Site	Initial	Aged
1	.3936	.3872
2	.3930	.3870
3	.3934	.3870
4	.3933	.3871
Avg:	.3933	.3871
Compression Set:		5.9

RD 15107

Site	Initial	Aged
1	.3305	.3180
2	.3301	.3204
3	.3298	.3185
4	.3326	.3183
Avg:	.3308	.3188
Compression Set:		12.6

RD 15107 (70% cure)

Site	Initial	Aged
1	.3354	.3272
2	.3363	.3275
3	.3357	.3280
4	.3358	.3273
Avg:	.3358	.3275
Compression Set:		10.8

RD 15107 (45% cure)

Site	Initial	Aged
1	.3539	.3401
2	.3548	.3409
3	.3527	.3417
4	.3504	.3415
Avg:	.3530	.3411
Compression Set:		13.5

Precision 19052A

Site	Initial	Aged
1	.3190	.2980
2	.3196	.3004
3	.3194	.2996
4	.3196	.2992
Avg:	.3194	.2993
Compression Set:		24.0

Precision 19895A

Site	Initial	Aged
1	.4064	.3792
2	.4071	.3785
3	.4050	.3793
4	.4052	.3790
Avg:	.4059	.3790
Compression Set:		22.8

Appendix H: Tensile Strength and Elongation Test Data

Contents:

Table H-1. Tensile Data vs. Fixture Parameters and Test Speed
(ten tests/value for all but loop study which used six tests/value)

Fixture Type	Test Speed (in./min.)	Lubed?	No of Loops	Maximum load (pounds)	Tensile Elongation (percent)	Tensile Modulus (psi)		
						100% elong.	200% elong.	300% elong.
Non-rotating, grooved, split-spools*	10	yes	1	75±6	530±44			
	10	no	1	70±4	486±36			
	20	yes	1	75±3	525±25			
	20	no	1	74±3	516±31			
Non-rotating rod*	10	yes	1	76±6	523±56			
	10	no	1	79±2	545±20			
	20	yes	1	72±6	504±50			
	20	no	1	73±7	503±50			
Rotating rod*	10	yes	1	74±3	516±29			
	10	no	1	74±2	519±20			
	20	yes	1	72±3	501±4			
	20	no	1	77±1	531±19			
Rotating rod*	20	yes	1	no break	no break	810±20	1850±590	NA
	20	yes	2	151±15	392±49	870±30	2230±30	3860±70
	20	yes	3	234±14	424±49	810±60	2090±130	3680±170

* All measurements carried out on
**All measurements carried out on Parker Buna-S O-rings, 7.484 x 0.139 inches.

Table H-2. Tensile Strength and Elongation Data on Butyl Rubber O-Rings

Vendor	Ring size	Rubber Batch	Rings	Loops	max stress(psi) unaged	max stress(psi) aged	% diff.	percent elongation unaged	percent elongation aged	% diff.
Parker	0.116 x 0.038	318466	8/8	1	1891 ± 309	1823 ± 164	-4	278 ±41	264 ± 25	-5
Parker	0.301 x 0.054	316104	5/5	1	1959 ± 101	1964 ± 177	0	259 ± 12	261 ± 11	1
Parker		316710	8/8	1	2015 ± 91	2032 ± 74	1	272 ± 14	271 ± 10	0
Parker	1.364 x 0.070	316104	5/5	1	1591 ± 123	1573 ± 38	-1	209 ± 12	210 ± 4	0
Parker		317403	8/8	1	1790 ± 207	1708 ± 284	-5	281 ± 26	269 ± 45	-4
Parker	7.688 x 0.070	316104	5/5	3	1447 ± 78	1561 ± 94	8	178 ± 9	188 ± 10	6
Parker		317851	8/8	3	1469 ± 391	1671 ± 271	14	362 ± 85	341 ± 52	-6
Parker	16.339 x 0.103	316104	8/8	3	1309 ± 53	1430 ± 61	9	168 ± 5	177 ± 6	5
Parker		316710	8/8	3	1294 ± 257	1430 ± 148	11	188 ± 31	203 ± 16	8
RD	0.301 x 0.054	15107	8/8	1	2236±406	2423±122	8	308±46	303±13	-2
RD	0.551 x 0.070	14810	8/8	1	2524 ± 71	2414 ± 304	-4	402 ± 22	344 ± 44	-14
RD		15107	8/8	1	1965 ± 455	1864 ± 232	-5	293 ± 56	261 ± 28	-11
RD	1.114 x 0.070	14810	8/8	1	2142 ± 209	2063 ± 294	-4	314 ± 32	293 ± 43	-7
RD		15107	8/8	1	2039 ± 236	2153 ± 107	6	296 ± 49	300 ± 23	1
RD	7.185 x 0.103	14810	8/8	3	1734 ± 454	1782 ± 431	3	231 ± 53	220 ± 39	-5
RD		15107	8/8	3	1579 ± 302	1255 ± 384	-21	215 ± 30	171 ± 39	-20
RD	11.196 x 0.103	14936	8/8	3	1334 ± 409	1458 ± 379	9	180 ± 38	184 ± 33	-2
RD		15107	8/8	3	1436 ± 355	1396 ± 451	-3	175 ± 29	152 ± 30	-13
Precision	0.301 x 0.054	19052	7/7	1	2218 ± 378	2162 ±229	-3	380 ±63	300 ±31	-21
Precision		19895	8/8	1	2233 ± 167	2138 ± 313	-4	369 ± 29	289 ± 37	-22
Precision	1.364 x 0.070	17405	6/8	1	2078 ±86	1971 ±181	-5	313 ± 15	261 ± 26	-17
Precision		19895	8/8	1	1935 ± 112	1937 ± 210	0	275 ± 18	247 ± 39	-10
Precision	7.739 x 0.070	19052	8/8	3	1578 ±342	1653 ±225	5	192 ± 64	152 ± 24	-21
Precision		19921	6/6	3	1496 ± 504	1616 ± 199	8	226 ± 23	181 ± 17	-20
Precision	16.955 x 0.139	19422	8/8	3	1129 ±250	832 ± 517	-26	188 ± 35	114 ± 63	-39
Precision		19895	8/8	3	1315 ± 190	1379 ± 126	5	223 ± 23	179 ± 12	-20

Table H-3. Tensile Strength Data for RD Rubber O-Rings, Batch 15107 Cure Study

0.301x0.054 **RD 15107**

Ring	Initial	Ring	Aged
1	1412	9	2381
2	1816	10	2395
3	2418	11	2482
4	2553	12	2594
5	2353	13	2199
6	2429	14	2553
7	2368	15	2396
8	2543	16	2384
Avg:	2237±406		2423±122
Strength Change:			8 %

0.301x0.054 (4 min. cure) **RD 15107**

Ring	Initial	Ring	Aged
1	2270	9	2457
2	2443	10	2333
3	2397	11	2342
4	2394	12	2056
5	2435	13	2459
6	2425	14	2416
7	2384	15	2317
8	2244	16	2575
Avg:	2374±75		2369±153
Strength Change:			0 %

0.301x0.054 (3 min. cure) **RD 15107**

Ring	Initial	Ring	Aged
1	2510	9	2524
2	N/A	10	2605
3	2553	11	2290
4	2446	12	2752
5	2521	13	2643
6	2366	14	2539
7	2443	15	2614
8	2163	16	2481
Avg:	2429±133		2556±136
Strength Change:			5 %

1.114x0.070 **RD 15107**

Ring	Initial	Ring	Aged
1	2247	9	2071
2	1795	10	2213
3	2044	11	1939
4	2182	12	2179
5	2223	13	2206
6	2191	14	2121
7	2050	15	2280
8	1582	16	2217
Avg:	2039±236		2153±107
Strength Change:			6 %

1.114x0.070 (4 min. cure) **RD 15107**

Ring	Initial	Ring	Aged
1	2307	9	2134
2	1904	10	2530
3	2151	11	2405
4	2234	12	2277
5	1907	13	2301
6	2248	14	217
7	2426	15	2408
8	1773	16	2518
Avg:	2119±230		2099±771
Strength Change:			-1 %

1.114x0.070 (3 min. cure) **RD 15107**

Ring	Initial	Ring	Aged
1	2380	9	1891
2	2206	10	2272
3	2281	11	2173
4	2269	12	2154
5	2364	13	2007
6	2321	14	2337
7	1983	15	1880
8	1608	16	1998
Avg:	2177±261		2089±171
Strength Change:			-4 %

7.185x0.103 **RD 15107**

Ring	Initial	Ring	Aged
1	1660	9	1124
2	1125	10	1327
3	1243	11	1362
4	1704	12	536
5	1607	13	1246
6	1515	14	1878
7	2114	15	1071
8	1662	16	1498
Avg:	1579±302		1255±384
Strength Change:			-20 %

7.185x0.103 (4 min. cure) **RD 15107**

Ring	Initial	Ring	Aged
1	1034	9	1564
2	1658	10	1749
3	999	11	1854
4	1025	12	1709
5	1016	13	1731
6	887	14	1073
7	1746	15	1607
8	995	16	1845
Avg:	1170±332		1642±251
Strength Change:			40 %

7.185x0.103 (3 min. cure) **RD 15107**

Ring	Initial	Ring	Aged
1	1502	9	1806
2	1850	10	1467
3	2174	11	1778
4	2026	12	1888
5	1886	13	1557
6	1690	14	1907
7	1694	15	1781
8	2211	16	1826
Avg:	1879±248		1751±157
Strength Change:			-7 %

11.196x0.103 **RD 15107**

Ring	Initial	Ring	Aged
1	1565	9	1640
2	1499	10	1546
3	1920	11	1083
4	1313	12	1557
5	1096	13	967
6	833	14	995
7	1798	15	1101
8	1460	16	2282
Avg:	1436±355		1396±451
Strength Change:			-3 %

11.196x0.103 (4 min. cure) **RD 15107**

Ring	Initial	Ring	Aged
1	1153	9	1708
2	1525	10	1841
3	1356	11	1827
4	1717	12	1936
5	1763	13	1454
6	921	14	2216
7	1472	15	1975
8	1131	16	1993
Avg:	1380±296		1869±224
Strength Change:			35 %

11.196x0.103 (3 min. cure) **RD 15107**

Ring	Initial	Ring	Aged
1	1776	9	1956
2	1473	10	2143
3	2066	11	1622
4	1528	12	1436
5	1870	13	2105
6	1680	14	1849
7	1919	15	2050
8	1653	16	2056
Avg:	1746±201		1902±252
Strength Change:			9 %

Table H-4. Tensile Elongation Data for RD Rubber O-Rings, Batch 15107 Cure Study

0.301x0.054 — RD 15107

Ring	Initial	Ring	Aged
1	218	9	307
2	255	10	307
3	323	11	305
4	344	12	319
5	326	13	280
6	329	14	316
7	321	15	301
8	346	16	289
Avg:	308±46		303±13
Elongation Change:			-2 %

0.301x0.054 (4 min. cure) — RD 15107

Ring	Initial	Ring	Aged
1	320	9	289
2	348	10	279
3	333	11	288
4	336	12	251
5	337	13	295
6	348	14	287
7	343	15	279
8	303	16	302
Avg:	334±15		284±15
Elongation Change:			-15 %

0.301x0.054 (3 min. cure) — RD 15107

Ring	Initial	Ring	Aged
1	354	9	280
2	N/A	10	283
3	344	11	266
4	338	12	296
5	347	13	281
6	321	14	271
7	362	15	272
8	303	16	258
Avg:	338±20		276±12
Elongation Change:			-18 %

1.114x0.070 — RD 15107

Ring	Initial	Ring	Aged
1	336	9	293
2	273	10	318
3	268	11	271
4	326	12	309
5	354	13	304
6	333	14	263
7	263	15	326
8	213	16	320
Avg:	296±49		301±23
Elongation Change:			2 %

1.114x0.070 (4 min. cure) — RD 15107

Ring	Initial	Ring	Aged
1	300	9	220
2	248	10	285
3	309	11	269
4	328	12	259
5	277	13	233
6	314	14	257
7	316	15	246
8	232	16	292
Avg:	291±35		258±25
Elongation Change:			-11 %

1.114x0.070 (3 min. cure) — RD 15107

Ring	Initial	Ring	Aged
1	351	9	191
2	322	10	223
3	332	11	255
4	328	12	273
5	353	13	244
6	347	14	229
7	294	15	178
8	224	16	191
Avg:	319±43		223±34
Elongation Change:			-30 %

7.185x0.103 — RD 15107

Ring	Initial	Ring	Aged
1	220	9	162
2	172	10	179
3	186	11	182
4	228	12	97
5	215	13	170
6	205	14	234
7	271	15	148
8	224	16	192
Avg:	215±30		171±39
Elongation Change:			-21 %

7.185x0.103 (4 min. cure) — RD 15107

Ring	Initial	Ring	Aged
1	140	9	148
2	192	10	159
3	140	11	170
4	140	12	164
5	139	13	166
6	131	14	133
7	198	15	157
8	141	16	172
Avg:	153±26		159±13
Elongation Change:			4 %

7.185x0.103 (3 min. cure) — RD 15107

Ring	Initial	Ring	Aged
1	183	9	156
2	210	10	140
3	238	11	159
4	235	12	162
5	217	13	142
6	211	14	169
7	201	15	154
8	251	16	157
Avg:	218±22		155±10
Elongation Change:			-29 %

11.196x0.103 — RD 15107

Ring	Initial	Ring	Aged
1	179	9	165
2	178	10	159
3	211	11	131
4	166	12	163
5	148	13	121
6	126	14	125
7	209	15	136
8	180	16	212
Avg:	175±29		152±30
Elongation Change:			-13 %

11.196x0.103 (4 min. cure) — RD 15107

Ring	Initial	Ring	Aged
1	169	9	184
2	204	10	195
3	184	11	186
4	226	12	201
5	226	13	158
6	149	14	229
7	201	15	205
8	161	16	195
Avg:	190±29		194±20
Elongation Change:			2 %

11.196x0.103 (3 min. cure) — RD 15107

Ring	Initial	Ring	Aged
1	228	9	190
2	199	10	218
3	266	11	159
4	201	12	138
5	244	13	199
6	224	14	175
7	246	15	195
8	216	16	194
Avg:	228±23		184±25
Elongation Change:			-20 %

Table H-5. Tensile Strength and Elongation Data for RD Rubber O-Rings, Various Batches and Sizes

0.551x0.070 — RD 14810

Ring	Initial	Ring	Aged
1	2420	9	2353
2	2482	10	2424
3	2571	11	2598
4	2495	12	2429
5	2465	13	2607
6	2533	14	2603
7	2608	15	2593
8	2619	16	1704
Avg:	2524±71		2414±304
Tensile Strength Change:			-4%

0.551x0.070 — RD 15107

Ring	Initial	Ring	Aged
1	2324	9	1541
2	948	10	1651
3	1928	11	2082
4	2251	12	2039
5	1840	13	1634
6	2162	14	2154
7	1920	15	1970
8	2345	16	1843
Avg:	1965±455		1864±232
Tensile Strength Change:			-5%

1.114x0.070 — RD 14810

Ring	Initial	Ring	Aged
1	2130	9	1664
2	2128	10	2414
3	2359	11	1682
4	2210	12	2260
5	2267	13	2325
6	2242	14	1934
7	2134	15	2267
8	1664	16	1954
Avg:	2142±209		2063±294
Tensile Strength Change:			-4%

7.185x0.103 — RD 14810

Ring	Initial	Ring	Aged
1	2393	9	2324
2	1278	10	1656
3	1416	11	1910
4	1793	12	2054
5	2386	13	1962
6	1765	14	1615
7	1224	15	868
8	1620	16	1865
Avg:	1734±454		1782±431
Tensile Strength Change:			3%

11.196x0.103 — RD 14936

Ring	Initial	Ring	Aged
1	1408	9	1282
2	1093	10	1332
3	1532	11	1221
4	1548	12	1196
5	586	13	1590
6	1895	14	1299
7	1038	15	2345
8	1573	16	1397
Avg:	1334±408		1458±379
Tensile Strength Change:			9%

0.551x0.070 — RD 14810

Ring	Initial	Ring	Aged
1	370	9	330
2	386	10	338
3	416	11	375
4	388	12	343
5	391	13	385
6	409	14	366
7	437	15	370
8	416	16	245
Avg:	402±22		344±44
Ten. Elongation Change:			-14%

0.551x0.070 — RD 15107

Ring	Initial	Ring	Aged
1	349	9	218
2	176	10	243
3	295	11	275
4	342	12	273
5	257	13	239
6	298	14	308
7	294	15	269
8	334	16	266
Avg:	293±56		261±28
Ten. Elongation Change:			-11%

1.114x0.070 — RD 14810

Ring	Initial	Ring	Aged
1	314	9	242
2	306	10	361
3	351	11	238
4	327	12	311
5	328	13	324
6	329	14	263
7	314	15	314
8	242	16	287
Avg:	314±32		293±43
Ten. Elongation Change:			-7%

7.185x0.103 — RD 14810

Ring	Initial	Ring	Aged
1	311	9	266
2	180	10	208
3	197	11	233
4	230	12	246
5	308	13	237
6	231	14	206
7	175	15	138
8	216	16	229
Avg:	231±53		220±39
Ten. Elongation Change:			-5%

11.196x0.103 — RD 14936

Ring	Initial	Ring	Aged
1	198	9	178
2	168	10	175
3	202	11	158
4	191	12	167
5	118	13	195
6	246	14	166
7	160	15	261
8	159	16	169
Avg:	180±38		184±33
Ten. Elongation Change:			2%

Table H-6. Tensile Strength Data for Parker O-Rings

0.116x0.038 Parker 318466

Ring	Initial	Ring	Aged
1	2220	9	1615
2	2066	10	1753
3	1748	11	1815
4	1326	12	1932
5	2034	13	1664
6	1656	14	1734
7	2229	15	2086
8	1851	16	1984
Avg:	1891±309		1823±164
Strength Change:			-4%

0.301X0.054 Parker 316104

Ring	Initial	Ring	Aged
1	1974	6	1946
2	1895	7	2049
3	2085	8	1663
4	2012	9	2068
5	1827	10	2094
Avg:	1959±101		1964±177
Strength Change:			0%

0.301x0.054 Parker 316710

Ring	Initial	Ring	Aged
1	2094	9	1898
2	1921	10	2107
3	1953	11	2064
4	2189	12	2109
5	2023	13	2029
6	1996	14	2089
7	1926	15	1984
8	2020	16	1980
Avg:	2015±91		2033±74
Strength Change:			1%

1.364x0.070 Parker 316104

Ring	Initial	Ring	Aged
1	1616	6	1532
2	1641	7	1618
3	1629	8	1549
4	1693	9	1559
5	1377	10	1610
Avg:	1591±123		1574±38
Strength Change:			-1%

1.364x0.070 Parker 317403

Ring	Initial	Ring	Aged
1	1876	9	1430
2	1499	10	1932
3	1446	11	1636
4	1779	12	2070
5	1923	13	1947
6	1865	14	1882
7	2011	15	1425
8	1924	16	1341
Avg:	1790±207		1708±284
Strength Change:			-5%

7.688x0.070 Parker 316104

Ring	Initial	Ring	Aged
1	1553	6	1667
2	1335	7	1415
3	1434	8	1542
4	1463	9	1576
5	1452	10	1605
Avg:	1447±78		1561±94
Strength Change:			8%

7.688x0.070 Parker 317851

Ring	Initial	Ring	Aged
1	995	9	1559
2	1097	10	1706
3	1877	11	1800
4	1235	12	1874
5	1939	13	1786
6	1521	14	1922
7	1899	15	1659
8	1190	16	1066
Avg:	1469±391		1672±271
Strength Change:			14%

16.339x0.103 Parker 316104

Ring	Initial	Ring	Aged
1	1296	9	1372
2	1358	10	1478
3	1283	11	1390
4	1273	12	1506
5	1416	13	1460
6	1258	14	1330
7	1320	15	1433
8	1272	16	1471
Avg:	1310±54		1430±61
Strength Change:			9%

16.339x0.103 Parker 316710

Ring	Initial	Ring	Aged
1	1423	9	1582
2	1338	10	1546
3	1583	11	1482
4	810	12	1437
5	1560	13	1460
6	1237	14	1148
7	1068	15	1516
8	1336	16	1270
Avg:	1294±257		1430±148
Strength Change:			10%

Table H-7. Tensile Elongation Data for Parker O-Rings

0.116x0.038 Parker 318466

Ring	Initial	Ring	Aged
1	326	9	234
2	298	10	259
3	255	11	269
4	205	12	284
5	300	13	233
6	242	14	255
7	320	15	306
8	278	16	274
Avg:	278±41		264±25
Elongation Change:			-5%

0.301X0.054 Parker 316104

Ring	Initial	Ring	Aged
1	260	6	250
2	244	7	257
3	277	8	274
4	261	9	252
5	253	10	271
Avg:	259±12		261±11
Elongation Change:			1 %

0.301x0.054 Parker 316710

Ring	Initial	Ring	Aged
1	288	9	264
2	249	10	286
3	269	11	257
4	285	12	281
5	261	13	274
6	283	14	278
7	262	15	265
8	276	16	260
Avg:	272±14		271±11
Elongation Change:			0 %

1.364x0.070 Parker 316104

Ring	Initial	Ring	Aged
1	212	6	204
2	214	7	214
3	213	8	207
4	218	9	212
5	188	10	214
Avg:	209±12		210±4
Elongation Change:			1 %

1.364x0.070 Parker 317403

Ring	Initial	Ring	Aged
1	302	9	224
2	226	10	300
3	261	11	274
4	280	12	335
5	281	13	298
6	301	14	287
7	295	15	215
8	301	16	217
Avg:	281±26		269±45
Elongation Change:			-4 %

7.688x0.070 Parker 316104

Ring	Initial	Ring	Aged
1	192	6	198
2	168	7	173
3	174	8	186
4	180	9	188
5	175	10	195
Avg:	178±9		188±10
Elongation Change:			6 %

7.688x0.070 Parker 317851

Ring	Initial	Ring	Aged
1	250	9	312
2	305	10	340
3	441	11	376
4	314	12	373
5	496	13	361
6	337	14	393
7	436	15	343
8	316	16	227
Avg:	362±85		341±52
Elongation Change:			-6 %

16.339x0.103 Parker 316104

Ring	Initial	Ring	Aged
1	165	9	171
2	172	10	182
3	166	11	173
4	165	12	183
5	179	13	179
6	164	14	167
7	170	15	176
8	166	16	182
Avg:	168±5		177±6
Elongation Change:			5 %

16.339x0.103 Parker 316710

Ring	Initial	Ring	Aged
1	202	9	217
2	188	10	219
3	222	11	207
4	129	12	205
5	222	13	206
6	181	14	173
7	165	15	211
8	193	16	183
Avg:	188±31		203±16
Elongation Change:			8 %

Table H-8. Tensile Strength Data for Precision O-Rings

0.301x0.054		Precision 19052	
Ring	Initial	Ring	Aged
1	2382	9	N/A
2	2385	10	2286
3	2477	11	2319
4	N/A	12	2092
5	2432	13	2108
6	2357	14	2329
7	1410	15	2307
8	2083	16	1695
Avg:	2218±378		2162±229
Strength Change:			-3 %

0.301x0.054		Precision 19895	
Ring	Initial	Ring	Aged
1	2264	9	2286
2	2218	10	2269
3	1935	11	1382
4	2386	12	2180
5	2024	13	2202
6	2372	14	2171
7	2330	15	2241
8	2333	16	2375
Avg:	2233±167		2138±313
Strength Change:			-4 %

1.364x0.070		Precision 17405	
Ring	Initial	Ring	Aged
1	2112	9	2103
2	2090	10	1984
3	N/A	11	2134
4	2073	12	2118
5	N/A	13	2138
6	2104	14	1807
7	2173	15	1714
8	1917	16	1766
Avg:	2078±86		1971±181
Strength Change:			-5 %

1.364x0.070		Precision 19895	
Ring	Initial	Ring	Aged
1	2050	9	2012
2	1890	10	1974
3	1912	11	1792
4	1994	12	1952
5	2027	13	2019
6	1884	14	2095
7	1710	15	2158
8	2014	16	1490
Avg:	1935±112		1937±210
Strength Change:			0 %

7.739x0.070		Precision 19052	
Ring	Initial	Ring	Aged
1	1590	9	1231
2	1322	10	1595
3	1327	11	1513
4	2192	12	1622
5	1417	13	1800
6	1377	14	1984
7	2027	15	1681
8	1370	16	1796
Avg:	1578±342		1653±225
Strength Change:			5 %

7.739x0.070		Precision 19921	
Ring	Initial	Ring	Aged
1	1891	7	1468
2	1483	8	1774
3	1650	9	1359
4	507	10	1495
5	1653	11	1836
6	1789	12	1761
Avg:	1496±504		1616±198
Strength Change:			8 %

16.955x0.139		Precision 19422	
Ring	Initial	Ring	Aged
1	958	9	796
2	910	10	482
3	1133	11	1627
4	1098	12	155
5	1119	13	1399
6	825	14	1085
7	1471	15	804
8	1514	16	308
Avg:	1129±250		832±518
Strength Change:			-26 %

16.955x0.139		Precision 19895	
Ring	Initial	Ring	Aged
1	1411	9	1289
2	1065	10	1542
3	1260	11	1251
4	1088	12	1206
5	1585	13	1527
6	1242	14	1346
7	1333	15	1421
8	1533	16	1448
Avg:	1315±190		1379±126
Strength Change:			5 %

Table H-9. Tensile Elongation Data for Precision O-Rings

0.301x0.054		Precision 19052	
Ring	Initial	Ring	Aged
1	393	9	N/A
2	428	10	309
3	415	11	318
4	N/A	12	297
5	413	13	286
6	404	14	329
7	246	15	322
8	359	16	239
Avg:	380±63		300±31
Elongation Change:			-21 %

0.301x0.054		Precision 19895	
Ring	Initial	Ring	Aged
1	374	9	305
2	359	10	308
3	316	11	198
4	394	12	303
5	339	13	291
6	390	14	298
7	393	15	293
8	387	16	315
Avg:	369±29		289±38
Elongation Change:			-22 %

1.364x0.070		Precision 17405	
Ring	Initial	Ring	Aged
1	321	9	287
2	316	10	262
3	N/A	11	278
4	301	12	283
5	N/A	13	281
6	323	14	234
7	331	15	226
8	290	16	233
Avg:	314±15		261±26
Elongation Change:			-17 %

1.364x0.070		Precision 19895	
Ring	Initial	Ring	Aged
1	284	9	293
2	275	10	252
3	282	11	230
4	297	12	250
5	296	13	253
6	265	14	274
7	249	15	261
8	253	16	161
Avg:	275±18		247±39
Elongation Change:			-10 %

7.739x0.070		Precision 19052	
Ring	Initial	Ring	Aged
1	188	9	125
2	154	10	138
3	142	11	135
4	318	12	140
5	160	13	160
6	155	14	201
7	263	15	151
8	158	16	164
Avg:	192±64		152±24
Elongation Change:			-21 %

7.739x0.070		Precision 19921	
Ring	Initial	Ring	Aged
1	267	7	173
2	207	8	203
3	231	9	159
4	207	10	171
5	210	11	199
6	231	12	180
Avg:	226±23		181±17
Elongation Change:			-20 %

16.955x0.139		Precision 19422	
Ring	Initial	Ring	Aged
1	159	9	111
2	161	10	78
3	199	11	206
4	180	12	23
5	193	13	185
6	142	14	146
7	236	15	111
8	236	16	53
Avg:	188±35		114±63
Elongation Change:			-39 %

16.955x0.139		Precision 19895	
Ring	Initial	Ring	Aged
1	227	9	174
2	228	10	195
3	236	11	160
4	179	12	169
5	249	13	191
6	206	14	170
7	212	15	185
8	245	16	186
Avg:	223±23		179±12
Elongation Change:			-20 %

Table H-10. Tensile Strength Data for Test Slabs

Parker 316104

Site	Initial	Aged
1	1689	1550
2	1390	1580
3	1563	1396
4	1608	1304
Avg:	1563±126	1458±130
Strength Change:		-7%

Parker 316710

Site	Initial	Aged
1	2469	2015
2	2618	2507
3	2379	2292
4	2546	2315
Avg:	2503±103	2282±203
Strength Change:		-9%

Parker 317403

Site	Initial	Aged
1	1761	1766
2	1605	1768
3	1569	1668
4	1424	1856
Avg:	1590±138	1765±77
Strength Change:		11%

Parker 317851

Site	Initial	Aged
1	2669	2180
2	2599	2216
3	2370	1427
4	2481	1938
Avg:	2530±132	1940±364
Strength Change:		-23%

Parker 318466

Site	Initial	Aged
1	1657	1584
2	1122	1651
3	1531	1655
4	1528	NA
Avg:	1459±233	1630±40
Strength Change:		12%

RD 14810

Site	Initial	Aged
1	2252	2137
2	2162	2161
3	2157	2046
4	2300	2337
Avg:	2218±70	2170±122
Strength Change:		-2%

RD 15107

Site	Initial	Aged
1	2055	2079
2	2161	2132
3	2173	1819
4	2101	2009
Avg:	2123±55	2010±137
Strength Change:		-5%

RD 15107 (4 min. cure)

Site	Initial	Aged
1	2123	1895
2	2133	N/A
3	2057	2114
4	2052	1842
Avg:	2091±43	1950±144
Strength Change:		-7%

RD 15107 (3 min. cure)

Site	Initial	Aged
1	2343	1924
2	2057	2118
3	2017	2100
4	2046	1994
Avg:	2116±152	2034±91
Strength Change:		-4%

Precision 19052A

Site	Initial	Aged
1	1744	1737
2	1556	1723
3	1587	1603
4	1957	1721
Avg:	1711±183	1696±62
Strength Change:		-1%

Precision 19895A

Site	Initial	Aged
1	1673	1448
2	1659	1672
3	1578	1424
4	1717	1716
Avg:	1657±58	1565±150
Strength Change:		-6%

Table H-11. Tensile Elongation Data for Test Slabs

Parker 316104

Site	Initial	Aged
1	216	164
2	188	186
3	187	153
4	206	161
Avg:	199±14	166±14
Elongation Change		-17%

Parker 316710

Site	Initial	Aged
1	186	166
2	193	185
3	174	168
4	191	169
Avg:	186±9	172±9
Elongation Change		-8%

Parker 317403

Site	Initial	Aged
1	227	201
2	241	215
3	223	234
4	193	232
Avg:	221±20	221±16
Elongation Change		0%

Parker 317851

Site	Initial	Aged
1	181	163
2	188	169
3	164	131
4	181	144
Avg:	179±10	152±17
Elongation Change		-15%

Parker 318466

Site	Initial	Aged
1	569	632
2	412	569
3	522	562
4	636	NA
Avg:	535±95	588±39
Elongation Change		10%

RD 14810

Site	Initial	Aged
1	261	246
2	279	241
3	269	231
4	283	271
Avg:	273±10	247±17
Elongation Change		-9%

RD 15107

Site	Initial	Aged
1	236	232
2	230	226
3	238	218
4	266	205
Avg:	243±16	220±12
Elongation Change		-9%

RD 15107 (4 min. cure)

Site	Initial	Aged
1	243	187
2	250	N/A
3	238	187
4	259	164
Avg:	248±9	179±13
Elongation Change		-28%

RD 15107 (3 min. cure)

Site	Initial	Aged
1	234	167
2	216	202
3	218	187
4	217	198
Avg:	221±9	189±16
Elongation Change		-15%

Precision 19052A

Site	Initial	Aged
1	263	208
2	245	218
3	327	190
4	270	216
Avg:	276±35	208±13
Elongation Change		-25%

Precision 19895A

Site	Initial	Aged
1	248	189
2	217	210
3	229	172
4	222	219
Avg:	229±14	198±21
Elongation Change		-14%

Appendix I: Tensile Modulus and Work Test Data

Contents:

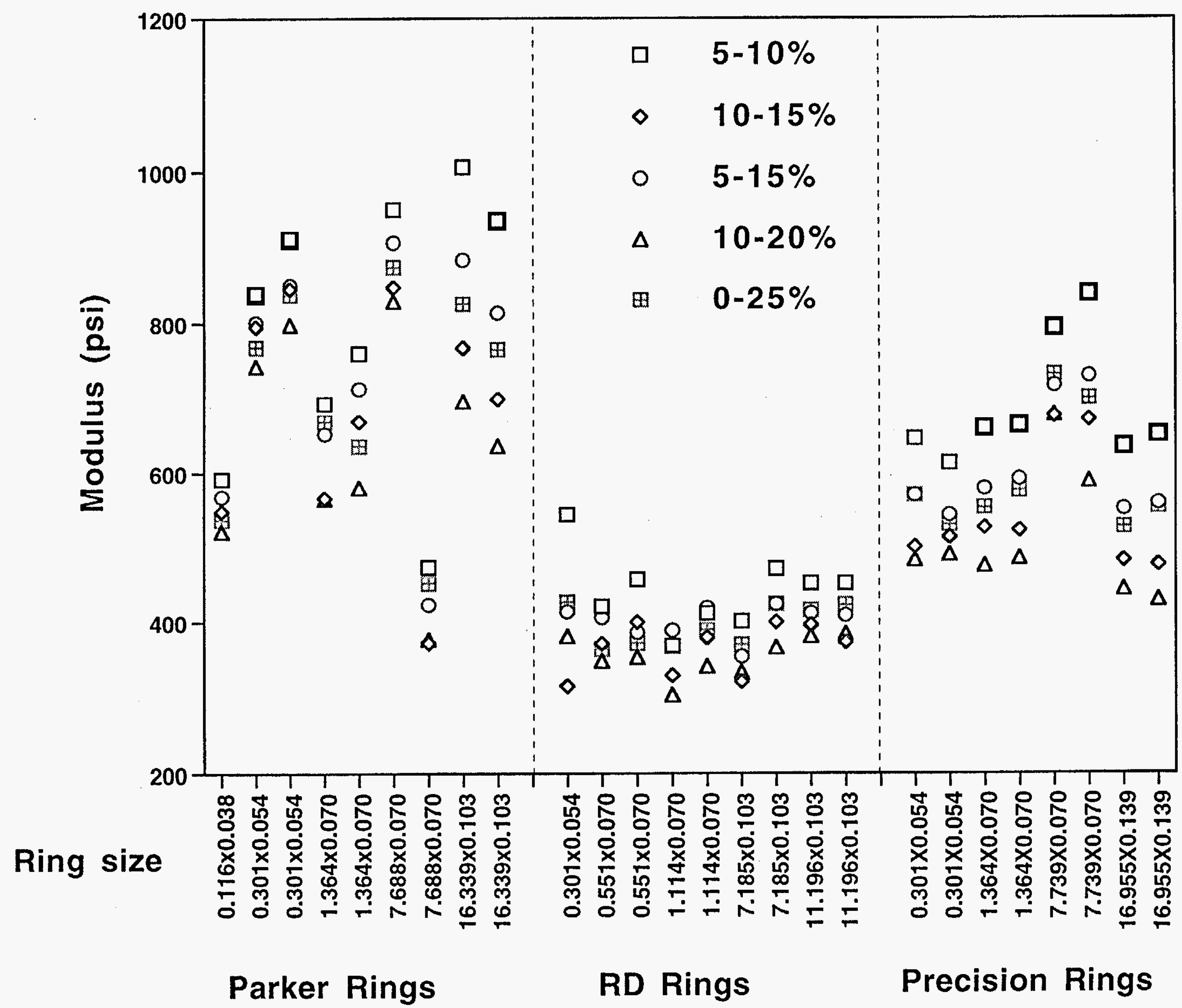
Table I-1. Non-Linear, Tangential Tensile Modulus Data (all elongation ranges) on Butyl Rubber O-Rings

Vendor	Ring size	Rubber Batch	Ring No.	Modulus 5-10%			Modulus 10-15%			Modulus 5-15%			Modulus 10-20%			Modulus 0-25%		
				unaged	aged	Δ%	unaged	aged	Δ%	unaged	aged	Δ%	unaged	aged	Δ%	unaged	aged	Δ%
Parker	0.116 x 0.038	318466	8/8	592±36	575±55	-3	548±79	652±60	19	568±57	622±53	10	521±75	621±31	19	537±46	596±32	11
Parker	0.301 x 0.054	316104	5/4	839±67	887±156	6	795±83	785±83	-1	801±56	825±118	3	743±47	752±125	1	768±35	797±101	4
Parker		316710	7/5	912±125	981±154	8	846±65	846±219	0	851±77	882±174	4	798±40	814±102	2	838±48	840±99	0
Parker	1.364 x 0.070	316104	4/3	693±27	906±30	31	566±69	655±36	16	652±41	782±17	20	565±57	714±14	26	669±36	752±18	12
Parker		317403	7/8	760±59	744±84	-2	669±61	672±68	0	713±31	694±62	-3	580±28	635±43	9	636±13	663±32	4
Parker	7.688 x 0.070	316104	5/5	951±182	815±236	-14	848±75	749±89	-12	907±125	774±149	-15	829±85	756±92	-9	875±49	812±77	-7
Parker		317851	8/7	473±33	605±33	28	372±41	533±34	43	423±28	569±32	35	377±48	481±27	28	452±34	558±21	23
Parker	16.339 x 0.103	316104	8/8	1006±13	1044±146	4	767±16	759±32	-1	884±11	891±79	1	696±11	691±21	-1	826±5	845±33	2
Parker		316710	8/8	936±19	962±45	3	699±16	674±15	-4	814±14	808±23	-1	636±17	613±15	-4	765±15	769±19	1
RD	0.301 x 0.054	15107	8/8	544±67	517±53	-5	315±46	479±60	52	414±15	490±44	18	381±31	504±27	32	427±17	494±24	16
RD	0.551 x 0.070	14810	7/8	421±171	440±100	5	371±19	404±53	9	406±43	397±37	-2	348±9	394±21	13	364±8	395±12	9
RD		15107	8/6	457±88	507±64	11	400±66	403—63	1	386±26	452±28	17	353±29	398±25	13	372±14	422±25	13
RD	1.114 x 0.070	14810	7/8	368±44	428±42	16	329±60	380±37	16	389±12	410±25	5	303±40	347±26	15	368±12	385±21	5
RD		15107	7/8	412±71	484±35	17	379±54	398±54	5	419±27	457±14	9	341±38	376±26	10	390±26	428±19	10
RD	7.185 x 0.103	14810	7/8	401±22	420±16	5	321±14	344±13	7	354±7	384±9	8	333±12	345±13	4	370±14	386±19	4
RD		15107	8/8	471±23	519±17	10	400±15	443±16	11	424±11	467±11	10	366±12	420±21	15	424±18	474±17	12
RD	11.196 x 0.103	14936	7/7	452±23	493±16	9	396±27	447±31	13	412±12	459±22	11	381±22	423±39	11	416±15	453±28	9
RD		15107	7/8	452±30	529±25	17	373±16	476±32	28	409±8	396±20	-3	385±25	477±25	24	423±21	508±18	20
Precision	0.301 x 0.054	19052	7/7	646±90	623±39	-4	500±157	543±135	9	570±42	630±19	11	483±45	514±45	6	570±29	630±18	11
Precision		19895	8/8	613±93	682±50	11	513±49	583±62	14	543±43	611±59	13	490±17	537±62	10	530±17	625±27	18
Precision	1.364 x 0.070	17405	6/8	660±39	698±28	6	526±9	575±27	9	579±24	636±19	10	475±18	561±34	18	553±20	633±23	14
Precision		19895	8/7	664±58	662±47	0	522±29	526±39	1	592±20	590±33	0	485±20	511±46	5	576±19	600±37	4
Precision	7.739 x 0.070	19052	8/8	794±36	841±35	6	676±71	776±31	15	717±48	812±26	13	678±63	768±45	13	732±53	849±36	16
Precision		19921	6/6	839±41	890±32	6	671±32	722±21	8	730±32	797±19	9	589±21	648±10	10	700±23	772±14	10
Precision	16.955 x 0.139	19422	8/8	635±29	702±32	11	482±25	547±19	13	551±22	617±23	12	444±23	519±15	17	527±17	610±17	16
Precision		19895	8/8	651±34	746±34	15	476±14	561±29	18	559±18	652±26	17	430±13	539±27	25	554±13	654±28	18

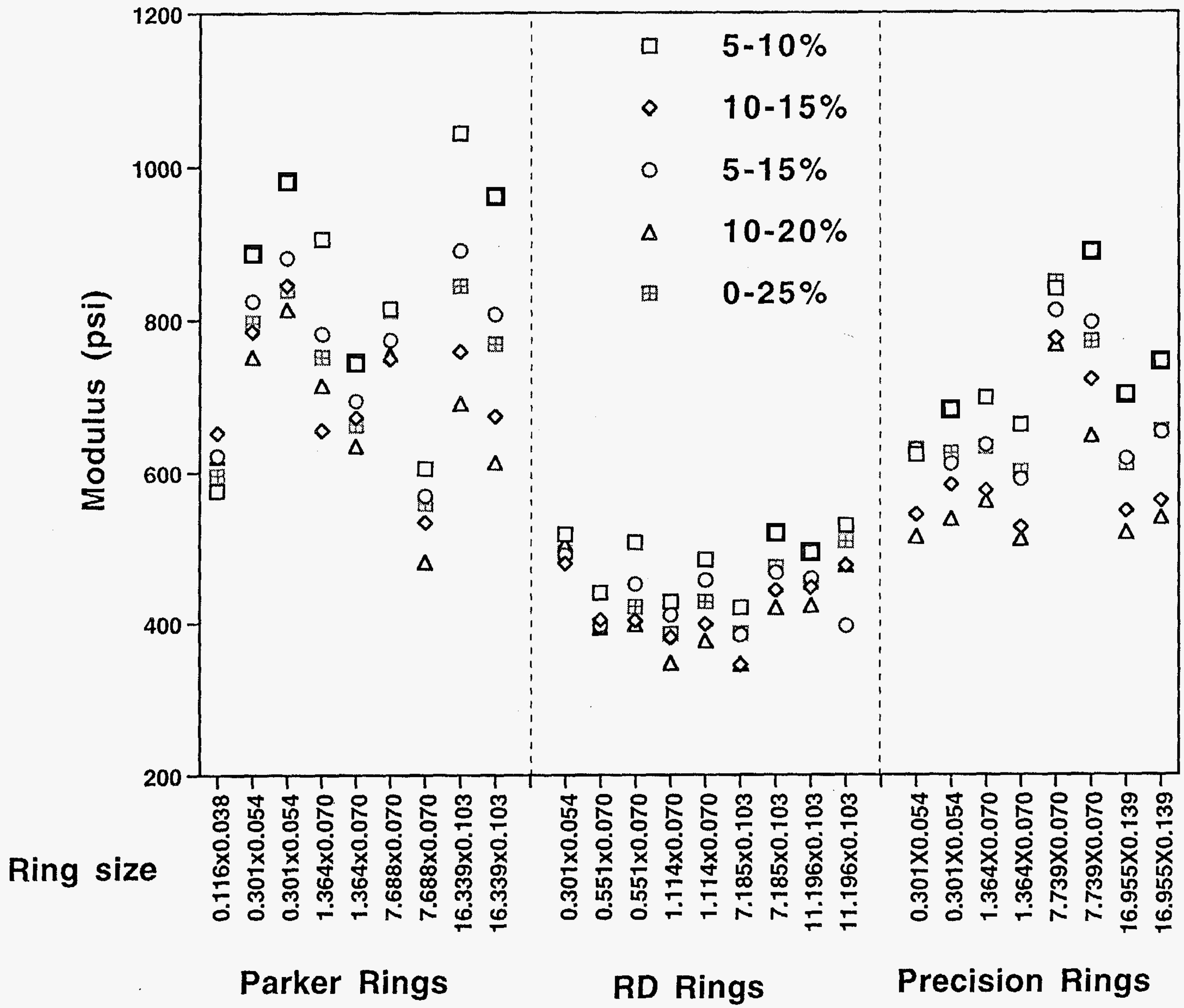
Table I-2. Non-Linear, Tangential Tensile Modulus Data (all elongation ranges and averages) on Butyl Rubber O-Rings

Vendor	Ring size	Rubber Batch	Modulus 5-10%		Modulus 10-15%		Modulus 5-15%		Modulus 10-20%		Modulus 0-25%		Average Modulus	
			unaged	aged	unaged	aged	unaged	aged	unaged	aged	unaged	aged	unaged	aged
Parker	0.116 x 0.038	318466	592	575	548	652	568	622	521	621	537	596	553	613
Parker	0.301 x 0.054	316104	839	887	795	785	801	825	743	752	768	797	789	809
Parker		316710	912	981	846	846	851	882	798	814	838	840	849	873
Parker	1.364 x 0.070	316104	693	906	566	655	652	782	565	714	669	752	629	762
Parker		317403	760	744	669	672	713	694	580	635	636	663	672	682
Parker	7.688 x 0.070	316104	951	815	848	749	907	774	829	756	875	812	882	781
Parker		317851	473	605	372	533	423	569	377	481	452	558	419	549
Parker	16.339 x 0.103	316104	1006	1044	767	759	884	891	696	691	826	845	836	846
Parker		316710	936	962	699	674	814	808	636	613	765	769	770	765
		avg.	796	835	679	703	735	761	638	675	708	737	711	742
RD	0.301x 0.054	15107	544	517	315	479	414	490	381	504	427	494	416	497
RD	0.551 x 0.070	14810	421	440	371	404	406	397	348	394	364	395	382	406
RD		15107	457	507	400	403	386	452	353	398	372	422	394	436
RD	1.114 x 0.070	14810	368	428	329	380	389	410	303	347	368	385	351	390
RD		15107	412	484	379	398	419	457	341	376	390	428	388	429
RD	7.185 x 0.103	14810	401	420	321	344	354	384	333	345	370	386	356	376
RD		15107	471	519	400	443	424	467	366	420	424	474	417	465
RD	11.196 x 0.103	14936	452	493	396	447	412	459	381	423	416	453	411	455
RD		15107	452	529	373	476	409	396	385	477	423	508	408	477
		avg.	442	482	365	419	401	435	355	409	395	438	391	437
Precision	0.301 x 0.054	19052	646	623	500	543	570	630	483	514	570	630	554	588
Precision		19895	613	682	513	583	543	611	490	537	530	625	538	608
Precision	1.364 x 0.070	17405	660	698	526	575	579	636	475	561	553	633	559	621
Precision		19895	664	662	522	526	592	590	485	511	576	600	568	578
Precision	7.739 x 0.070	19052	794	841	676	776	717	812	678	768	732	849	719	809
Precision		19921	839	890	671	722	730	797	589	648	700	772	706	766
Precision	16.955 x 0.139	19422	635	702	482	547	551	617	444	519	527	610	528	599
Precision		19895	651	746	476	561	559	652	430	539	554	654	534	630
		avg.	688	731	546	604	605	668	509	575	593	672	588	650

Plot I-3. Modulus vs. Percent Elongation Range of Unaged O-Ring Samples



Plot I-4. Modulus vs. Percent Elongation Range of Aged O-Ring Samples



Plot I-5. Average Modulus of Aged and Unaged O-Ring Samples

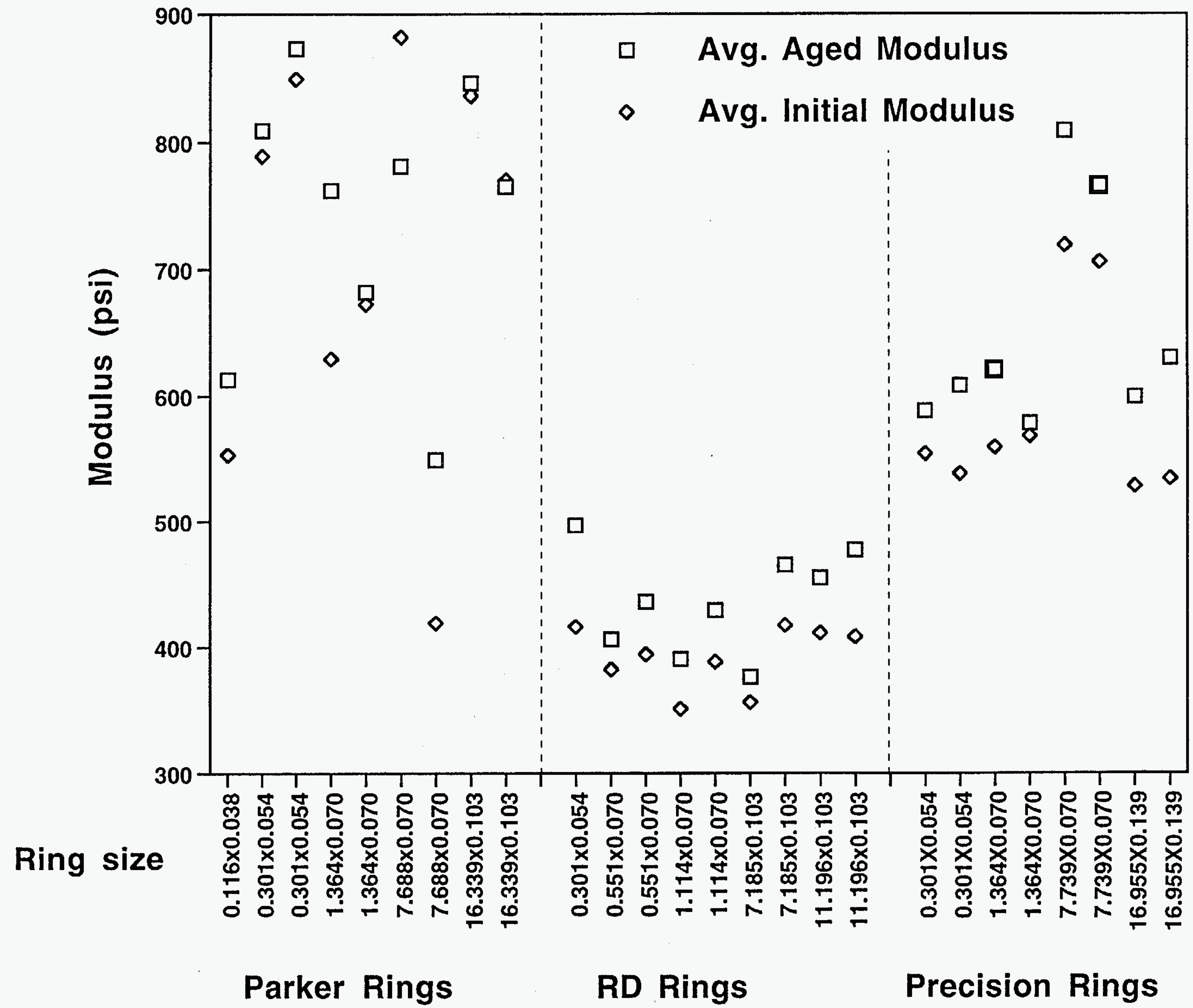


Table I-6. Tensile Work Integration (0-20% elongation) Data on Butyl Rubber O-Rings

Vendor	Ring size	Rubber Batch	Rings	Loops	IN-LB/SQ.IN. unaged	IN-LB/SQ.IN. aged	Δ%	PERCENT-LB/SQ.IN. unaged	PERCENT-LB/SQ.IN. aged	Δ%
Parker	0.116 x 0.038	318466	8/8	1	2.00±0.14	2.18±0.18	9	1095±79	1197±97	9
Parker	0.301 x 0.054	316104	5/4	1	7.86±0.63	8.13±1.10	3	1662±133	1720±229	3
Parker		316710	7/5	1	8.27±0.63	7.86±1.10	-5	1749±134	1691±182	-3
Parker	1.364 x 0.070	316104	4/3	1	31.4±1.5	34.8±0.7	11	1464±70	1622±33	11
Parker		317403	7/8	1	32.8±1.7	33.6±2.5	2	1530±81	1568±118	2
Parker	7.688 x 0.070	316104	5/5	3	383±29	351±44	-8	2027±188	1856±274	-8
Parker		317851	8/7	3	221±11	267±9	21	1280±55	1522±63	19
Parker	16.339 x 0.103	316104	8/8	3	837±8	873±66	4	2233±30	2354±230	5
Parker		316710	8/8	3	799±12	834±38	4	2155±33	2297±138	7
RD	0.301 x 0.054	15107	8/8	1	5.02±0.60	5.09±0.47	1	1061±128	1076±99	1
RD	0.551 x 0.070	14810	7/8	1	6.70±0.52	7.95±0.33	19	774±60	918±38	19
RD		15107	8/6	1	7.17±0.44	7.79±0.15	9	828±51	900±17	9
RD	1.114 x 0.070	14810	7/8	1	14.9±0.5	15.3±1.0	3	853±29	876±57	3
RD		15107	7/8	1	15.8±0.9	17.9±0.6	13	900±53	1023±37	14
RD	7.185 x 0.103	14810	7/8	3	173±6	177±10	2	1048±40	1068±74	2
RD		15107	8/8	3	210±11	226±11	8	1310±80	1375±85	5
RD	11.196 x 0.103	14936	7/7	3	302±14	317±18	5	1172±62	1206±62	3
RD		15107	7/8	3	308±17	355±16	15	1194±76	1352±60	13
Precision	0.301 x 0.054	19052	7/7	1	6.25±0.35	7.38±0.29	18	1322±75	1561±61	18
Precision		19895	8/8	1	5.63±0.21	7.01±0.31	25	1190±44	1483±66	25
Precision	1.364 x 0.070	17405	6/8	1	30.3±1.3	33.3±1.1	10	1414±59	1556±51	10
Precision		19895	8/7	1	29.7±1.6	32.0±1.7	8	1384±77	1491±77	8
Precision	7.739 x 0.070	19052	8/8	3	338±15	391±12	16	1857±74	2143±75	15
Precision		19921	6/6	3	347±12	378±13	9	1990±68	2159±85	8
Precision	16.955 x 0.139	19422	8/8	3	577±9	643±11	11	1492±40	1642±24	10
Precision		19895	8/8	3	628±9	729±26	16	1686±22	1934±71	15

Table I-7. Linear Tensile Modulus (0-25% elongation) Data on Butyl Rubber O-Rings

Vendor	Ring size	Rubber Batch	Rings	Loops	PSI unaged	PSI aged	Δ%
Parker	0.116 x 0.038	318466	8/8	1	527±39	581±31	10.2
Parker	0.301 x 0.054	316104	5/4	1	754±22	780±96	3.4
Parker		316710	7/5	1	812±37	819±65	0.9
Parker	1.364 x 0.070	316104	4/3	1	683±26	736±12	7.8
Parker		317403	7/8	1	639±18	675±32	5.6
Parker	7.688 x 0.070	316104	5/5	3	896±31	860±58	-4.0
Parker		317851	8/7	3	489±29	586±19	19.8
Parker	16.339 x 0.103	316104	8/8	3	868±7	906±32	4.4
Parker		316710	8/8	3	819±9	842±28	2.8
RD	0.301 x 0.054	15107	8/8	1	447±29	493±27	10.3
RD	0.551 x 0.070	14810	7/8	1	358±16	403±13	12.6
RD		15107	8/6	1	367±15	414±24	12.8
RD	1.114 x 0.070	14810	7/8	1	369±14	387±25	4.9
RD		15107	7/8	1	389±25	431±22	10.8
RD	7.185 x 0.103	14810	7/8	3	418±17	435±24	4.1
RD		15107	8/8	3	507±30	553±22	9.1
RD	11.196 x 0.103	14936	7/7	3	465±22	496±31	6.7
RD		15107	7/8	3	477±26	560±21	17.4
Precision	0.301 x 0.054	19052	7/7	1	554±38	628±24	13.4
Precision		19895	8/8	1	516±16	642±22	24.4
Precision	1.364 x 0.070	17405	6/8	1	577±17	658±18	14.0
Precision		19895	8/7	1	585±27	623±46	6.5
Precision	7.739 x 0.070	19052	8/8	3	788±50	919±37	16.6
Precision		19921	6/6	3	760±21	834±18	9.7
Precision	16.955 x 0.139	19422	8/8	3	576±10	660±12	14.6
Precision		19895	8/8	3	614±10	729±29	18.7

Table I-8. Linear Tensile Modulus (0-25% elongation) Data for RD Rubber O-Rings, Batch 15107 Cure Study

0.301x0.054			RD 15107	0.301x0.054 (4 min. cure)			RD 15107	0.301x0.054 (3 min. cure)			RD 15107
Ring	Initial	Ring	Aged	Ring	Initial	Ring	Aged	Ring	Initial	Ring	Aged
1	451	9	448	1	442	9	503	1	521	9	500
2	448	10	486	2	427	10	446	2	N/A	10	529
3	481	11	500	3	452	11	442	3	467	11	523
4	481	12	523	4	414	12	464	4	453	12	541
5	421	13	502	5	443	13	472	5	456	13	544
6	442	14	532	6	417	14	480	6	444	14	526
7	394	15	472	7	408	15	467	7	475	15	554
8	456	16	479	8	439	16	487	8	437	16	547
Avg:	447±29		493±27	Avg:	430±16		470±20	Avg:	465±28		533±17
Modulus Change:			10%	Modulus Change:			9%	Modulus Change:			15%

1.114x0.070			RD 15107	1.114x0.070 (4 min. cure)			RD 15107	1.114x0.070 (3 min. cure)			RD 15107
Ring	Initial	Ring	Aged	Ring	Initial	Ring	Aged	Ring	Initial	Ring	Aged
1	383	9	431	1	378	9	499	1	378	9	483
2	373	10	415	2	400	10	458	2	363	10	466
3	423	11	408	3	413	11	469	3	382	11	451
4	400	12	421	4	353	12	415	4	408	12	388
5	376	13	427	5	373	13	487	5	407	13	426
6	353	14	475	6	384	14	482	6	378	14	470
7	N/A	15	418	7	416	15	445	7	349	15	505
8	416	16	454	8	406	16	417	8	400	16	474
Avg:	389±25		431±22	Avg:	390±22		459±31	Avg:	383±21		458±36
Modulus Change:			11%	Modulus Change:			19%	Modulus Change:			19%

7.185x0.103			RD 15107	7.185x0.103 (4 min. cure)			RD 15107	7.185x0.103 (3 min. cure)			RD 15107
Ring	Initial	Ring	Aged	Ring	Initial	Ring	Aged	Ring	Initial	Ring	Aged
1	544	9	537	1	489	9	623	1	511	9	578
2	451	10	561	2	501	10	562	2	544	10	655
3	491	11	547	3	492	11	607	3	569	11	634
4	495	12	603	4	495	12	542	4	517	12	584
5	532	13	544	5	492	13	587	5	529	13	567
6	534	14	554	6	489	14	537	6	495	14	666
7	507	15	533	7	504	15	557	7	504	15	588
8	499	16	545	8	468	16	582	8	551	16	587
Avg:	507±30		553±22	Avg:	491±11		575±31	Avg:	527±25		607±38
Modulus Change:			12%	Modulus Change:			17%	Modulus Change:			15%

11.196x0.103			RD 15107	11.196x0.103 (4 min. cure)			RD 15107	11.196x0.103 (3 min. cure)			RD 15107
Ring	Initial	Ring	Aged	Ring	Initial	Ring	Aged	Ring	Initial	Ring	Aged
1	525	9	601	1	433	9	526	1	445	9	552
2	490	10	552	2	433	10	526	2	445	10	531
3	486	11	560	3	436	11	526	3	443	11	582
4	460	12	541	4	418	12	542	4	443	12	613
5	N/A	13	566	5	433	13	542	5	433	13	557
6	448	14	558	6	436	14	542	6	439	14	577
7	460	15	531	7	436	15	542	7	439	15	567
8	468	16	571	8	427	16	562	8	449	16	582
Avg:	477±26		560±21	Avg:	432±6		538±12	Avg:	442±5		570±25
Modulus Change:			18%	Modulus Change:			25%	Modulus Change:			29%

Table I-9. Linear Tensile Modulus (0-25% elongation) Data for RD Rubber O-Rings, Various Batches and Sizes

0.551x0.070			RD 14810
Ring	Initial	Ring	Aged
1	361	9	380
2	372	10	413
3	339	11	413
4	N/A	12	409
5	373	13	397
6	340	14	403
7	373	15	417
8	347	16	392
Avg:	358±16		403±13
Modulus Change:			13%

0.551x0.070			RD 15107
Ring	Initial	Ring	Aged
1	359	9	442
2	372	10	401
3	347	11	447
4	357	12	401
5	377	13	396
6	392	14	N/A
7	356	15	N/A
8	376	16	396
Avg:	367±15		414±24
Modulus Change:			13%

1.114x0.070			RD 14810
Ring	Initial	Ring	Aged
1	352	9	372
2	368	10	355
3	364	11	386
4	364	12	424
5	N/A	13	380
6	398	14	415
7	368	15	405
8	372	16	359
Avg:	369±14		387±25
Modulus Change:			5%

7.185x0.103			RD 14810
Ring	Initial	Ring	Aged
1	396	9	488
2	435	10	439
3	406	11	426
4	407	12	442
5	442	13	420
6	N/A	14	434
7	425	15	419
8	413	16	410
Avg:	418±17		435±24
Modulus Change:			4%

11.196x0.103			RD 14936
Ring	Initial	Ring	Aged
1	459	9	478
2	443	10	489
3	438	11	523
4	504	12	465
5	464	13	461
6	473	14	N/A
7	475	15	519
8	N/A	16	540
Avg:	465±22		496±31
Modulus Change:			7%

Table I-10. Linear Tensile Modulus (0-25% elongation) Data for Parker O-Rings

0.116x0.038 Parker 318466

Ring	Initial	Ring	Aged
1	479	9	564
2	544	10	565
3	587	11	586
4	487	12	602
5	488	13	629
6	535	14	557
7	532	15	606
8	566	16	536
Avg:	527±39		581±31
Modulus Change:			10%

0.301X0.054 Parker 316104

Ring	Initial	Ring	Aged
1	727	6	643
2	750	7	795
3	746	8	864
4	789	9	817
5	757	10	N/A
Avg:	754±22		780±96
Modulus Change:			3%

0.301x0.054 Parker 316710

Ring	Initial	Ring	Aged
1	N/A	9	706
2	811	10	N/A
3	829	11	839
4	783	12	N/A
5	841	13	857
6	746	14	825
7	853	15	865
8	823	16	N/A
Avg:	812±37		819±65
Modulus Change:			1%

1.364x0.070 Parker 316104

Ring	Initial	Ring	Aged
1	672	6	724
2	652	7	N/A
3	711	8	748
4	N/A	9	735
5	696	10	N/A
Avg:	683±26		736±12
Modulus			8%

1.364x0.070 Parker 317403

Ring	Initial	Ring	Aged
1	621	9	661
2	652	10	662
3	621	11	645
4	N/A	12	665
5	631	13	636
6	649	14	707
7	668	15	698
8	628	16	728
Avg:	639±18		675±32
Modulus Change:			6%

7.688x0.070 Parker 316104

Ring	Initial	Ring	Aged
1	901	6	812
2	872	7	789
3	915	8	871
4	858	9	918
5	934	10	911
Avg:	896±31		860±58
Modulus Change:			-4%

7.688x0.070 Parker 317851

Ring	Initial	Ring	Aged
1	466	9	600
2	448	10	589
3	506	11	559
4	483	12	595
5	472	13	559
6	540	14	595
7	512	15	603
8	488	16	N/A
Avg:	489±29		586±19
Modulus Change:			20%

16.339x0.103 Parker 316104

Ring	Initial	Ring	Aged
1	867	9	837
2	874	10	895
3	876	11	925
4	864	12	938
5	876	13	913
6	867	14	910
7	858	15	934
8	861	16	895
Avg:	868±7		906±32
Modulus Change:			4%

16.339x0.103 Parker 316710

Ring	Initial	Ring	Aged
1	826	9	909
2	836	10	821
3	815	11	844
4	821	12	832
5	811	13	844
6	825	14	826
7	807	15	831
8	813	16	830
Avg:	819±9		842±28
Modulus Change:			3%

Table I-11. Linear Tensile Modulus (0-25% elongation) Data for Precision O-Rings

0.301x0.054		Precision 19052	
Ring	Initial	Ring	Aged
1	553	9	N/A
2	504	10	587
3	582	11	669
4	N/A	12	625
5	586	13	619
6	594	14	628
7	560	15	637
8	502	16	634
Avg:	554±38		628±24
Modulus Change:			13%

0.301x0.054		Precision 19895	
Ring	Initial	Ring	Aged
1	496	9	637
2	531	10	675
3	517	11	609
4	531	12	615
5	503	13	657
6	517	14	635
7	538	15	649
8	496	16	657
Avg:	516±16		642±22
Modulus Change:			24%

1.364x0.070		Precision 17405	
Ring	Initial	Ring	Aged
1	547	9	620
2	572	10	661
3	N/A	11	653
4	588	12	653
5	N/A	13	678
6	572	14	674
7	588	15	670
8	592	16	657
Avg:	577±17		658±18
Modulus Change:			14%

1.364x0.070		Precision 19895	
Ring	Initial	Ring	Aged
1	574	9	545
2	565	10	614
3	594	11	627
4	570	12	655
5	569	13	N/A
6	590	14	598
7	569	15	631
8	647	16	693
Avg:	585±27		623±46
Modulus Change:			7%

7.739x0.070		Precision 19052	
Ring	Initial	Ring	Aged
1	799	9	859
2	705	10	945
3	863	11	958
4	739	12	957
5	793	13	923
6	819	14	876
7	767	15	900
8	819	16	932
Avg:	788±50		919±37
Modulus Change:			17%

7.739x0.070		Precision 19921	
Ring	Initial	Ring	Aged
1	786	7	850
2	786	8	830
3	752	9	859
4	740	10	819
5	752	11	812
6	740	12	832
Avg:	760±21		834±18
Modulus Change:			10%

16.955x0.139		Precision 19422	
Ring	Initial	Ring	Aged
1	568	9	669
2	565	10	643
3	572	11	663
4	571	12	658
5	566	13	643
6	588	14	665
7	590	15	680
8	585	16	655
Avg:	576±10		660±12
Modulus Change:			15%

16.955x0.139		Precision 19895	
Ring	Initial	Ring	Aged
1	617	9	752
2	605	10	702
3	614	11	727
4	625	12	671
5	628	13	743
6	597	14	757
7	616	15	736
8	608	16	744
Avg:	614±10		729±29
Modulus Change:			19%

Table I-12. Linear Tensile Modulus (0-25% elongation) Data for Test Slabs

Parker 316104

Site	Initial	Aged
1	876	1202
2	894	1037
3	872	1134
4	400	1105
Avg:	761±240	1120±68
Modulus Change:		47%

Parker 316710

Site	Initial	Aged
1	1001	910
2	965	954
3	1058	960
4	902	1002
Avg:	981±65	956±37
Modulus Change:		-3%

Parker 317403

Site	Initial	Aged
1	941	992
2	884	1156
3	886	1038
4	977	1038
Avg:	922±45	1056±70
Modulus Change:		15%

Parker 317851

Site	Initial	Aged
1	970	1002
2	958	943
3	1007	904
4	958	983
Avg:	973±23	958±43
Modulus Change:		-2%

Parker 318466

Site	Initial	Aged
1	574	545
2	651	610
3	592	659
4	458	N/A
Avg:	569±81	604±57
Modulus Change:		6%

RD 14810

Site	Initial	Aged
1	581	562
2	551	596
3	570	613
4	613	583
Avg:	579±26	589±21
Modulus Change:		2%

RD 15107

Site	Initial	Aged
1	629	684
2	633	678
3	679	688
4	621	614
Avg:	641±26	666±35
Modulus Change:		4%

RD 15107 (4 min. cure)

Site	Initial	Aged
1	600	654
2	612	N/A
3	583	682
4	536	739
Avg:	583±34	692±43
Modulus Change:		19%

RD 15107 (3 min. cure)

Site	Initial	Aged
1	674	721
2	621	681
3	633	659
4	638	641
Avg:	642±23	676±35
Modulus Change:		5%

Precision 19052A

Site	Initial	Aged
1	758	765
2	735	840
3	714	863
4	716	824
Avg:	731±20	823±42
Modulus Change:		13%

Precision 19895A

Site	Initial	Aged
1	777	771
2	792	793
3	754	825
4	743	822
Avg:	766±22	803±26
Modulus Change:		5%

Appendix J: Properties vs. Cure Cycle Data

Contents:

Detailed ring and test slab data is contained in Tables in the preceding appendices.

Table J-1. Hardness and Compression Set Data on RD Rubber Materials With Differing Cure Schedules

All rings prepared from RD Rubber Batch No. 15107.

3 min. 12 sec. = 45% cure. 4 min. 18 sec. = 70% cure. 10 min. = 95% cure

Ring Size	Cure Time	Initial Hardness	Hardness after Aging[1]	Change in Hardness	Initial Thickness	Thickness after Aging[2]	Compression Set (%)
0.301 x 0.054	3 min. 12 sec.	75.9 ± 1.1	80.8 ± 0.8	+ 4.9	0.05552±0.00057	0.05433±0.00069	7.9
	4 min. 18 sec.	75.6 ± 1.0	80.1 ± 0.6	+ 4.5	0.05490±0.00033	0.05389±0.00031	7.0
	10 min.	76.1 ± 0.4	79.3 ± 0.6	+ 3.2	0.05524±0.00044	0.05429±0.00041	6.5
1.114 x 0.070	3 min. 12 sec.	73.3 ± 1.2	80.0 ± 0.3	+ 6.7	0.06967±0.00033	0.06782±0.00013	10.8
	4 min. 18 sec.	72.9 ± 0.8	77.2 ± 0.5	+ 4.3	0.06951±0.00025	0.06839±0.00028	6.6
	10 min.	75.2 ± 0.8	76.8 ±0.6	+ 1.6	0.06930±0.00022	0.06811±0.00019	7.1
7.185 x 0.103	3 min. 12 sec.	72.8 ± 1.5	76.9 ± 0.9	+ 4.1	0.10432±0.00038	0.10164±0.00030	9.8
	4 min. 18 sec.	73.1 ± 0.5	77.7 ± 0.3	+ 4.6	0.10538±0.00072	0.10126±0.00080	14.5
	10 min.	74.2 ± 0.8	76.1 ± 0.7	+ 1.9	0.10473±0.00064	0.10318±0.00058	5.6
11.196 x 0.103	3 min. 12 sec.	72.3 ± 1.7	76.9 ± 0.9	+ 4.6	0.10468±0.00051	0.10246±0.00034	8.0
	4 min. 18 sec.	73.6 ± 0.6	76.6 ± 0.7	+ 3.0	0.10386±0.00042	0.10206±0.00033	6.7
	10 min.	72.8 ± 0.9	75.4 ± 1.4	+ 2.6	0.10685±0.00078	0.10540±0.00069	4.9
Test Slabs	3 min. 12 sec.	67.3 ± 0.8	69.8 ± 0.8	+ 2.5	0.3530±0.0016	0.3411±0.0006	13.5
	4 min. 18 sec.	66.8 ± 0.8	70.0 ± 1.2	+ 3.2	0.3358±0.0003	0.3275±0.0003	10.8
	10 min.	65.5 ± 0.5	64.8 ± 0.4	- 0.7	0.3308±0.0011	0.3188±0.0009	12.6

1. 70 hours at 212°F plus 24 hours at room temperature.
2. 22 hours compression set aging at 25% compression and 158°F plus 30 min. at room temperature.

Table J-2. Tensile Strength and Elongation Data on RD Rubber Materials With Differing Cure Schedules

All rings prepared from RD Rubber Batch No. 15107.

3 min. 12 sec. = 45% cure. 4 min. 18 sec. = 70% cure. 10 min. = 95% cure

Ring Size	Cure Time	Initial Tensile Strength	Ten. Strength after Aging	Percent Change	Initial Elongation	Elongation after Aging	Percent Change
0.301 x 0.054	3 min. 12 sec.	2429±133	2556±136	5	340±20	276±12	-18
	4 min. 18 sec.	2374±76	2369±153	0	334±15	284±15	-15
	10 min.	2236±406	2423±122	8	308±46	303±13	-2
1.114 x 0.070	3 min. 12 sec.	2177±262	2089±171	-4	319±43	223±34	-30
	4 min. 18 sec.	2119±230	2099±771	-1	291±35	258±24	-11
	10 min.	2039±236	2153±107	6	296±49	300±23	2
7.185 x 0.103	3 min. 12 sec.	1879±249	1751±157	-7	218±22	155±10	-29
	4 min. 18 sec.	1170±332	1641±251	40	153±26	159±13	4
	10 min.	1579±302	1255±384	-20	215±30	171±39	-21
11.196 x 0.103	3 min. 12 sec.	1746±201	1902±252	9	228±23	184±25	-20
	4 min. 18 sec.	1380±296	1869±224	35	190±29	194±20	2
	10 min.	1436±355	1396±451	-3	175±29	152±30	-13
Test Slabs	3 min. 12 sec.	2116±153	2034±91	-4	221±9	189±16	-14
	4 min. 18 sec.	2092±42	1950±144	-7	247±9	179±13	-28
	10 min.	2123±55	2010±137	-5	243±16	220±12	-9

Aging conditions: 70 hours at 212°F plus 24 hours at room temperature.

Table J-3. Tensile Modulus Data on RD Rubber Materials With Differing Cure Schedules

All rings prepared from RD Rubber Batch No. 15107.

3 min. 12 sec. = 45% cure. 4 min. 18 sec. = 70% cure. 10 min. = 95% cure

Ring Size	Cure Time	Modulus 5-10%			Modulus 10-15%			Modulus 5-15%			Modulus 10-20%			Modulus 0-25%		
		unaged	aged	Δ%	unaged	aged	Δ%	unaged	aged	Δ%	unaged	aged	Δ%	unaged	aged	Δ%
0.301 x 0.054	3 min. 12 sec.	616±79	604±78	-2	410±77	537±74	31	471±31	558±46	18	432±71	566±32	31	469±31	547±24	17
	4 min. 18 sec.	511±47	525±30	3	370±47	468±35	26	444±27	479±20	8	384±25	479±22	25	433±19	471±6	9
	10 min.	544±67	517±53	-5	315±46	479±60	52	414±15	490±44	18	381±31	504±27	32	427±17	494±24	16
1.114 x 0.070	3 min. 12 sec.	451±34	508±42	13	391±23	450±49	15	425±22	499±38	17	346±20	467±49	35	390±17	479±39	23
	4 min. 18 sec.	465±22	548±42	18	400±21	461±29	15	431±19	509±21	18	356±15	426±22	20	391±17	464±24	19
	10 min.	412±71	484±35	17	379±54	398±54	5	419±27	457±14	9	341±38	376±26	10	390±26	428±19	10
7.185 x 0.103	3 min. 12 sec.	558±28	643±34	15	503±24	572±42	14	532±20	612±37	15	477±27	541±24	13	513±21	588±33	15
	4 min. 18 sec.	533±8	617±41	16	450±21	531±32	18	497±9	579±25	16	435±15	510±20	17	479±11	556±25	16
	10 min.	471±23	519±17	10	400±15	443±16	11	424±11	467±11	10	366±12	420±21	15	424±18	474±17	12
11.196 x 0.103	3 min. 12 sec.	486±11	646±35	33	401±9	524±34	31	449±8	585±26	30	379±6	500±25	32	421±4	546±24	30
	4 min. 18 sec.	470±13	619±25	32	391±11	478±11	22	441±10	553±11	25	365±9	463±8	27	411±7	514±9	25
	10 min.	452±30	529±25	17	373±16	476±32	28	409±8	396±20	-3	385±25	477±25	24	423±21	508±18	20
Test Slabs	3 min. 12 sec.	785±89	793±28	1	556±35	580±93	4	656±31	651±55	-1	501±14	512±77	2	613±16	635±43	4
	4 min. 18 sec.	587±42	698±30	19	556±82	568±57	2	552±54	636±30	15	482±77	526±41	9	536±38	640±28	19
	10 min.	578±152	744±85	29	499±98	528±54	6	528±11	633±39	20	493±58	493±30	0	584±27	625±16	7

Aging conditions: 70 hours at 212°F plus 24 hours at room temperature.

Table J-4. Tensile Modulus Data and Averages on RD Rubber Materials With Differing Cure Schedules

All rings prepared from RD Rubber Batch No. 15107.

3 min. 12 sec. = 45% cure. 4 min. 18 sec. = 70% cure. 10 min. = 95% cure

Ring Size	Cure Time	Modulus 5-10%		Modulus 10-15%		Modulus 5-15%		Modulus 10-20%		Modulus 0-25%		Average Modulus	
		unaged	aged	unaged	aged	unaged	aged	unaged	aged	unaged	aged	unaged	aged
0.301 x 0.054	3 min. 12 sec.	616	604	410	537	471	558	432	566	469	547	480	562
	4 min. 18 sec.	511	525	370	468	444	479	384	479	433	471	428	484
	10 min.	544	517	315	479	414	490	381	504	427	494	416	497
1.114 x 0.070	3 min. 12 sec.	451	508	391	450	425	499	346	467	390	479	401	481
	4 min. 18 sec.	465	548	400	461	431	509	356	426	391	464	409	482
	10 min.	412	484	379	398	419	457	341	376	390	428	388	429
7.185 x 0.103	3 min. 12 sec.	558	643	503	572	532	612	477	541	513	588	517	591
	4 min. 18 sec.	533	617	450	531	497	579	435	510	479	556	479	559
	10 min.	471	519	400	443	424	467	366	420	424	474	417	465
11.196 x 0.103	3 min. 12 sec.	486	646	401	524	449	585	379	500	421	546	427	560
	4 min. 18 sec.	470	619	391	478	441	553	365	463	411	514	416	525
	10 min.	452	529	373	476	409	396	385	477	423	508	408	477
Test Slabs	3 min. 12 sec.	785	793	556	580	656	651	501	512	613	635	622	634
	4 min. 18 sec.	587	698	556	568	552	636	482	526	536	640	543	614
	10 min.	578	744	499	528	528	633	493	493	584	625	536	605

Aging conditions: 70 hours at 212°F plus 24 hours at room temperature.

Table J-5. Tensile Work (0-20% elongation) Data on RD Rubber Materials With Differing Cure Schedules

All rings prepared from RD Rubber Batch No. 15107.

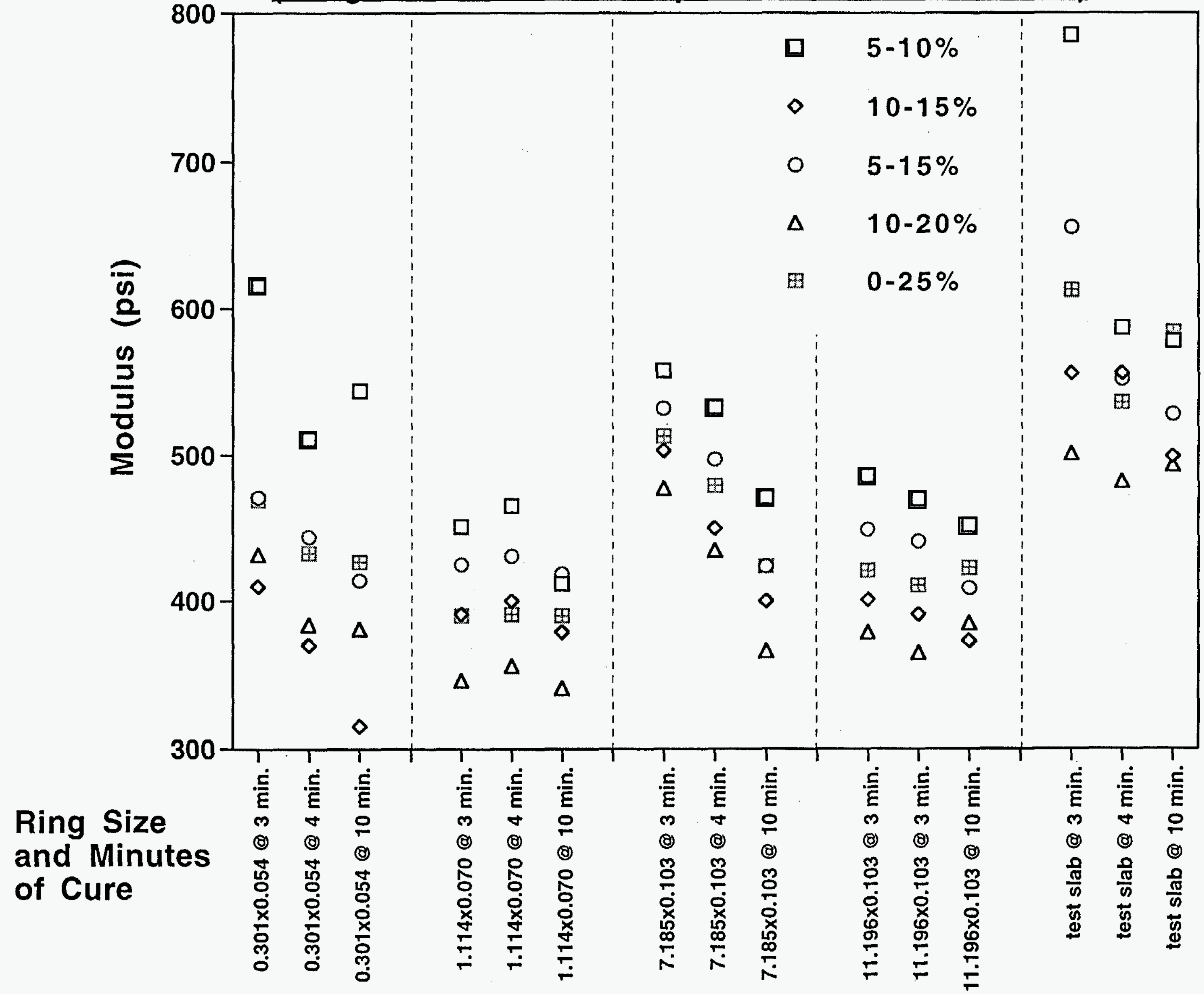
3 min. 12 sec. = 45% cure. 4 min. 18 sec. = 70% cure. 10 min. = 95% cure

Ring Size	Cure Time	IN-LB/SQ.IN. UNAGED	IN-LB/SQ.IN. AGED	PERCENT CHANGE	PERCENT-LB/SQ.IN. UNAGED	PERCENT-LB/SQ.IN. AGED	PERCENT CHANGE
0.301 x 0.054	3 min. 12 sec.	4.71 ± 0.25	5.20 ± 0.40	10	997 ± 53	1100 ± 85	10
	4 min. 18 sec.	4.49 ± 0.25	4.48 ± 0.51	0	949 ± 54	948 ± 107	0
	10 min.	5.02 ± 0.60	5.09 ± 0.47	1	1061 ± 128	1076 ± 99	1
1.114 x 0.070	3 min. 12 sec.	15.6 ± 1.2	17.0 ± 1.3	9	893 ± 70	970 ± 74	9
	4 min. 18 sec.	15.8 ± 1.5	18.2 ± 1.8	15	900 ± 83	1040 ± 103	16
	10 min.	15.8 ± 0.9	17.9 ± 0.6	13	900 ± 53	1023 ± 37	14
7.185 x 0.103	3 min. 12 sec.	217 ± 9	244 ± 15	12	1260 ± 48	1411 ± 100	12
	4 min. 18 sec.	234 ± 12	203 ± 6	-13	1366 ± 77	1192 ± 40	-13
	10 min.	210 ± 11	226 ± 11	8	1310 ± 80	1375 ± 85	5
11.196 x 0.103	3 min. 12 sec.	284 ± 3	364 ± 13	28	1073 ± 11	1365 ± 50	27
	4 min. 18 sec.	278 ± 4	348 ± 8	25	1050 ± 18	1310 ± 35	25
	10 min.	308 ± 17	355 ± 16	15	1194 ± 76	1352 ± 60	13
Test Slabs	3 min. 12 sec.	16.9 ± 0.6	17.8 ± 0.7	5	1690 ± 63	1784 ± 71	6
	4 min. 18 sec.	15.3 ± 2.4	20.9 ± 6.1	37	1534 ± 243	2090 ± 612	36
	10 min.	18.2 ± 2.2	18.5 ± 1.6	2	1815 ± 222	1846 ± 156	2

Aging conditions: 70 hours at 212°F plus 24 hours at room temperature.

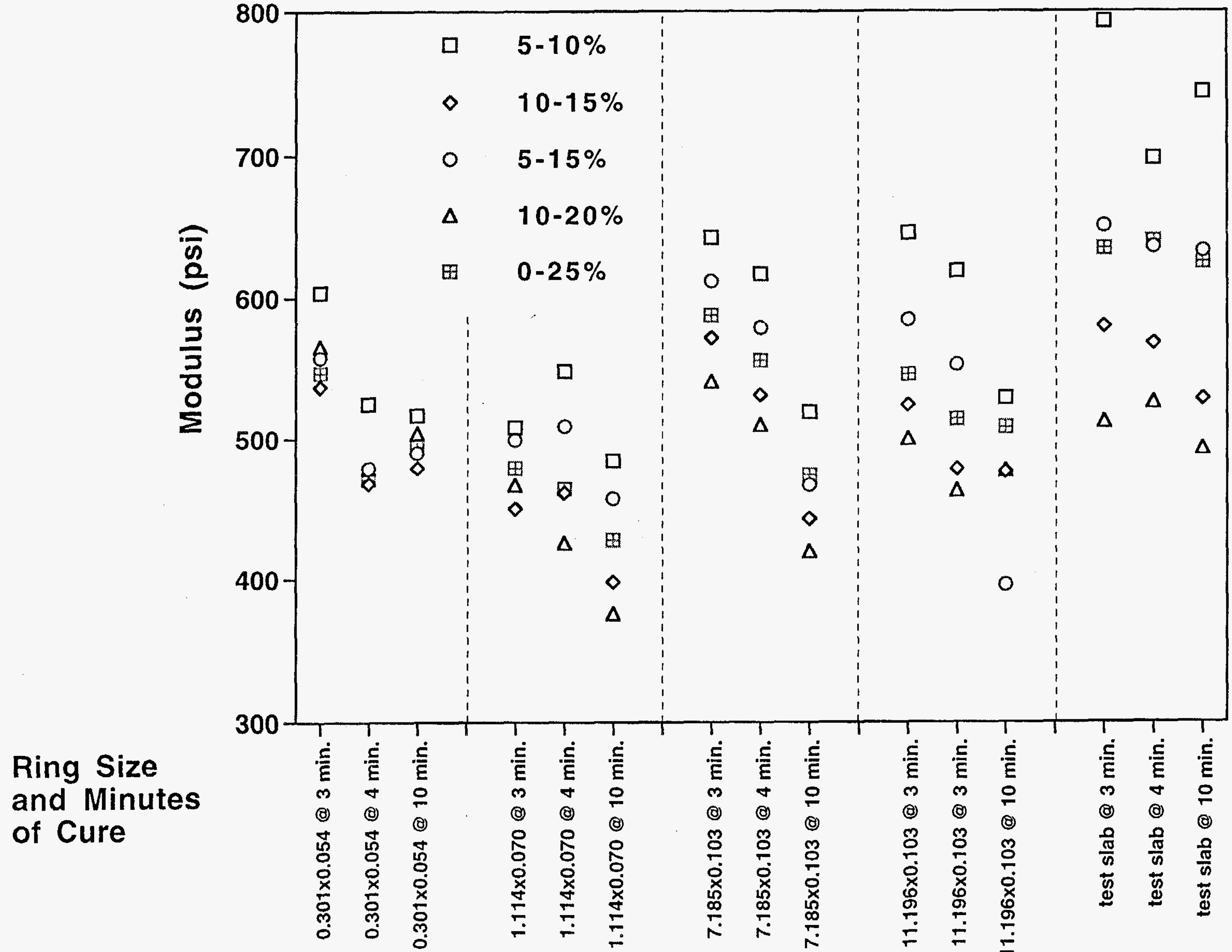
Plot J-6. Modulus vs. Percent Elongation Range

(Unaged RD Rubber Samples with Different Cures)



Plot J-7. Modulus vs. Percent Elongation Range

(Aged RD Rubber Samples with Different Cures)



Appendix K: DSC Scans on Rubber Materials

Contents:

Figure K-1. DSC Scans of Butyl Rubber Materials from Different Vendors

(endotherms are positive, exotherms are negative)

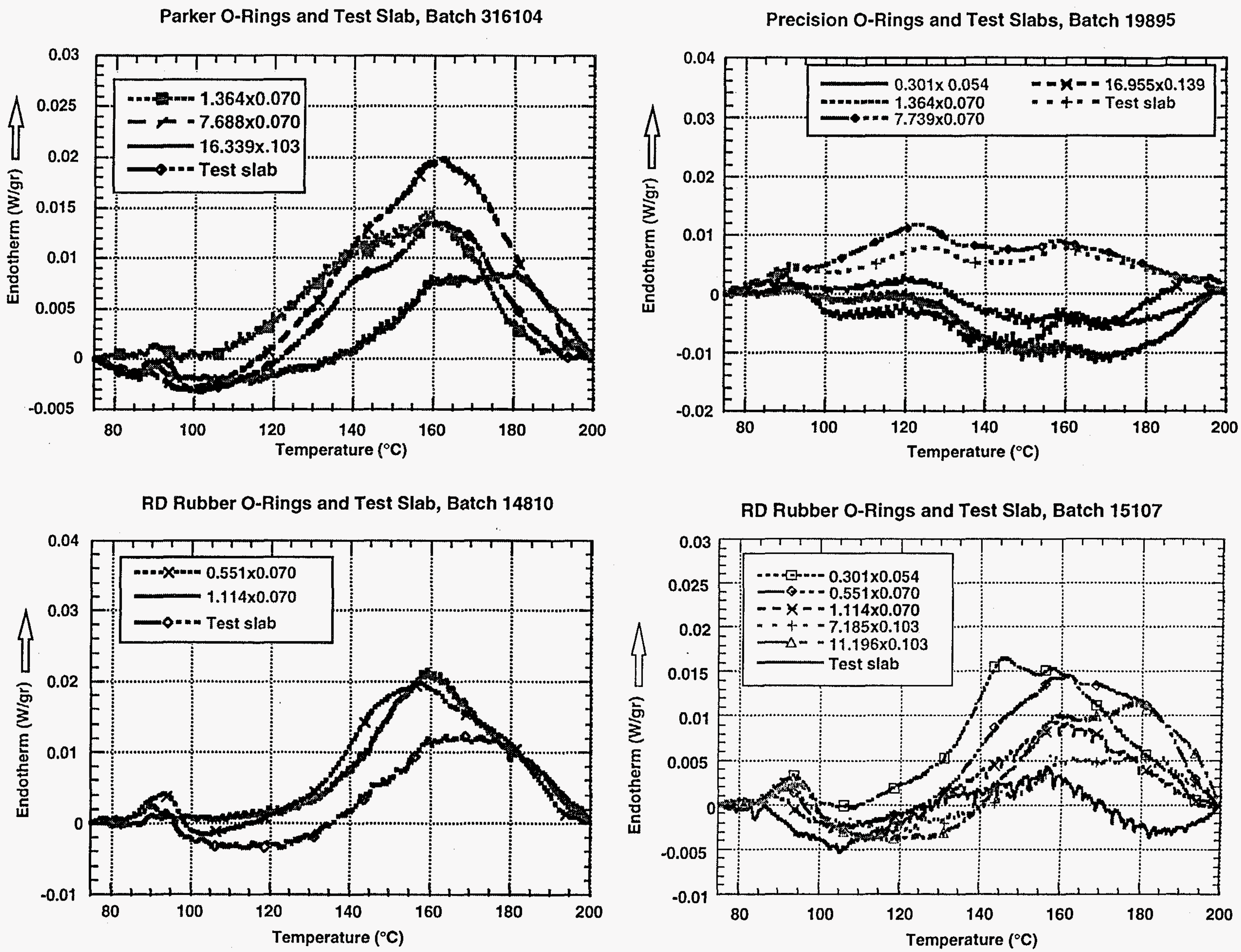
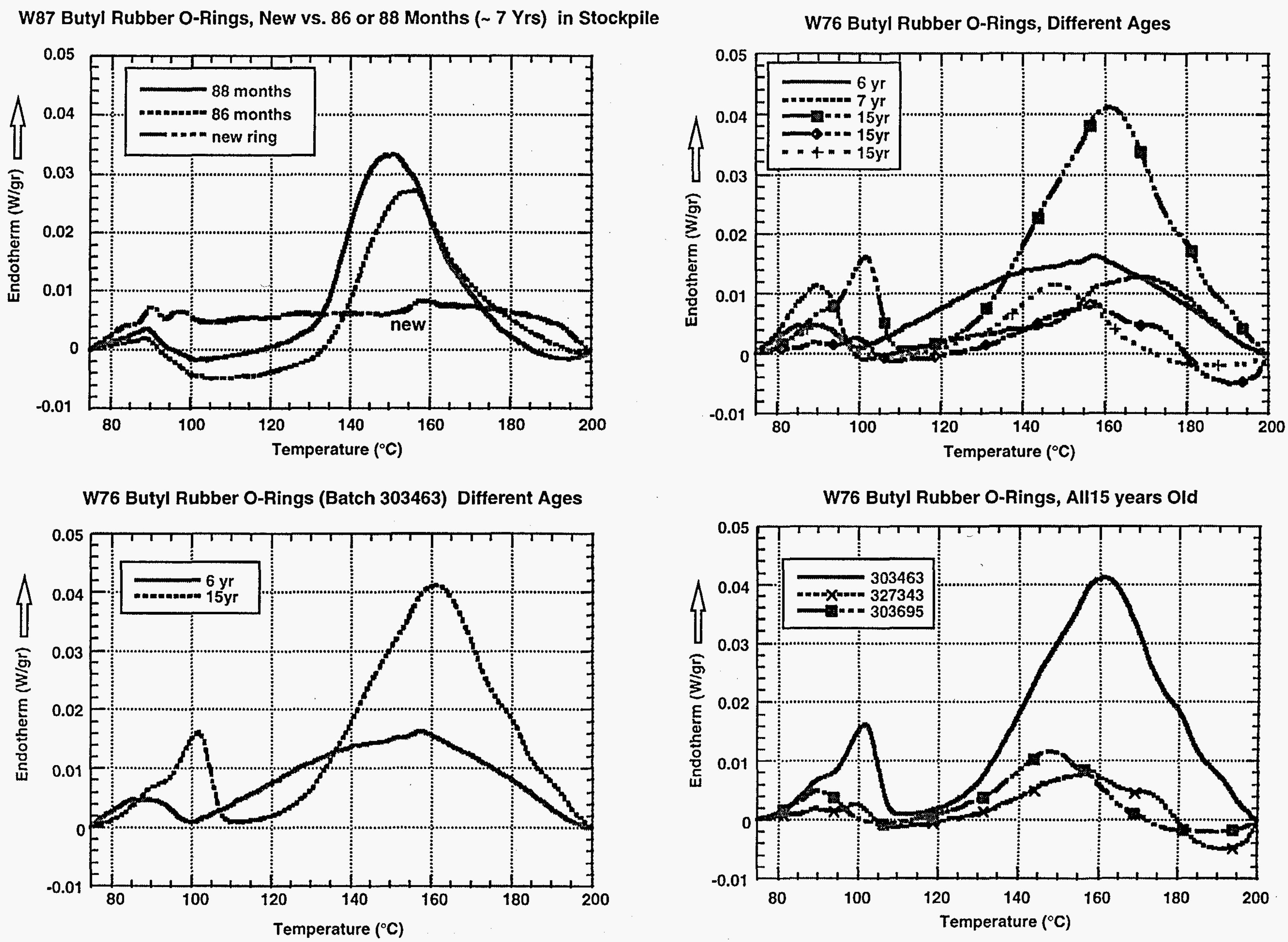


Figure K-2. DSC Scans of Stockpile Aged W76 and W87 Butyl Rubber O-Rings

(endotherms are positive, exotherms are negative)

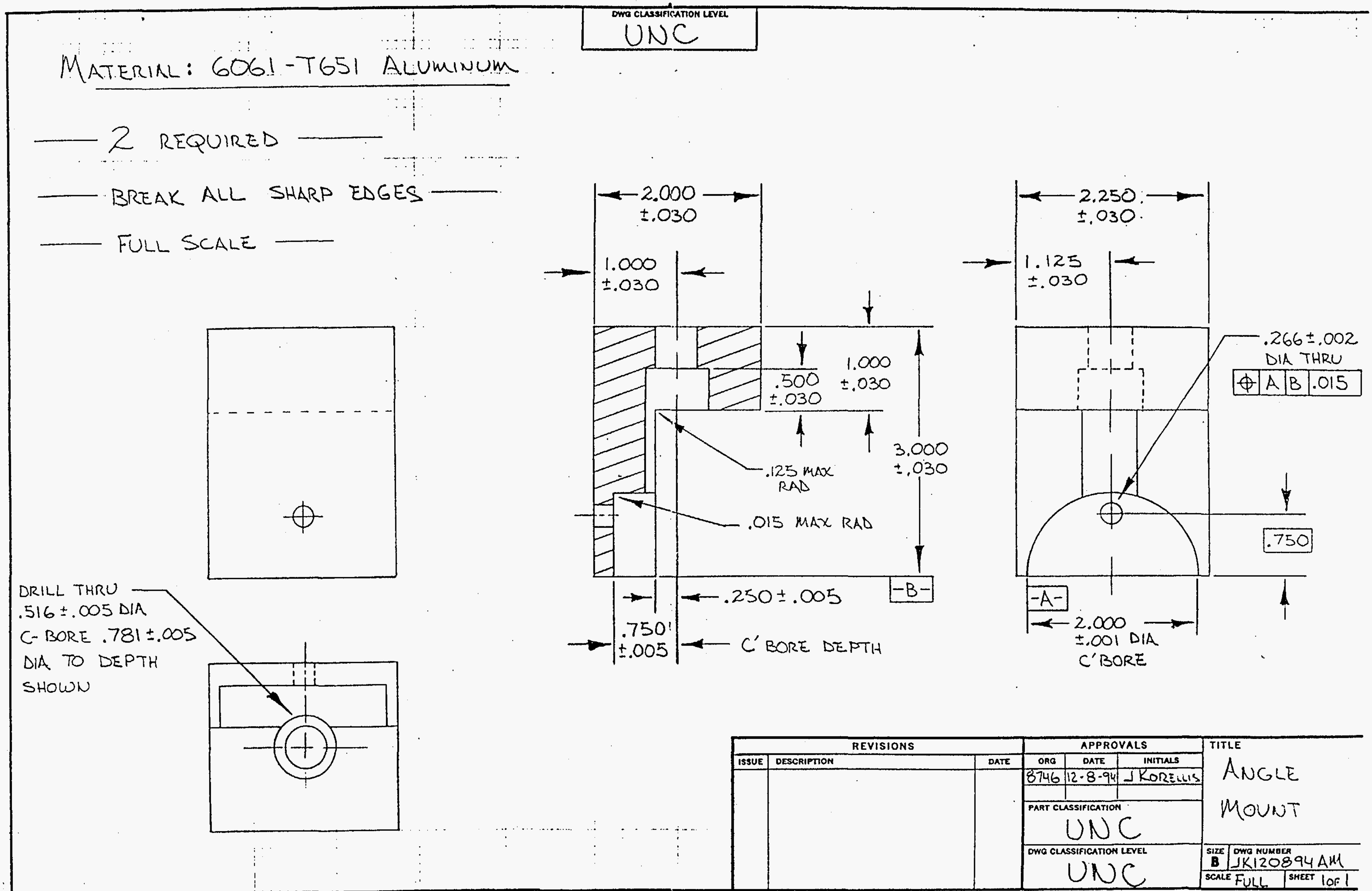


Appendix L: Drawings for Tensile Test Fixtures

Contents:

1) Angle Mount Drawing
2) 0.038 inch cross section Mount Insert Drawing
3) 0.054 inch cross section Mount Insert Drawing
4) 0.070 inch cross section Mount Insert Drawing
5) 0.103 inch cross section Mount Insert Drawing
6) 0.139 inch cross section Mount Insert Drawing

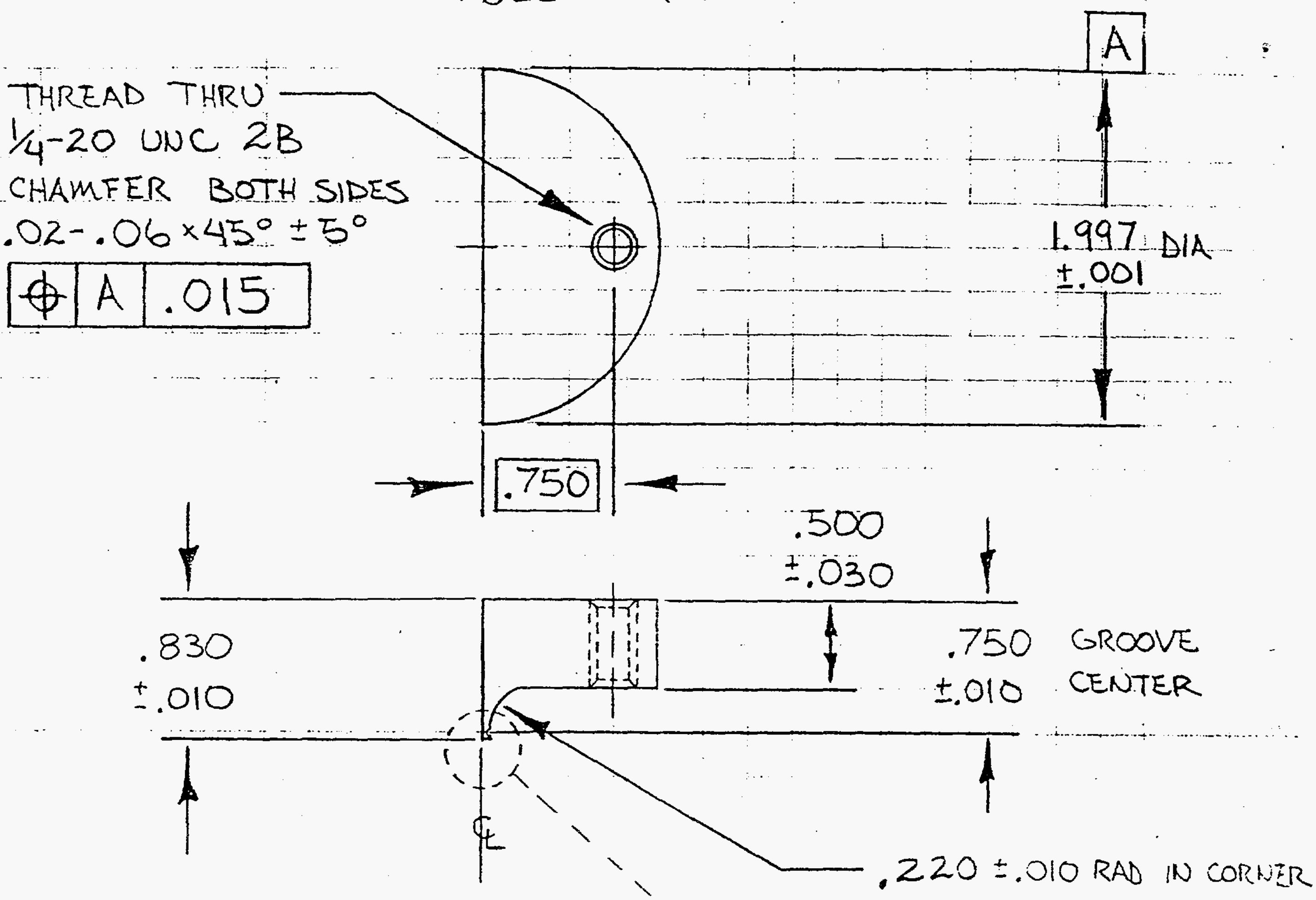
All aluminum except No. 2.

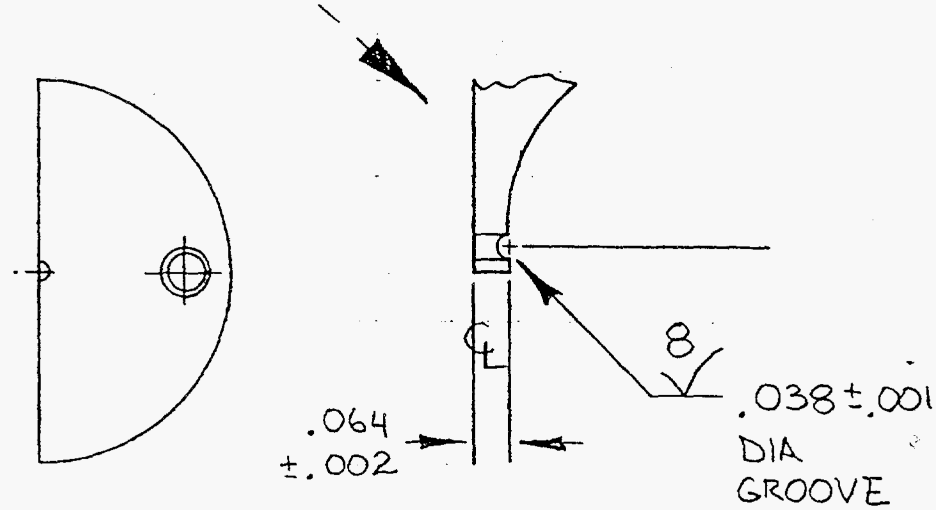


DWG CLASSIFICATION LEVEL
UNC
MATERIAL: 6061-T651 ALUMINUM
2 REQUIRED
BREAK ALL SHARP EDGES
FULL SCALE
2.000 ±.030
1.000 ±.030
.500 ±.030
1.000 ±.030
3.000 ±.030
.125 MAX RAD
.015 MAX RAD
.250 ±.005
-B-
.750 ±.005
C' BORE DEPTH
2.250 ±.030
1.125 ±.030
.266 ±.002 DIA THRU
A B .015
.750
-A-
2.000 ±.001 DIA C'BORE
DRILL THRU .516 ±.005 DIA C-BORE .781 ±.005 DIA TO DEPTH SHOWN
REVISIONS
ISSUE
DESCRIPTION
DATE
APPROVALS
ORG
DATE
INITIALS
8746
12-8-94
J KORELLIS
PART CLASSIFICATION
UNC
DWG CLASSIFICATION LEVEL
UNC
TITLE
ANGLE MOUNT
SIZE
B
DWG NUMBER
JK120894AM
SCALE
FULL
SHEET
1 OF 1

MATERIAL: ANY TOOL STEEL (NO HEAT TREAT REQUIRED)

FULL SCALE



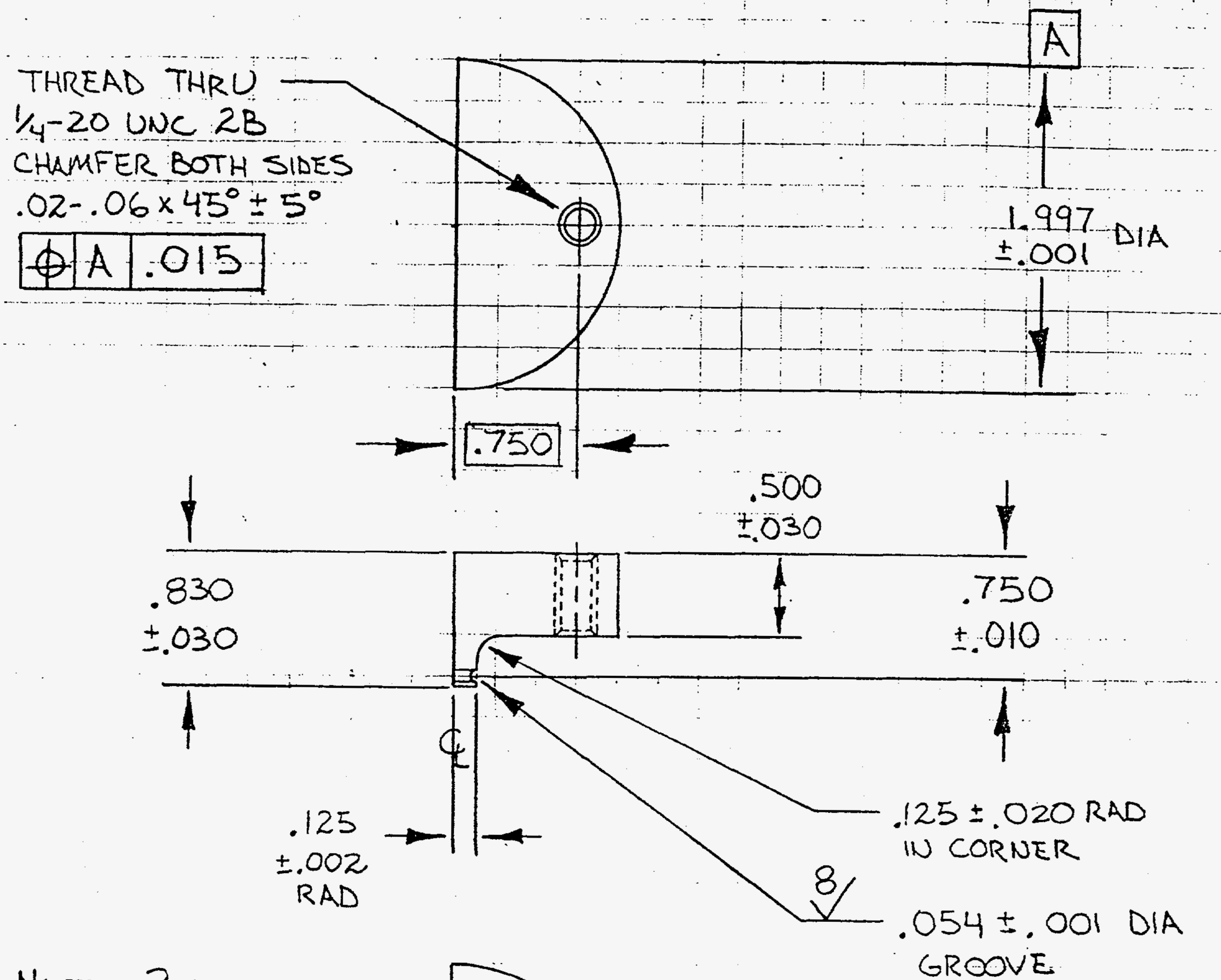


NOTE: 2 REQUIRED
ALL DIMENSIONS BEFORE WIRE CUTTING (.003-.006 CUT WIDTH ±.003 ABOUT TRUE CENTERLINE

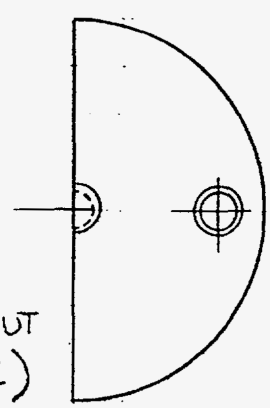
BY J. KORELLIS DATE 12-7-94 SUBJECT 54 MOUNT #JK120794M54 SHEET NO. 1 OF 1

CHKD. BY ______ DATE ______ JOB NO. ______

MATERIAL: 6061-T651 ALUMINUM — FULL SCALE —



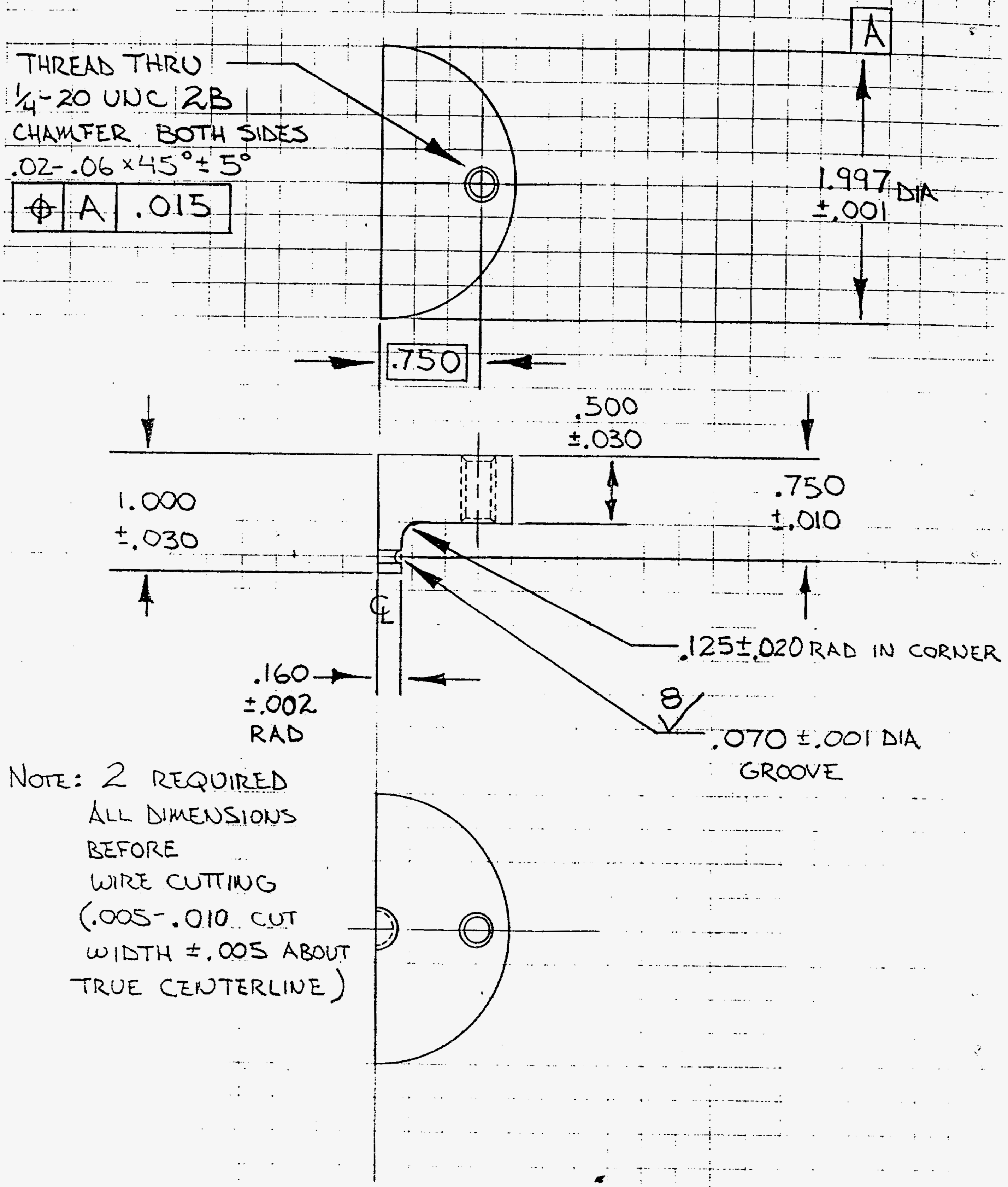
NOTE: 2 REQUIRED
ALL DIMENSIONS
BEFORE
WIRE CUTTING
(.005-.010 CUT
WIDTH ±.005 ABOUT
TRUE CENTERLINE)



BY [illegible] DATE 12-7-94 SUBJECT 70 MOUNT #JK120794M70 SHEET NO. 1 OF 1

CHKD. BY ______ DATE ______ JOB NO. ______

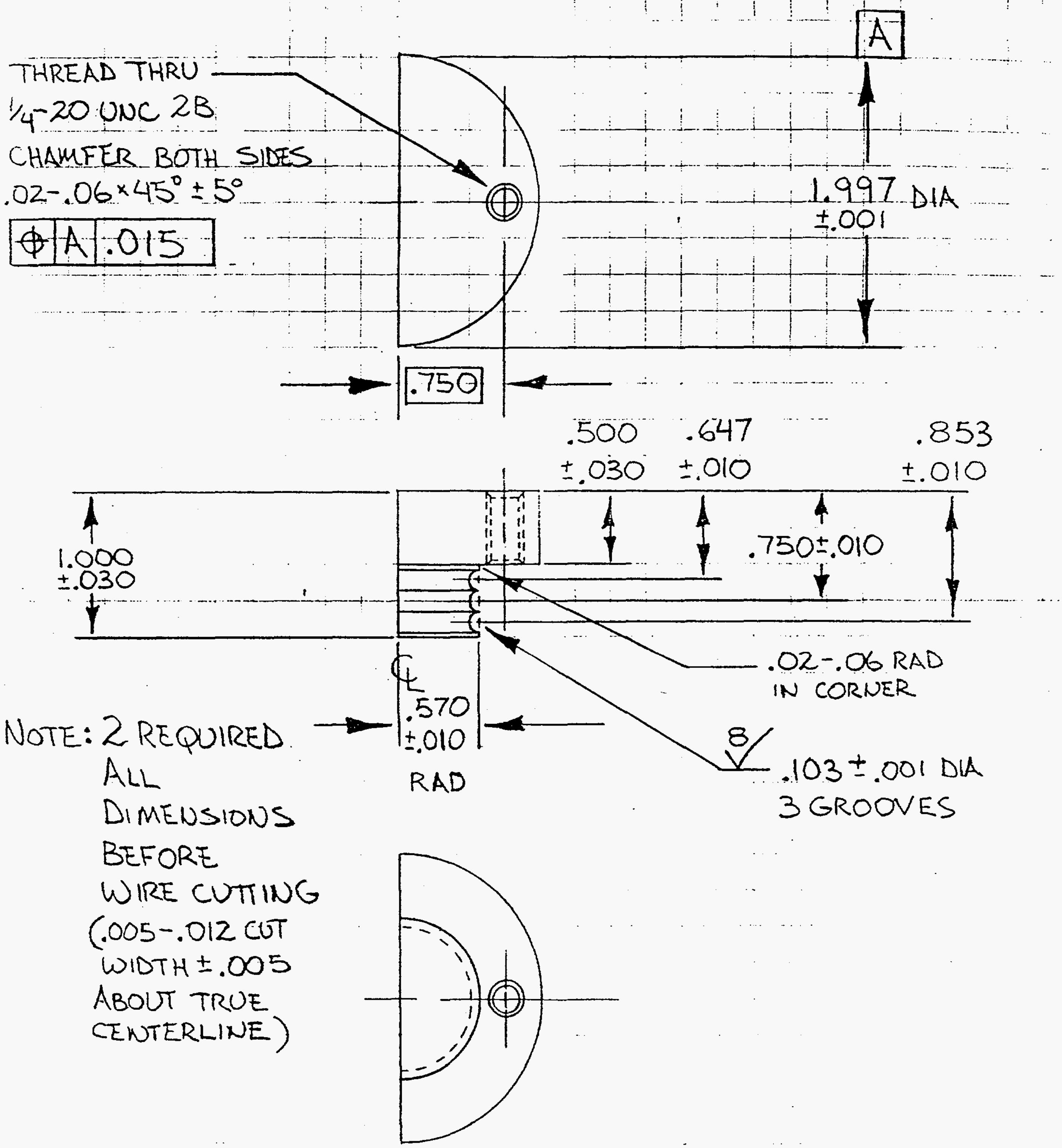
MATERIAL: 6061-T651 ALUMINUM — FULL SCALE



BY J KORELLIS DATE 12-6-94 SUBJECT 103 MOUNT #JK120694M103 SHEET NO. 1 OF 1

CHKD. BY ______ DATE ______ JOB NO. ______

MATERIAL: 6061-T651 ALUMINUM — FULL SCALE —

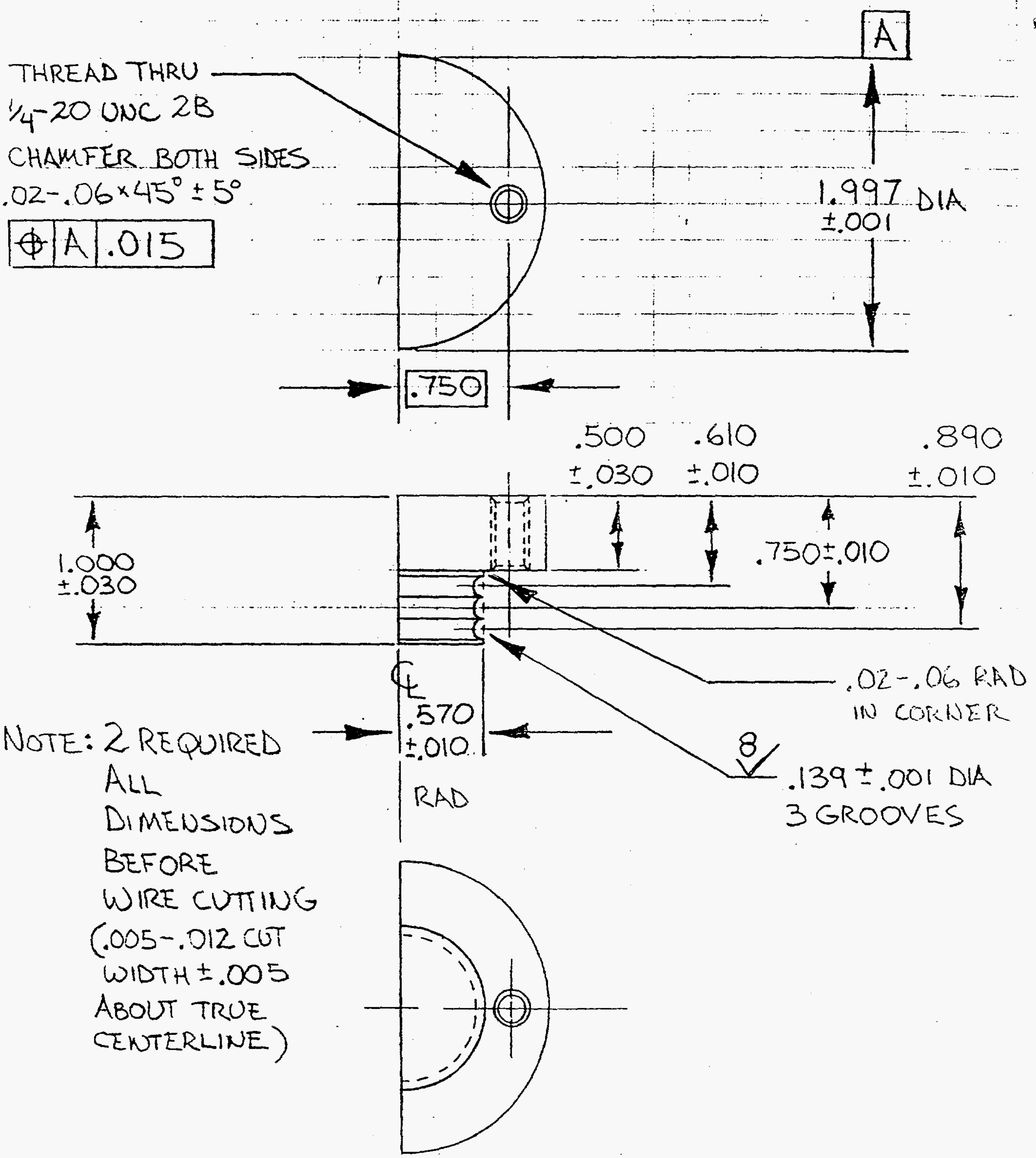


NOTE: 2 REQUIRED
ALL DIMENSIONS BEFORE WIRE CUTTING (.005-.012 CUT WIDTH ±.005 ABOUT TRUE CENTERLINE)

BY J KORELLIS DATE 12-6-94 SUBJECT 139 MOUNT #JK120694M139 SHEET NO.____ OF____

CHKD. BY____ DATE____ JOB NO.____

MATERIAL: 6061-T651 ALUMINUM — FULL SCALE



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