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NORTHROP AIRCRAFT, INC.

NORTHROP DIVISION
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REPORT NO. NOR-59-472

METHODS OF TESTING FOR HYDROGEN EMBRITTLEMENT
(FINAL REPORT ON ARTC PROJECT W-95)

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ABSTRACT

This report presents the results of a cooperative test program conducted by members of the AIA-ARTC in an attempt to establish a standard test method for hydrogen embrittlement. The six basic methods investigated were the tensile test, stressed ring test, sustained load notched tensile test, constant-rate bend test, torqued bolt test, and static bend test. Modifications of the test specimens and procedures brought the total number of methods investigated to twelve. Conclusions are drawn as to the most accurate methods now available and the direction that further work on hydrogen embrittlement testing should take.

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1. INTRODUCTION

A survey on methods of testing for hydrogen embrittlement, conducted in September 1957 by the Aerospace Research and Testing Committee of the Aerospace Industries Association, revealed that while twenty-five of the twenty-seven companies replying were concerned with hydrogen embrittlement of ferrous metals used in aircraft and missiles, only thirteen companies had one or more methods that they considered suitable for evaluating relative embrittlement susceptibility. Four additional companies reported that they had been experimenting to find a satisfactory method. Among the methods then in use were the standard tensile test, either alone or in conjunction with a sustained load test; seven types of bend tests; and sustained load tests of notched or smooth tensile bars, torqued bolts, flat bars, round rings, and C-rings. Twenty-two companies favored an attempt at standardizing engineering test methods for hydrogen embrittlement.

ARTC Project W-95, Standard Method for Evaluation of Susceptibility of Ferrous Metals to Hydrogen Embrittlement, was established in October 1957 with Norair as sponsoring company. The approved objective was defined as follows:

> Select, refine, or develop a short-term test method that will yield an accurate indication of degree of hydrogen embrittlement. The method should provide results in a form that permits ready comparison between different alloys and different strength levels.

Resolution of the project objective was attempted through a cooperative testing program in which the following ARTC member companies participated:

Convair, A Division of General Dynamics Corporation, San Diego, California

Douglas Aircraft Company, Incorporated, Santa Monica, California

Lockheed Aircraft Corporation, California Division, Burbank, California

McDonnell Aircraft Corporation, Saint Louis, Missouri

Norair, A Division of Northrop Corporation, Hawthorne, California

North American Aviation, Incorporated, Los Angeles Division, Los Angeles, California

Ryan Aeronautical Company, San Diego, California

In addition, much helpful assistance and advice was provided by other ARTC member companies and by the Naval Research Laboratory through correspondence, auxiliary testing, and participation in project meetings. Meeting reports and other significant ARTC correspondence are listed in Section 6 on page 35.

2. CONCLUSIONS AND RECOMMENDATIONS

Of all methods investigated, the sustained load notched tensile test was the most sensitive and reproducible. However, two versions of this test were used, and they showed considerable difference in time to failure for specimens embrittled under identical conditions by the same laboratory. No one version can be recommended until additional work has been conducted on methods of sample preparation; notch size, radius, and finish; and test duration. It is therefore recommended that ARTC undertake the work necessary to arrive at a standard sustained load notched tensile test.

The superiority of an experimental potassium cyanide plating bath used by Ryan in Phase I was evident from all test results. It is recommended that investigation of this and other high-efficiency plating baths be combined with the recommended efforts to standardize the notched tensile test. Such a combined investigation should provide the basic data for a performance standard defining an acceptable level of embrittlement as measured by time to failure in a standard sustained load notched tensile test.

Once a realistic performance standard has been developed, it is recommended that investigation of other test methods be resumed to determine their suitability as replacements for the sustained load notched tensile test, which is costly in terms of both time and equipment.

3. PHASE I TESTS

Each participating company used one of its current embrittlement test methods to test identical material. For introduction of hydrogen, equal lots of each company's specimens were first cadmium plated by the other participants; the intent was to permit recognition and analysis of any processing variables. From the test results, an attempt was made to select the short-term test method that provided the best correlation with long-term tests for the one material under investigation.

3.1 Test Material

Transverse-quality 4340 alloy steel heat treated to a strength level of 260,000 to 280,000 psi was selected for test. Annealed material produced by the A. M. Byers Steel Company and certified to Douglas Aircraft Company Specification DMS 1555 and Military Specification MIL-S-5000 was purchased by each participant from four consecutive bars ($10M_2$ through $10M_5$) from the middle bloom of heat No. 67353. These bars, in the form of 4-inch rounds, were reforged to 1-1/4 by 3-1/4 inches. Chemical analysis of the material, as determined by testing the top of bar $10M_2$ and the bottom of bar $10M_5$, is reported in Table I.

3.2 Heat Treatment

Rough-machined specimens of all participants were heat treated in one load by Douglas to avoid possible variables in this operation. Rockwell hardness measurements made on one heat-treated specimen from each participant ranged from R_C 51.5 to R_C 52.0. The heat-treatment procedure was as follows:

Normalizing -	Atmosphere:	neutralene, alnor dew point +22
	Temperature:	1650 ± 10F
	Soaking period:	55 minutes
Hardening -	Atmosphere:	neutralene, alnor dew point +27
	Temperature:	1500 ± 10F
	Soaking period:	55 minutes
	Quenching medium:	oil at 75F
Tempering -	Temperature:	400 ± 5F
	Soaking period:	4 hours

The soaking period for normalizing and austenitizing of all specimens was based on 15 minutes per 1/2 inch of thickness plus 30 minutes, giving a total of about 55 minutes for the thickest specimen (3/4 inch).

3.3 Introduction of Hydrogen

In order that the degree of embrittlement would be comparable to that to be encountered in production if electroplating of high-strength steels were performed, a standard procedure normally used for cadmium plating of low-strength steels was selected as the means of introducing hydrogen into the test specimens. Six of each type of specimen were plated by each of the participants according to the following processing sequence:

Clean mechanically using 600-grit alundum paper with oil and polishing in the direction of bend or stress.

Alkaline clean in steel cleaner for 5 minutes without current.

Acid dip in 10 percent by weight hydrochloric acid solution (approximately 3N) for 5 seconds. No inhibitor.

In-and-out cyanide dip in 2 - 6 oz/gal. sodium or potassium cyanide solution.

Cadmium plate specimens individually to a thickness of 0.0003 inch in a laboratory plating bath at a current density of 60 asf.

Soak specimens in water at 180F for 15 minutes.

Bake specimens at 375 ± 10F for 8 hours.

The sodium cyanide plating bath compositions used were as follows:

Convair	-	Cadmium	3.0	oz/gal.
		Sodium cyanide	13.0	oz/gal.
		Sodium hydroxide	2.0	oz/gal.
Douglas	-	Cadmium oxide	2.52	oz/gal.
		Sodium cyanide	9.00	oz/gal.
		Sodium carbonate	2.0	oz/gal.
		ROHCO 20XL brightener	1.3	oz/gal.
Lockheed	-	Cadmium oxide	4.1	oz/gal.
		Sodium cyanide	12.2	oz/gal.
		Sodium hydroxide	2.6	oz/gal.
		Sodium carbonate	4.3	oz/gal.
McDonnell	-	Cadmium oxide	3.6	oz/gal.
		Sodium cyanide	13.1	oz/gal.
		Brightener	6-8	lb/100 gal. (nominal)
		pH	13.5	

3.3 Introduction of Hydrogen (continued)

Norair	- Cadmium	3.3	oz/gal.
	Sodium cyanide (total)	17.3	oz/gal.
	Sodium carbonate	2.48	oz/gal.
	Sodium hydroxide	2.14	oz/gal.
North American	- Cadmium oxide	4.0	oz/gal.
	Sodium cyanide	13.5	oz/gal.
	Sodium hydroxide	to pH of 13	

* An experimental potassium cyanide plating procedure was used by Ryan on all except the North American specimens, which were plated in a production bath. The Ryan cleaning procedure was the same as stated above, except that a solution of 6 oz/gal. potassium cyanide and 2 oz/gal. potassium hydroxide was used for the cyanide dip. The experimental Ryan plating solution and procedure were:

Cadmium	1 - 1.7	oz/gal.
Potassium cyanide	22 - 23.8	oz/gal.
Potassium hydroxide	5.5 - 6.0	oz/gal.
Potassium carbonate	3 - 6	oz/gal.

No brightener
Deionized water
Vigorous agitation
Anode-to-cathode ratio - 1 : 1
Current supply - voltage-stabilized rectifier, maximum ripple 2%
Current density - 60 asf

* Specimens plated by Ryan were given a cold-water rinse, a hot-water rinse, and then baked for 8 hours at 375F, except for the North American samples, which either were not baked or were baked for a maximum of 4 hours.

3.4 Test Procedures and Results

3.4.1 Standard Tensile Test (Convair)

Standard short-term tensile tests were performed on longitudinal Type R1 specimens conforming to Federal Test Method Standard No. 151 (0.505-inch diameter by 2-inch gage length). Strain rate to yield was maintained at 0.005 inch/inch/minute. Rate of crosshead travel from yield to ultimate was 0.15 to 0.20 inch/minute. All test results are presented in Table II, and percent reduction of area is shown in Graph 1.

3.4.2 Special Ring Test (Douglas)

This test utilized a ring specimen and a spacer which applied a constant stress of approximately 240,000 psi. Figure 1 shows the specimen, spacer, and stressed specimen. To allow stressing the ring at 90° to the direction of grain flow, specimens are normally taken from 4340 steel tubing or round

* Revised 16 December 1959.

3.4.2 Special Ring Test (Douglas) (continued)

bar as shown in Figure 2A. Since it was considered essential that test material of all participants be identical, the Douglas procedure was modified by machining the rings from the rectangular bar stock as shown in Figure 2B. With this type of specimen, the maximum angle at which stress could be applied with respect to grain flow was 45°. The test results are given in Graph 2.

3.4.3 Notched Tensile Test (Lockheed)

The Lockheed notched tensile specimen is shown in Figure 3. The specimens were loaded at 75 percent of their notched tensile strength until failure, with the results given in Graph 3.

3.4.4 Notched Tensile Test (McDonnell)

The McDonnell specimen is illustrated in Figure 4. Specimens were loaded at 50 percent of the notched tensile strength until failure or for 100 hours, then loaded at 75 percent of the notched tensile strength until failure or for an additional 100 hours. The results are given in Graph 4.

3.4.5 Constant-Rate Bend Test (Norair)

In this test, the 0.250-inch-diameter round specimen shown in Figure 5 was bent around a mandrel of the same diameter until fractured. Bending rate was maintained at 4° per second. The results of these tests are given in Graph 5.

3.4.6 Torqued Bolt Test (North American)

The bolt specimens illustrated in Figure 6A were designed to exhibit delayed failure in the 0.0156-inch fillet below the head when statically loaded to the 0.2 percent offset yield stress (about 90 percent of the ultimate stress). One unembrittled control specimen was loaded in the test fixture as shown in Figures 6B and 6C together with the six specimens embrittled by each participant. Load was applied by tightening the nut until overall length increase of each bolt was 0.034 ± 0.002 inch, which had previously been found to correspond approximately to the yield strength as indicated by 0.006-inch average permanent set upon release of the load. The results of these tests are given in Table III and Graph 6.

3.4.7 Static Bend Test (Ryan)

These tests were made as shown in Figure 7 on specimens 0.108 by 0.5 by 4 inches. One specimen from each lot was subjected to each of the outer fiber tension stress levels noted by setting to a calculated deflection with the aid of a depth micrometer: 100,000, 140,000, 180,000, 220,000, 260,000, and 280,000 psi. One specimen (embrittled by McDonnell and stressed to 280,000 psi) failed in 46 days. The remainder of the tests were discontinued after 61 days.

3.5 Discussion of Results

Although all methods were in fair agreement as to which specimens were most embrittled and which least, no correlation existed in the medium-embrittlement range. The shorter methods (standard tensile test, constant-rate bend test, and static bend test) were not sensitive enough to indicate any but the more severe instances of embrittlement. Of the longer methods, the two sustained load notched tensile tests showed the greatest s sitivity, with the McDonnell method having somewhat less scatter than the Lockheed method. The torqued bolt test results showed considerable scatter except in those groups of specimens which it indicated as being most embrittled. The special ring test showed fairly broad scatter for the specimen groups it indicated as being in the medium-embrittlement range, which may be attributable to the fact, noted in paragraph 3.4.2, that 45° was the maximum angle at which stress could be applied with respect to direction of grain flow.

Since plating was performed in small laboratory baths and was applied to high-strength steel not usually electroplated, the test results are in no way indicative of normal production plating quality. With this in mind, it is noted that all test results showed specimens plated by Ryan in an experimental potassium cyanide bath to be superior to, or at least as good as, the other specimens, which were plated in sodium cyanide baths. Furthermore, in many instances the Ryan specimens were at least as good as the unplated controls. Since other high-efficiency baths were not used, it is not possible to determine from the results of this program if the Ryan bath was typical of other high-efficiency baths or if it was one that caused almost no embrittlement and was superior to all other standard and high-efficiency baths.

4. PHASE II TESTS

The Project had originally planned to test additional alloys by the best short-term method selected from Phase I and, as a check, by the best long-term method(s). Since the short-term tests were not sufficiently sensitive for the Phase I test material, this plan could not be pursued. It was decided to attempt improvement of the shorter methods using the same test material, and to repeat the McDonnell notched tensile tests for comparison.

4.1 Test Material

Transverse-quality 4340 alloy steel remaining from Phase I was used.

4.2 Heat Treatment

Participating companies heat treated their own specimens to a strength level of 260,000 to 280,000 psi, using the procedure described in paragraph 3.2.

4.3 Introduction of Hydrogen

Cadmium plating of specimens was performed by Douglas and North American according to the procedure given in paragraph 3.3. These two companies were selected because the Phase I test results showed their specimens to be in the medium-embrittlement range.

4.4 Test Procedures

4.4.1 Constant-Strain-Rate Tensile Test (Convair)

The standard tensile test was modified by maintaining a constant strain rate of 0.003 inch/inch/minute until failure. The results of tests on controls and embrittled specimens are given in Table IV; reduction of area is also shown in Graph 7.

4.4.2 Notched Tensile Test (McDonnell)

The procedure described in paragraph 3.4.4 was repeated to serve as a control, since this method proved to be the most sensitive in Phase I tests. The results are given in Graph 8.

4.4.3 Modified Bend Tests (Norair)

The Norair specimen was modified by inclusion of a shallow circumferential notch at the point of bending, as shown in Figure 5. Two modifications of the test procedure were used. In the first, the original bending rate of 4° per second was slowed to 1-1/8° per minute. In the second, specimens were bent to 35° at the rate of 4° per second, held at 35° for 2 hours, then bent further at the same rate until failure. The results of these tests are shown in Graphs 9 and 10.

4.4.4 Modified Bend Tests (Ryan)

Ryan performed two basic modifications of the static bend test described in paragraph 3.4.7. For the first, a 1/4-inch-diameter hole was drilled through the specimen at the point of load application. Preliminary studies showed that the hole-type specimens failed at a theoretical stress level of 402,000 psi*. Test specimens were stressed at this level and at 134,000 psi and 268,000 psi* for 2 and 34 days (controls), 2 and 45 days (specimens plated by Douglas), and 2 and 57 days (specimens plated by North American). None of the specimens tested by this method failed.

In the second modification, plain specimens were preloaded to 190,000 psi outer fiber stress for 1/2, 1, 2, 4, 7-1/2, and 16 hours, then bent slowly at the rate of 0.0357 inch per minute. One hole-type specimen was preloaded at 201,000 psi* and one at 402,000 psi*, then subjected to further bending. All preloaded specimens reached a total deflection of 0.625 inch without failure, at which point the test was stopped.

4.5 Discussion of Results

The McDonnell sustained load notched tensile test showed good correlation with the Phase I portion of the work, with a slightly greater degree of scatter as shown by comparison of Graphs 4 and 8. The change in specimen configuration and speed of bend improved the Norair method; however, this bend test was still not sensitive enough to determine the degree of embrittlement present in the one material tested. The changes in the Ryan specimen configuration and method did not result in any improvement, indicating that the method was still not sensitive enough for the test material.

* Theoretical stress if material were perfectly elastic. These figures are not true maximums, as yielding occurs to destroy the linear relationship between stress and deflection.

5. HYDROGEN ANALYSIS

Convair, Fort Worth, analyzed the test material for hydrogen to determine whether a correlation existed between embrittlement and the amount of hydrogen actually present.

5.1 Test Specimens

Five 1/2-inch-thick samples of transverse-quality 4340 alloy steel used in Phase I and II were heat treated by Norair, using the procedure outlined in paragraph 3.2. Two were cadmium plated by Douglas as specified in paragraph 3.3, except that only one was baked at 375F for 8 hours. Two specimens were cadmium plated by North American. The bath used in plating Phase I and II specimens had been destroyed, so these two specimens were plated at 20 asf in a production bath of the composition noted below. One of these specimens was baked at 375F for 8 hours. The fifth specimen was left unplated.

Cadmium oxide	3.4 - 4.5 oz/gal.
Sodium cyanide	13 - 14 oz/gal.
Sodium hydroxide	to pH of 13
ROHCO brightener	1 gal./gal. of solution
Sodium carbonate	6 oz/gal. max

5.2 Test Procedure

Convair cut specimens approximately 1/4 by 1/4 inch and analyzed them for hydrogen by a vacuum-extraction method, using a National Research Corporation Vacuum Hydrogen Determinator, Type 917. The extractions were carried out at 1000F for 5 minutes. The results are given in Table V.

5.3 Discussion of Results

The average amount of hydrogen found in embrittled specimens was not sufficiently greater than that found in control specimens to be considered meaningful in an embrittlement study of steel heat treated to a high strength level.

TABLE I. CHEMICAL ANALYSIS OF TEST MATERIAL

	Top of Bar $10M_2$	Bottom of Bar $10M_5$
Carbon	0.42 %	0.42 %
Manganese	.78	.77
Phosphorus	.01	.01
Sulfur	.016	.022
Silicon	.31	.31
Nickel	1.78	1.78
Chromium	.73	.72
Molybdenum	.27	.27
Aluminum	.01	.01
Copper	.10	.10
Tin	.011	.011
Vanadium	trace	trace

TABLE II. PHASE I STANDARD TENSILE TEST RESULTS (CONVAIR)

Plating Company	Specimen No.	Fty 0.2% Offset 10^3 psi	Ftu 10^3 psi	Elong in 2 in. %	Red. of Area %
Convair Control Tests As heat treated	CL1	225.2	290.3	13.5	32.0
	CH3	225.7	294.0	13.0	31.2
	Avg	225.4	292.1	13.2	31.6
Plated, not baked, tested immediately	CB1	225.3	289.9	6.0	10.9
	CR3	221.0	288.5	8.5	18.7
	Avg	223.1	289.2	7.2	14.8
Plated, not baked, 60-day test delay	CJ1	229.8	287.9	11.5	28.3
	CD3	225.3	287.8	9.5	20.7
	Avg	227.6	287.8	10.5	24.5
Convair	CA1	239.1	285.6	10.0	28.6
	CK1	228.7	284.2	10.5	28.0
	CG2	229.4	285.7	11.5	34.2
	CR2	219.2	285.3	12.0	33.7
	CC3	227.7	284.1	12.0	35.3
	CN3	227.8	284.2	11.0	33.9
	Avg	228.6	284.8	11.2	32.3
Douglas	CC1	—	—	—	—
	CM1	227.6	284.6	11.5	31.8
	CH2	237.4	286.4	12.5	37.6
	CS2	206.8	283.6	11.0	35.1
	CE3	229.4	282.8	12.0	32.4
	CO3	231.8	285.7	10.5	31.0
	Avg	226.6	284.6	11.5	33.6
Lockheed	CE1	—	—	—	—
	CO1	226.4	287.2	9.5	21.6
	CB2	226.3	288.8	12.0	31.3
	CK2	221.8	287.9	12.0	33.1
	CG3	230.0	286.9	10.5	25.1
	CL3	204.3	285.4	11.0	32.4
	Avg	221.8	287.2	11.0	28.7

TABLE II. PHASE I STANDARD TENSILE TEST RESULTS (continued)

Plating Company	Specimen No.	Fty 0.2% Offset 10^3 psi	Ftu 10^3 psi	Elong in 2 in. %	Red. of Area %
McDonnell	CF1	*	*	*	*
	CP1	219.4	287.0	7.5	14.3
	CM2	229.2	286.6	12.0	30.3
	CC2	224.3	287.0	12.0	30.7
	CL2	217.7	286.4	9.5	20.9
	CJ3	224.7	285.5	10.0	20.7
	Avg	223.1	286.5	10.2	23.4
Norair	CH1	227.7	285.1	12.5	37.5
	CS1	229.8	286.1	12.0	35.1
	CE2	*	*	*	*
	CP2	215.1	285.9	11.5	37.3
	CB3	231.4	286.9	12.0	36.7
	CM3	215.4	283.8	11.5	34.8
	Avg	223.9	285.6	11.9	36.3
North American	CG1	223.1	284.5	12.0	35.8
	CR1	204.0	284.5	12.5	33.8
	CD2	*	*	*	*
	CN2	226.8	290.7	11.5	36.1
	CA3	224.9	283.8	12.0	35.9
	CK3	224.2	284.0	11.5	33.0
	Avg	220.6	285.5	11.9	34.9
Ryan	CD1	226.4	290.3	13.0	34.5
	CN1	228.9	285.4	11.5	34.9
	CA2	227.0	290.9	12.0	37.3
	CJ2	226.1	287.8	11.5	34.9
	CF3	228.2	286.9	12.0	35.9
	CP3	228.4	286.2	12.0	35.1
	Avg	227.5	287.9	12.0	35.4

*Thread failure

TABLE III. PHASE I TORQUED BOLT TEST RESULTS
(NORTH AMERICAN)

Plating Company	Duration of Test hr	Specimen No.	Time to Failure hr	Location of Failure
Convair	2000	*C0	—	None
		C1	404	Head fillet
		C2	—	None
		C3	1246	Head fillet
		C4	404	Threads
		C5	404	Thread fillet
		C6	404	Thread fillet
Douglas	2000	*D0	—	None
		D1	—	None
		D2	933	Thread fillet
		D3	70	Threads
		D4	337	Head fillet
		D5	—	None
		D6	—	None
Lockheed	1300	*L0	—	None
		L1	334	Head fillet
		L2	530	Shank
		L3	—	None
		L4	1014	Thread fillet
		L5	438	Head fillet
		L6	362	Head fillet
McDonnell	2000	*M0	—	None
		M1	1	Threads
		M2	41	Head fillet
		M3	17	Threads
		M4	17	Threads
		M5	1	Threads
		M6	17	Threads

TABLE III. PHASE I TORQUED BOLT TEST RESULTS (continued)

Plating Company	Duration of Test hr	Specimen No.	Time to Failure hr	Location of Failure
Norair	2000	*N0	—	None
		N1	—	None
		N2	143	Head fillet
		N3	—	None
		N4	1415	Head fillet
		N5	775	Head fillet
		N6	1803	Head fillet
North American	1600	*NA0	—	None
		NA1	—	None
		NA2	—	None
		NA3	768	Head fillet
		NA4	—	None
		NA5	—	None
		NA6	—	None
Ryan	2000	*R0	—	None
		R1	1342	Head fillet
		R2	—	None
		R3	—	None
		R4	70	Threads
		R5	—	None
		R6	—	None

*Controls

TABLE IV. PHASE II CONSTANT-STRAIN-RATE TENSILE TEST RESULTS (CONVAIR)

Plating Company	Specimen No.	Fty 0.2% Offset 10^3 psi	Ftu 10^3 psi	Elong in 2 in. %	Red. of Area %
Convair Control Tests, Unplated	C3C	228.4	293.2	12.0	33.0
	C7A	226.9	293.2	11.0	23.8
	C11B	227.9	297.0	9.3	13.9
	C15C	227.6	292.9	11.0	28.8
	C19A	*	*	*	*
	C23B	226.1	294.1	12.5	35.3
	Avg	227.4	294.1	11.2	27.0
Douglas	C1A	225.1	292.1	10.5	22.1
	C5B	230.7	293.3	12.0	33.4
	C9C	228.7	292.8	13.0	33.2
	C13A	228.1	293.3	13.0	39.0
	C17B	*	*	*	*
	C21C	228.5	293.1	11.0	24.9
	Avg	228.2	292.9	11.9	30.5
North American	C2B	230.8	281.3	2.5	7.4
	C6C	227.1	289.2	12.5	37.5
	C10A	231.1	288.0	12.5	37.9
	C14B	228.6	290.5	11.0	29.5
	C18C	229.2	288.5	9.0	22.8
	C22A	230.7	289.5	11.3	37.8
	Avg	229.6	287.8	9.8	28.8

*Thread failure

TABLE V. HYDROGEN CONTENT OF TEST MATERIAL
IN PARTS PER MILLION BY WEIGHT

Unplated	Plated by Douglas Not Baked	Plated by Douglas Baked	Plated by North American Not Baked	Plated by North American Baked
4	12	9	6	8
5	9	10	6	7
4	12	8	6	7
8	7	8	8	9
4	7	9	11	7
4	12	13	5	6
		6	8	6
		7		
Avg 5	10	9	7	7

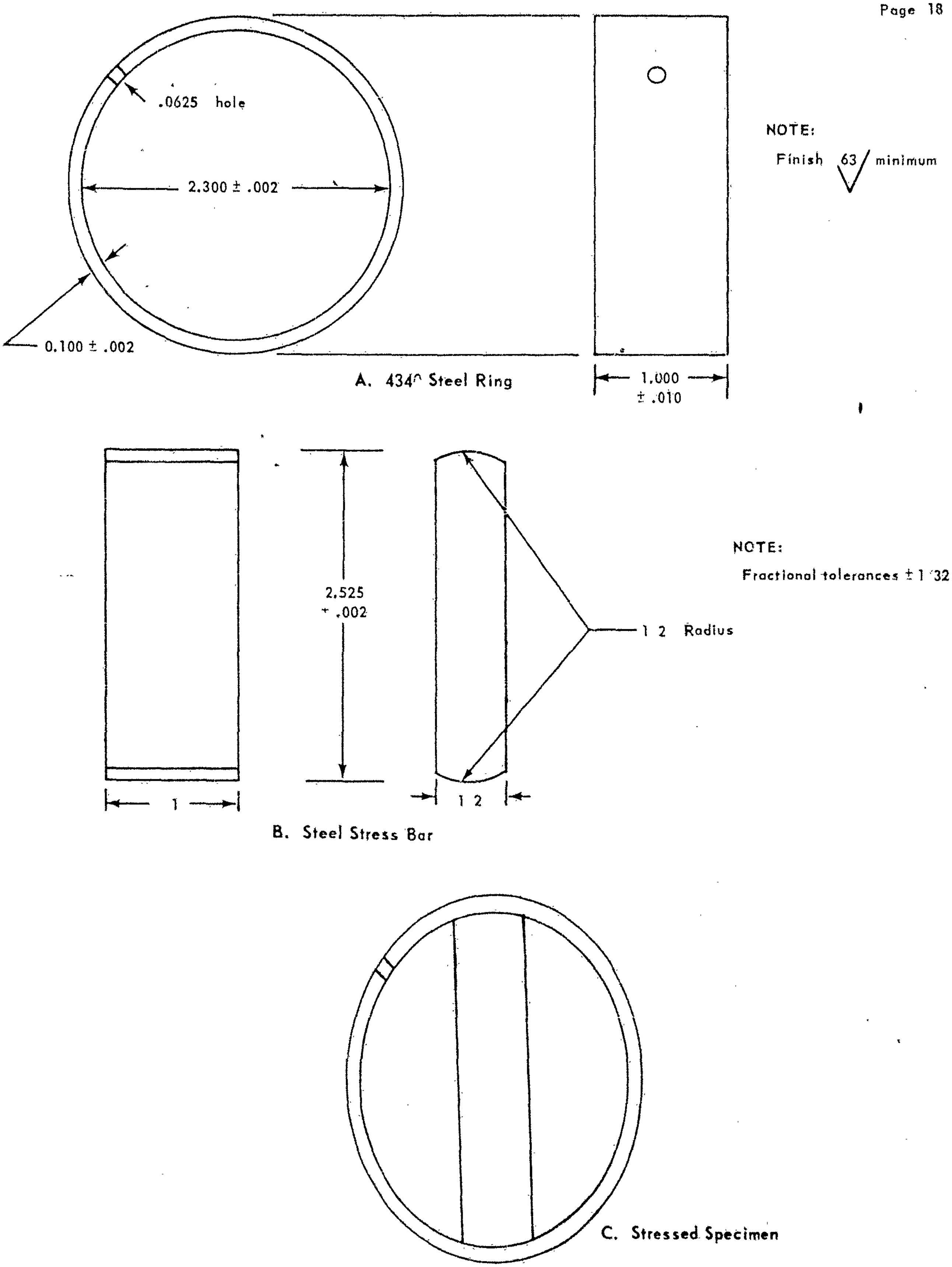
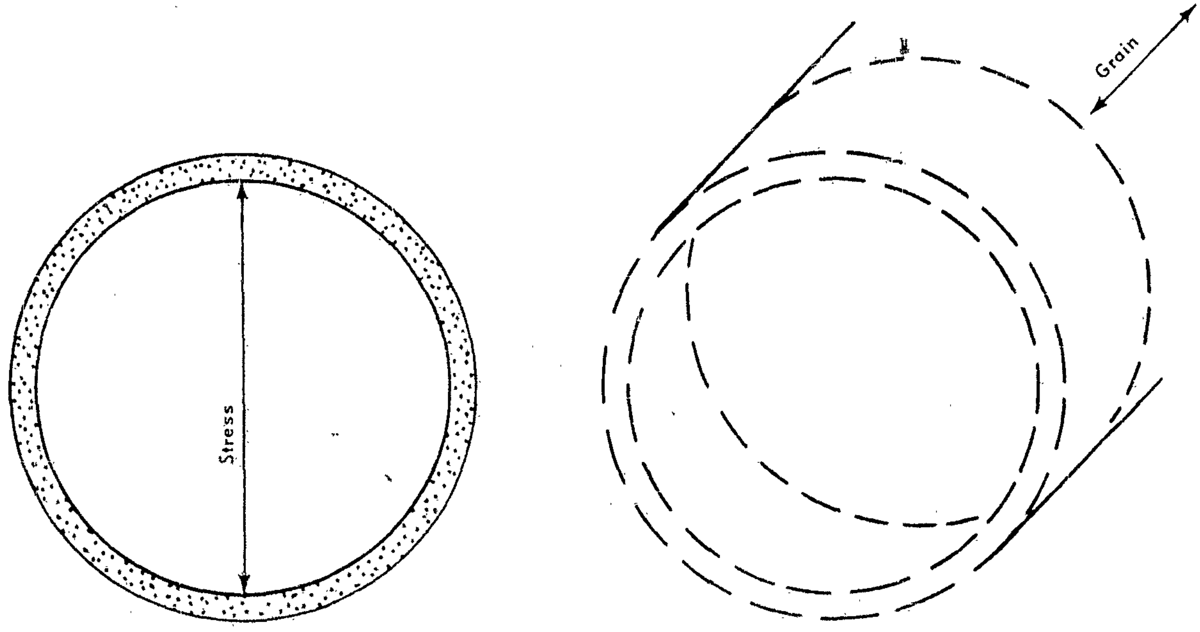
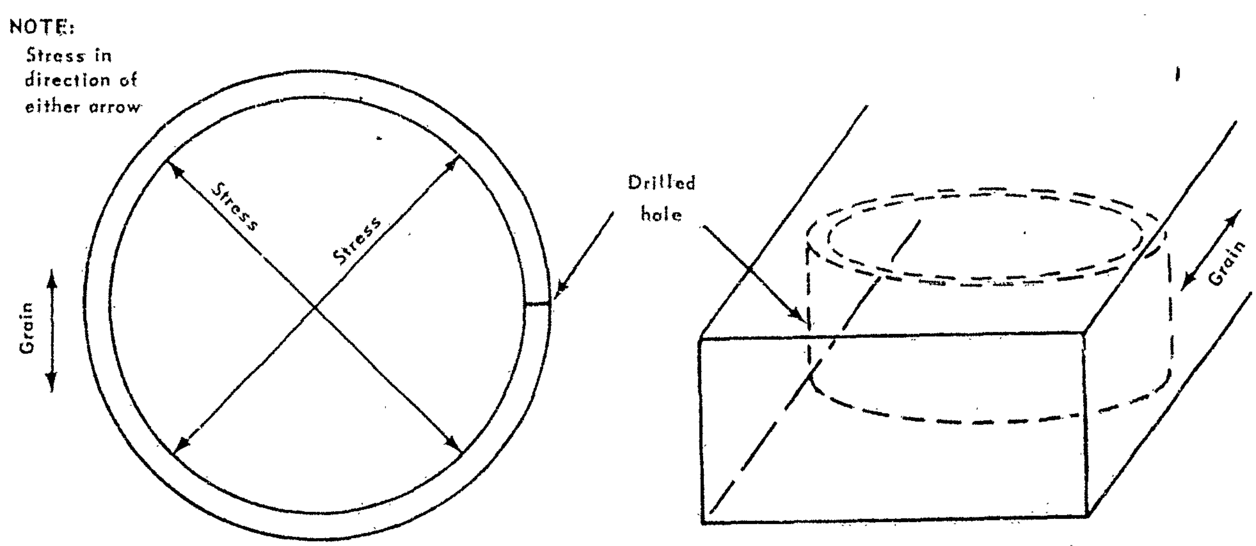


Figure 1. Special Ring Test Specimen and Stress Bar
(Douglas)

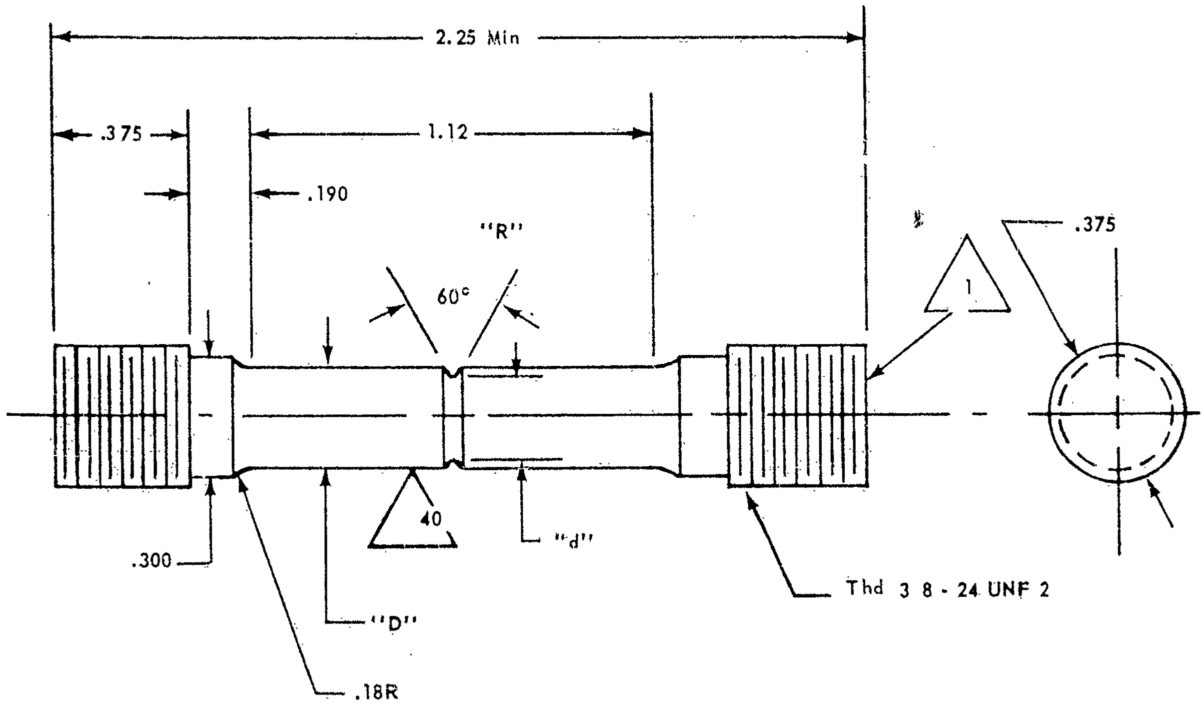


A. Specimen normally made from Tubing or Round Bar



B. W-95 Specimen made from Rectangular Bar

Figure 2. Direction of Stress Application in Special Ring Test (Douglas)



1 Rockwell and identify on ends only

Major diameter "D"	.2510
	.2490
Minor diameter "d"	.1778
	.1758
Notch radius "R"	.0040
	.0060
K_t	3.9
Linear tolerance:	.xx – ±.03
	.xxx – ±.010

Figure 3. Notched Tensile Test Specimen

(Lockheed)

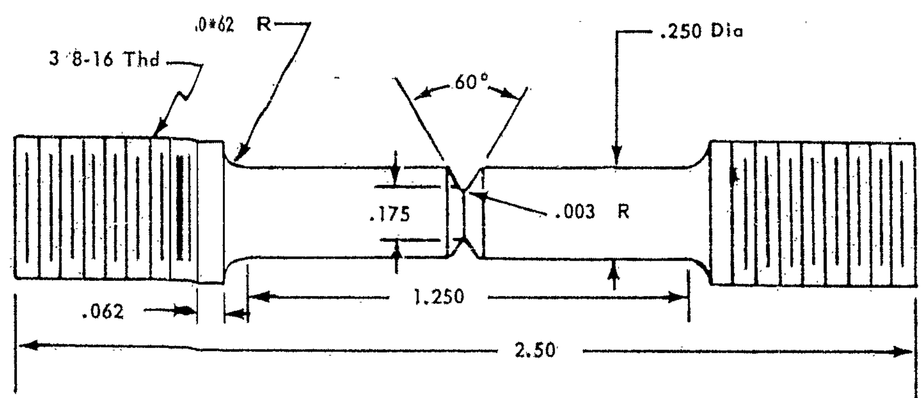
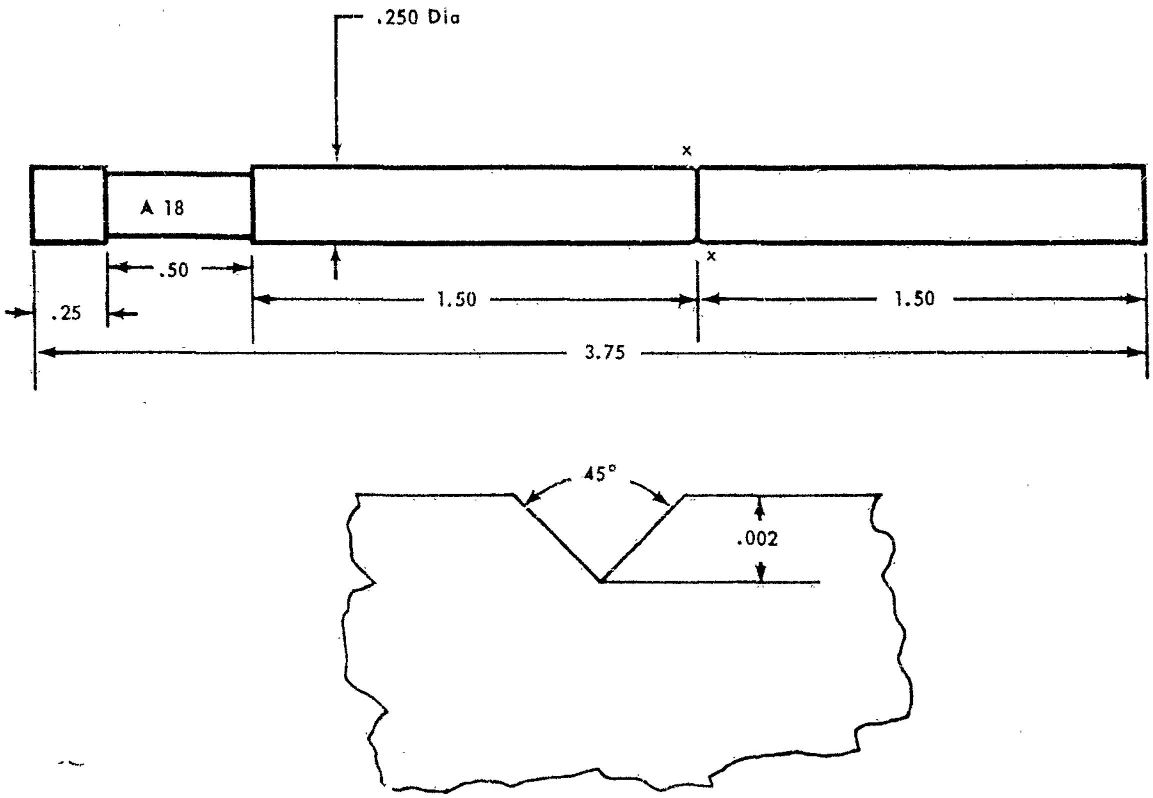


Figure 4. Notched Tensile Test Specimen
(McDonnell)



Notch at X – X
Phase II Specimens Only

Figure 5. Bend Test Specimen
(Norair)

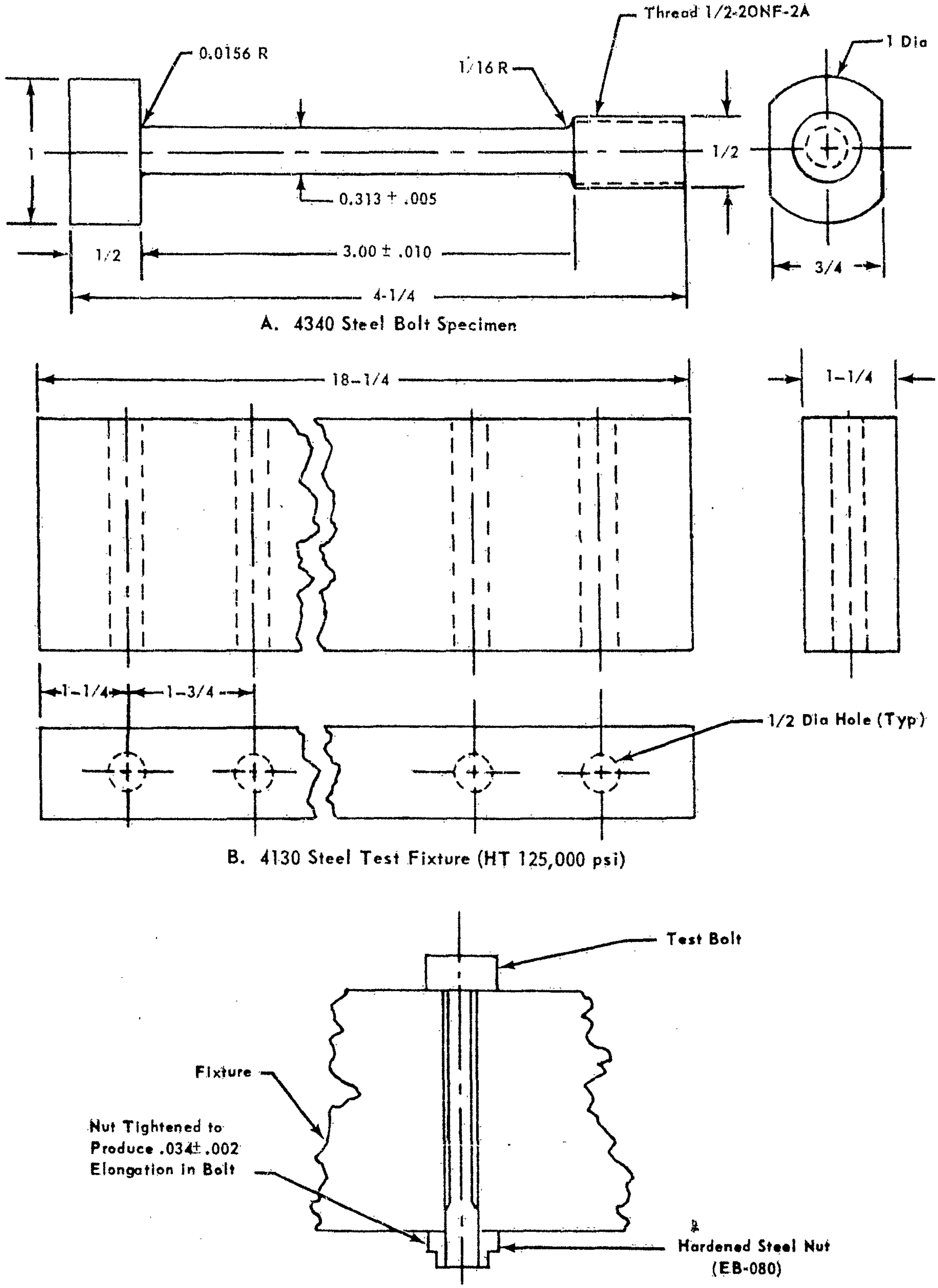


Figure 6. Torqued Bolt Test Specimen and Fixture (North American)

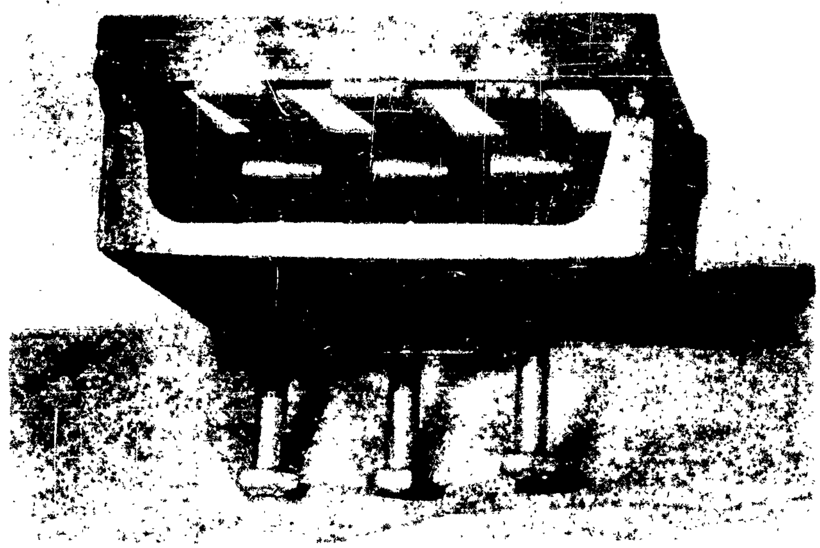
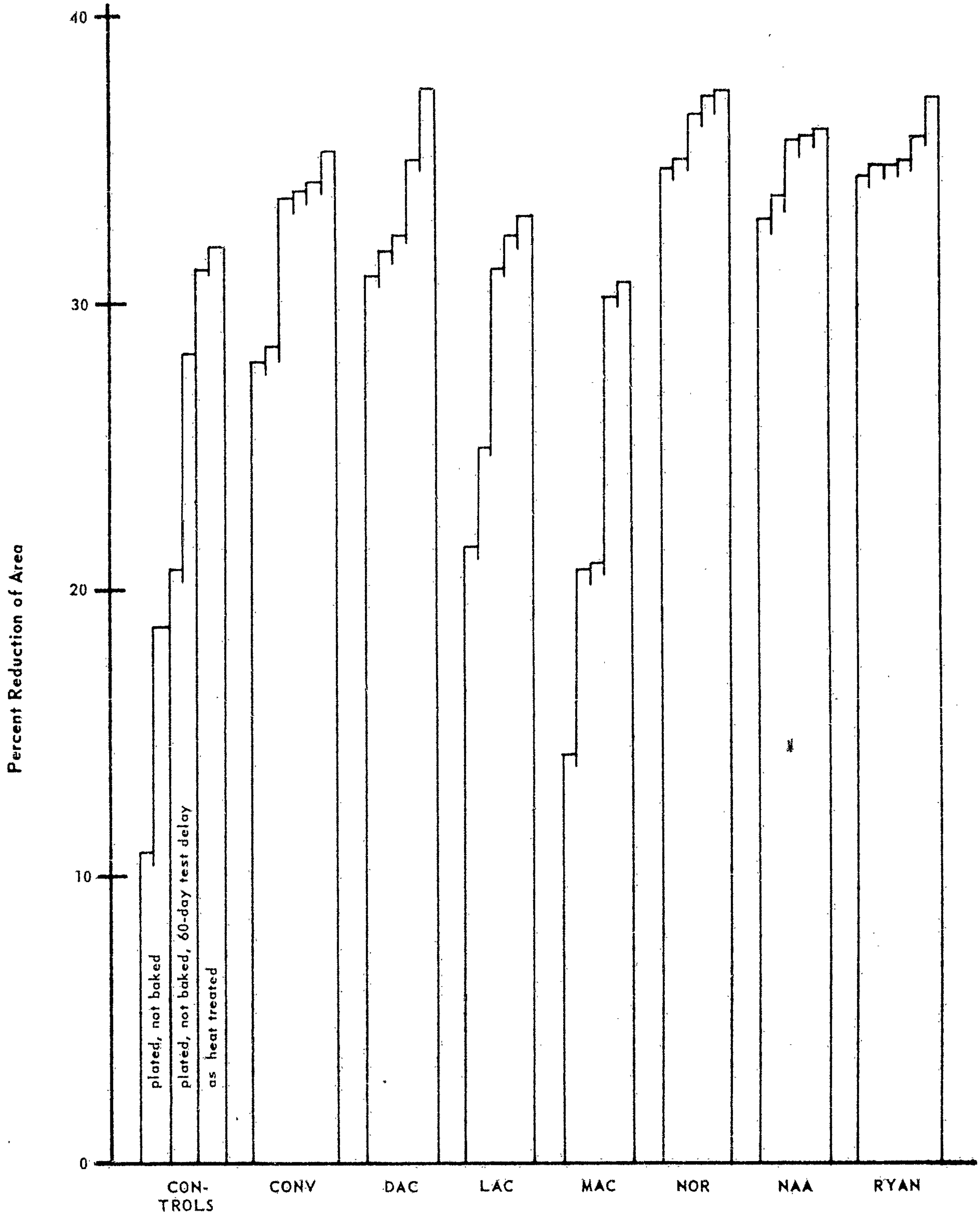
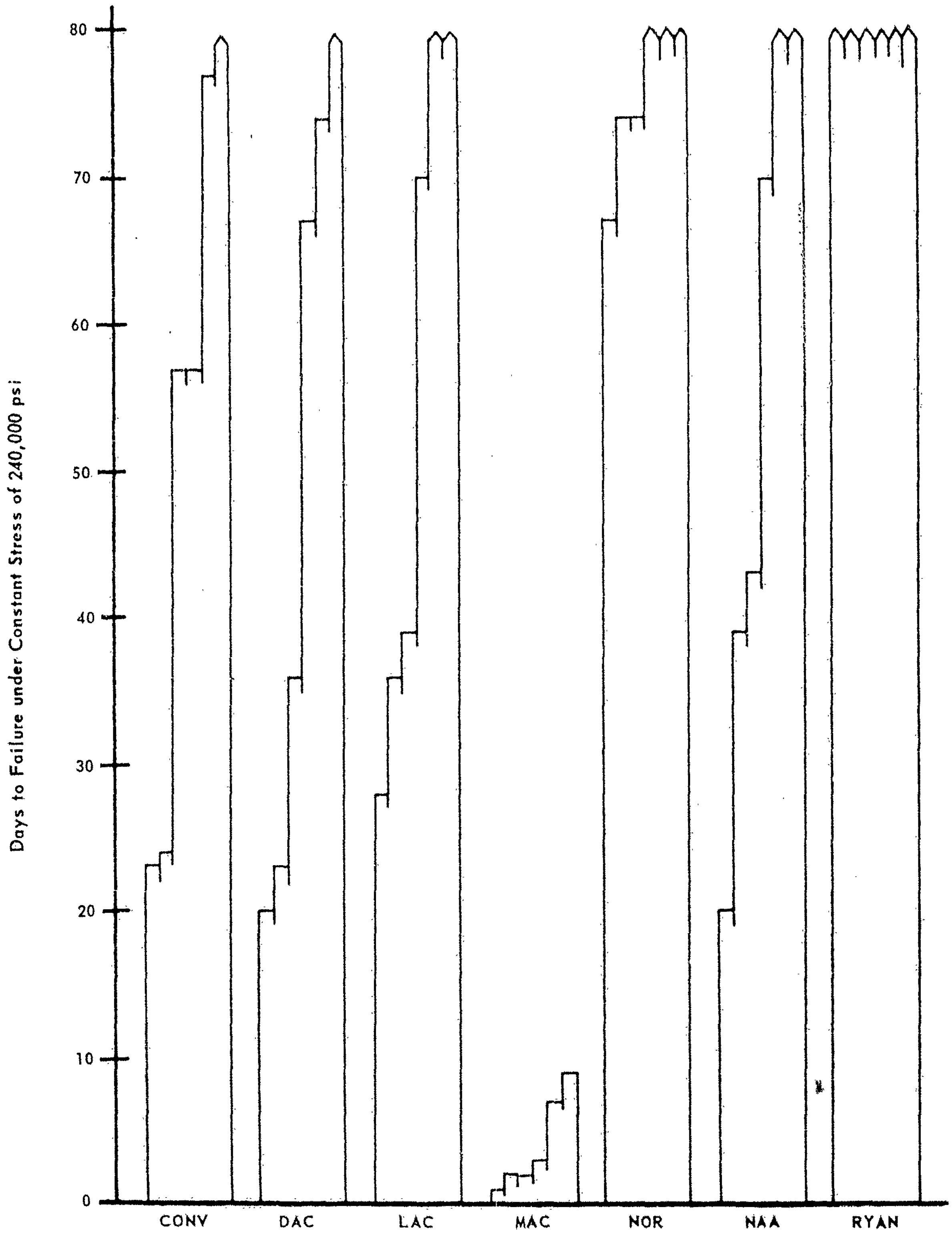


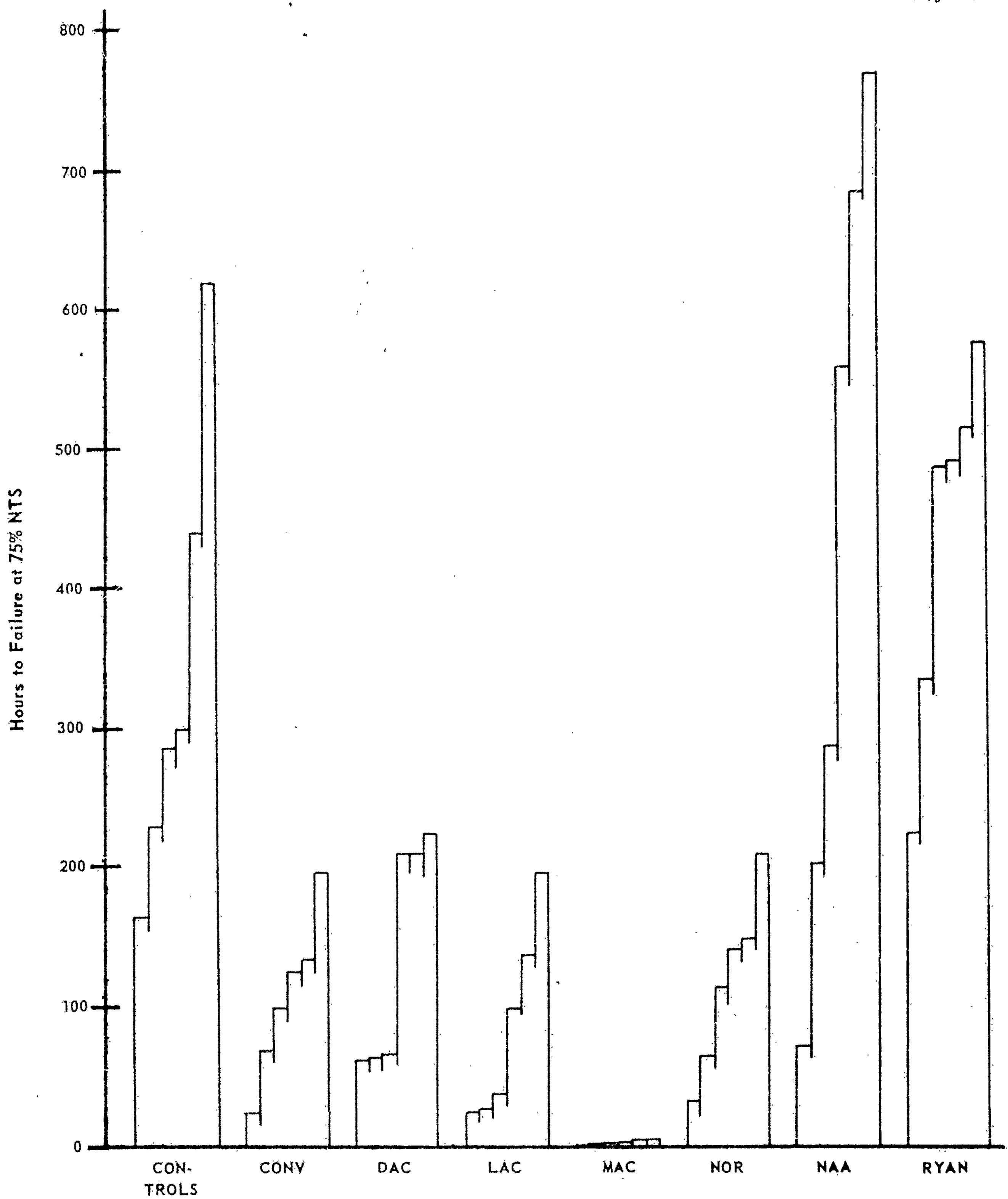
Figure 7. Bend Test Specimens in Fixture
(Ryan)



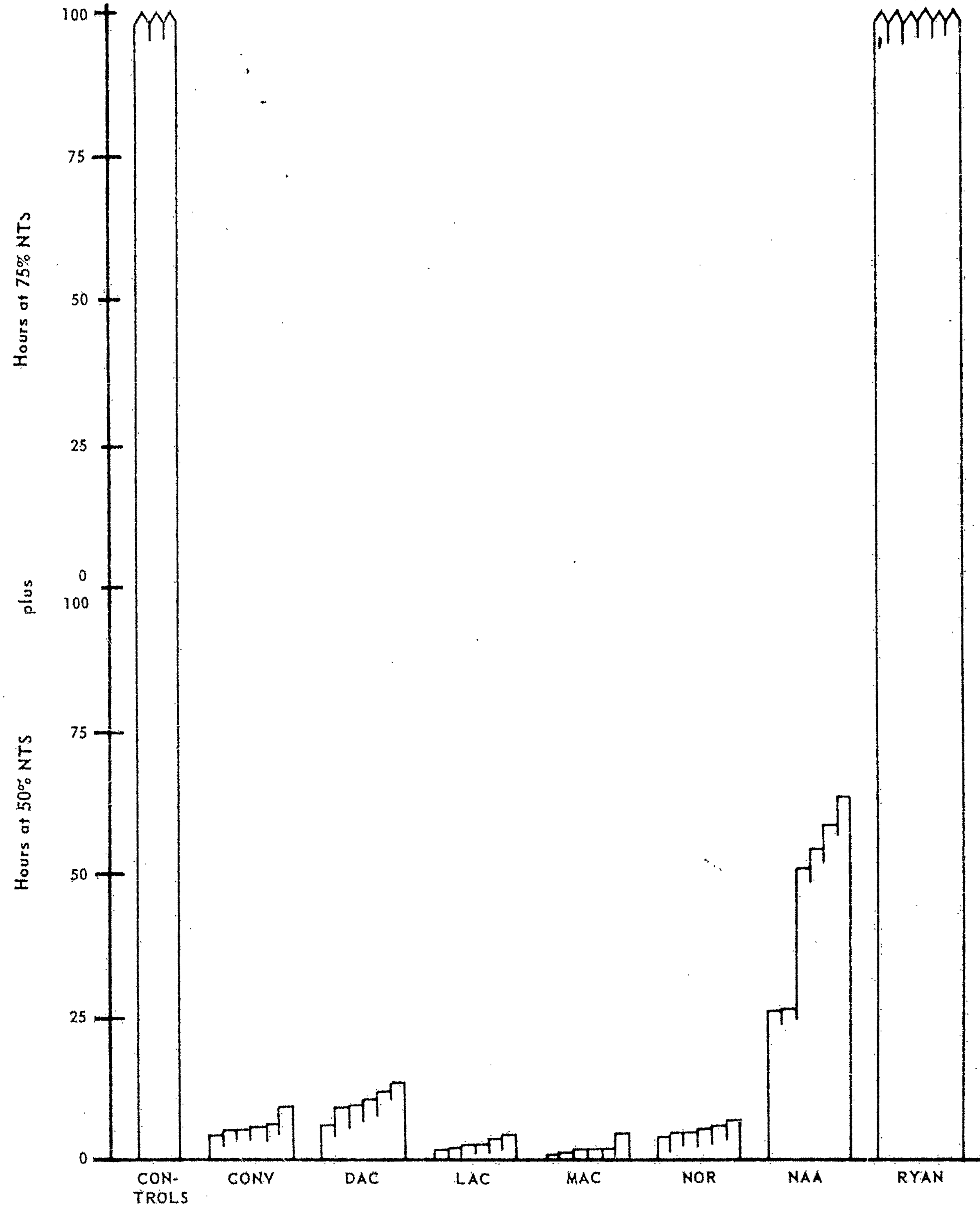
Graph 1. Phase I Standard Tensile Test Results
(Convair)



Graph 2. Phase I Special Ring Test Results
(Douglas)



Graph 3. Phase I Notched Tensile Test Results
(Lockheed)



Graph 4. Phase I Notched Tensile Test Results
(Mc Donnell)

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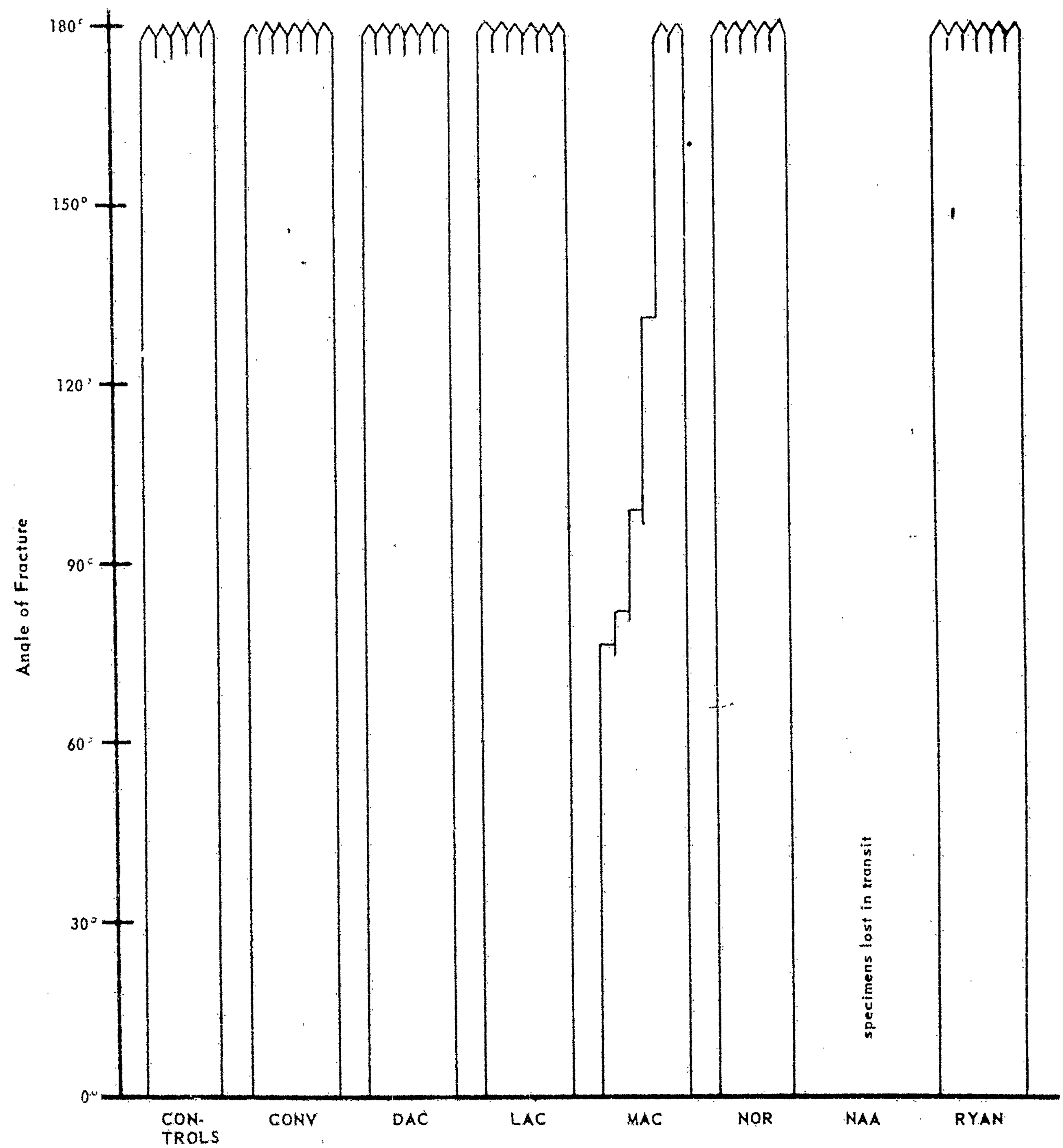
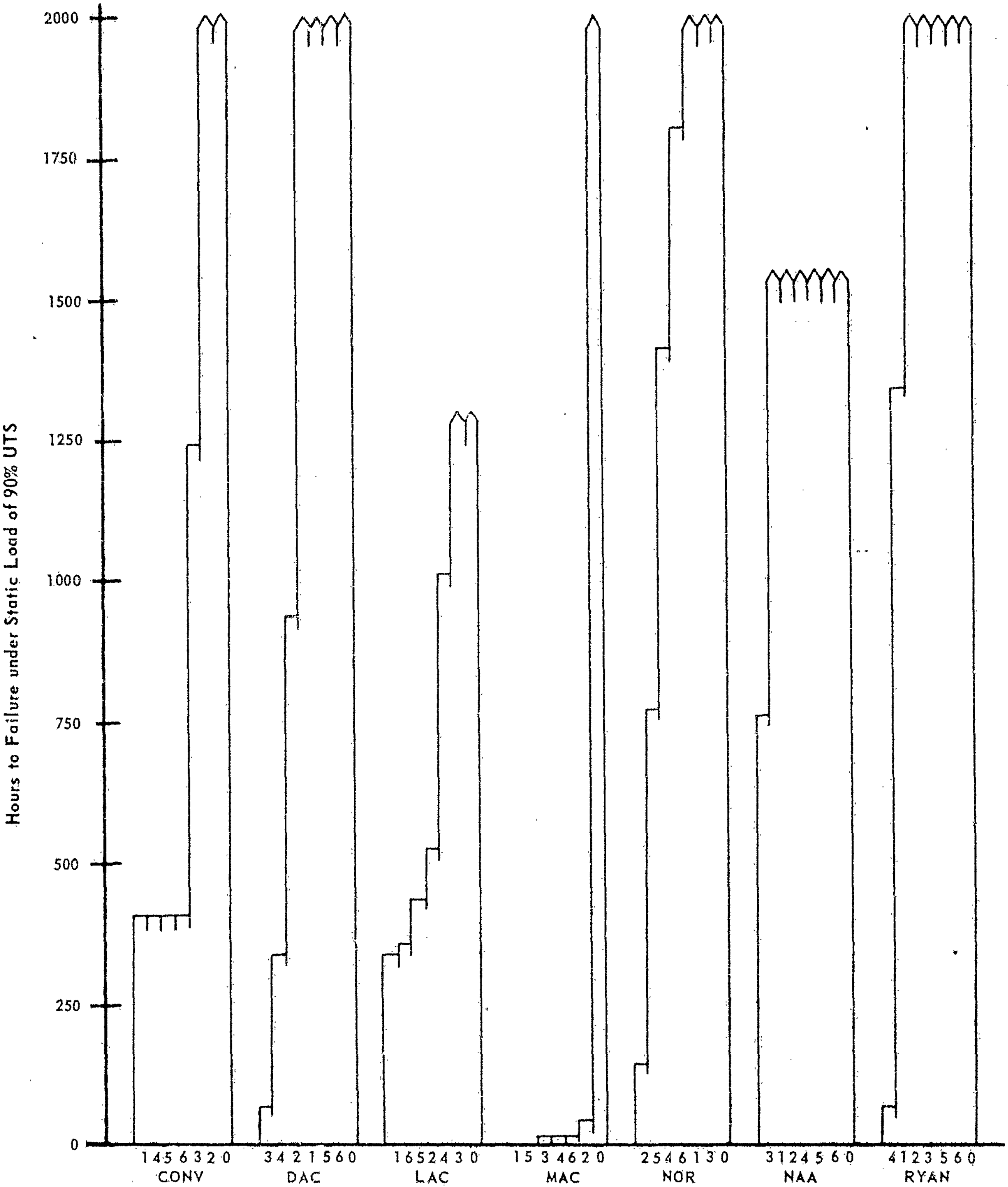
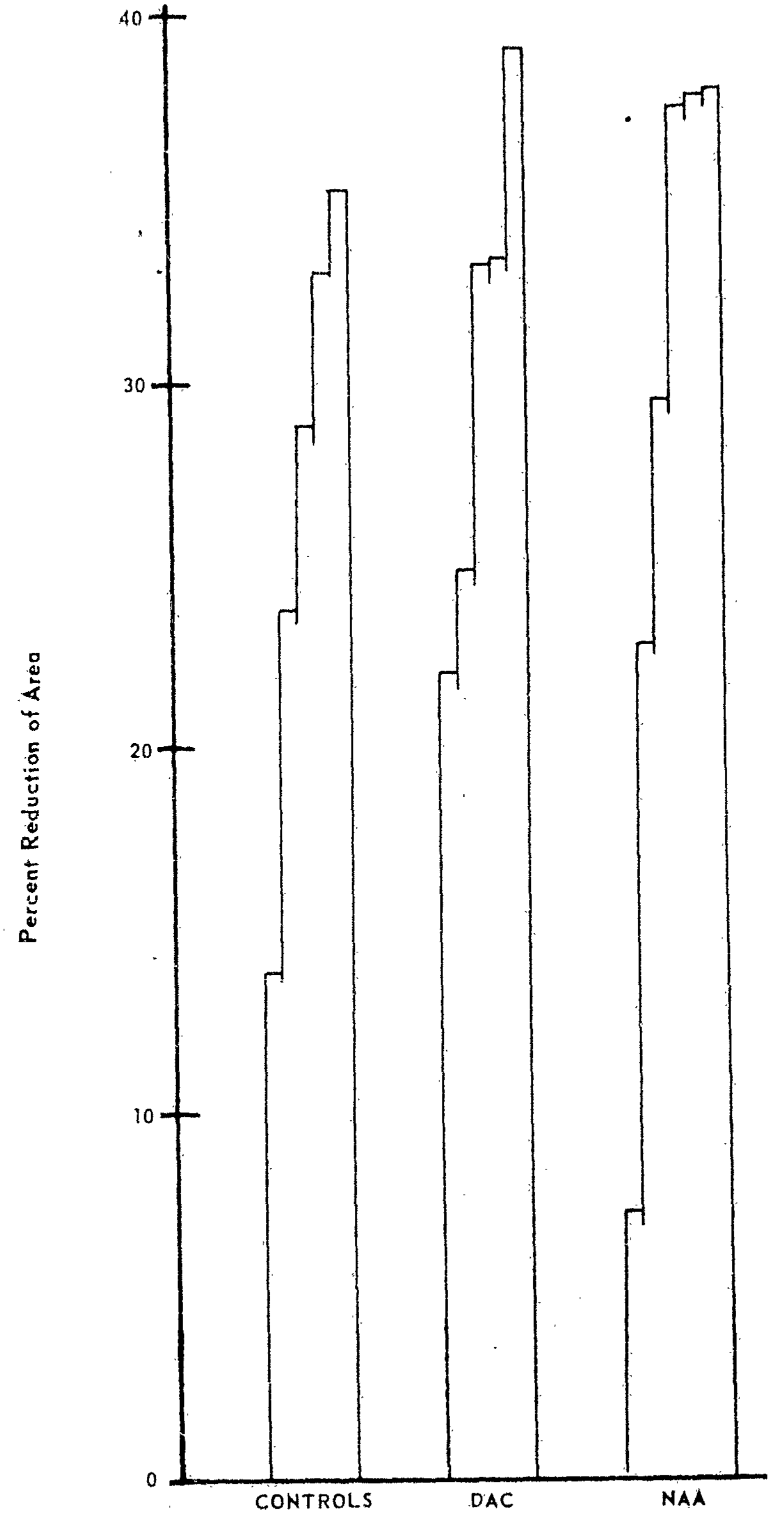


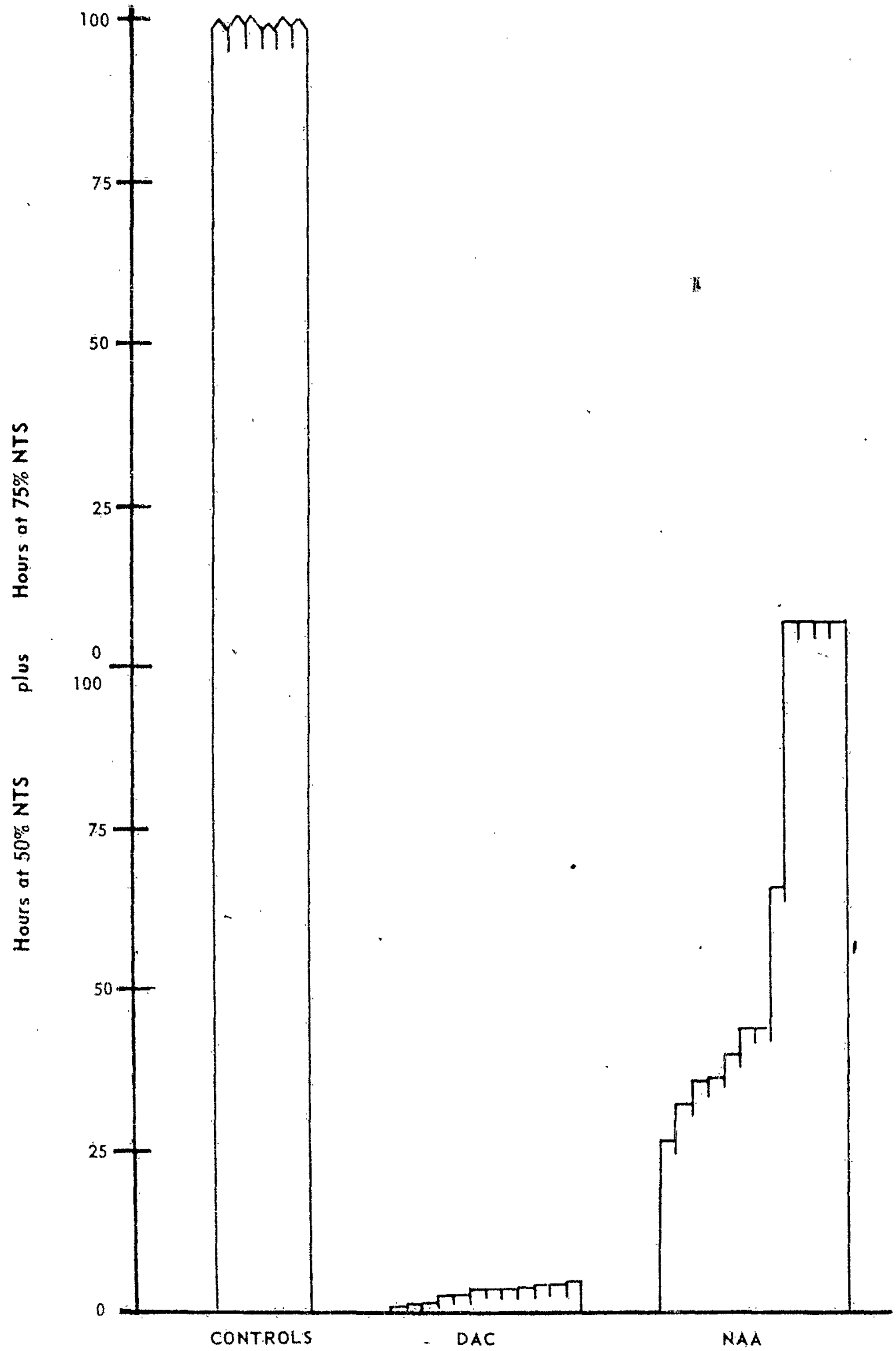
Graph 5. Phase I Constant-Rate Bend Test Results
(Norair)



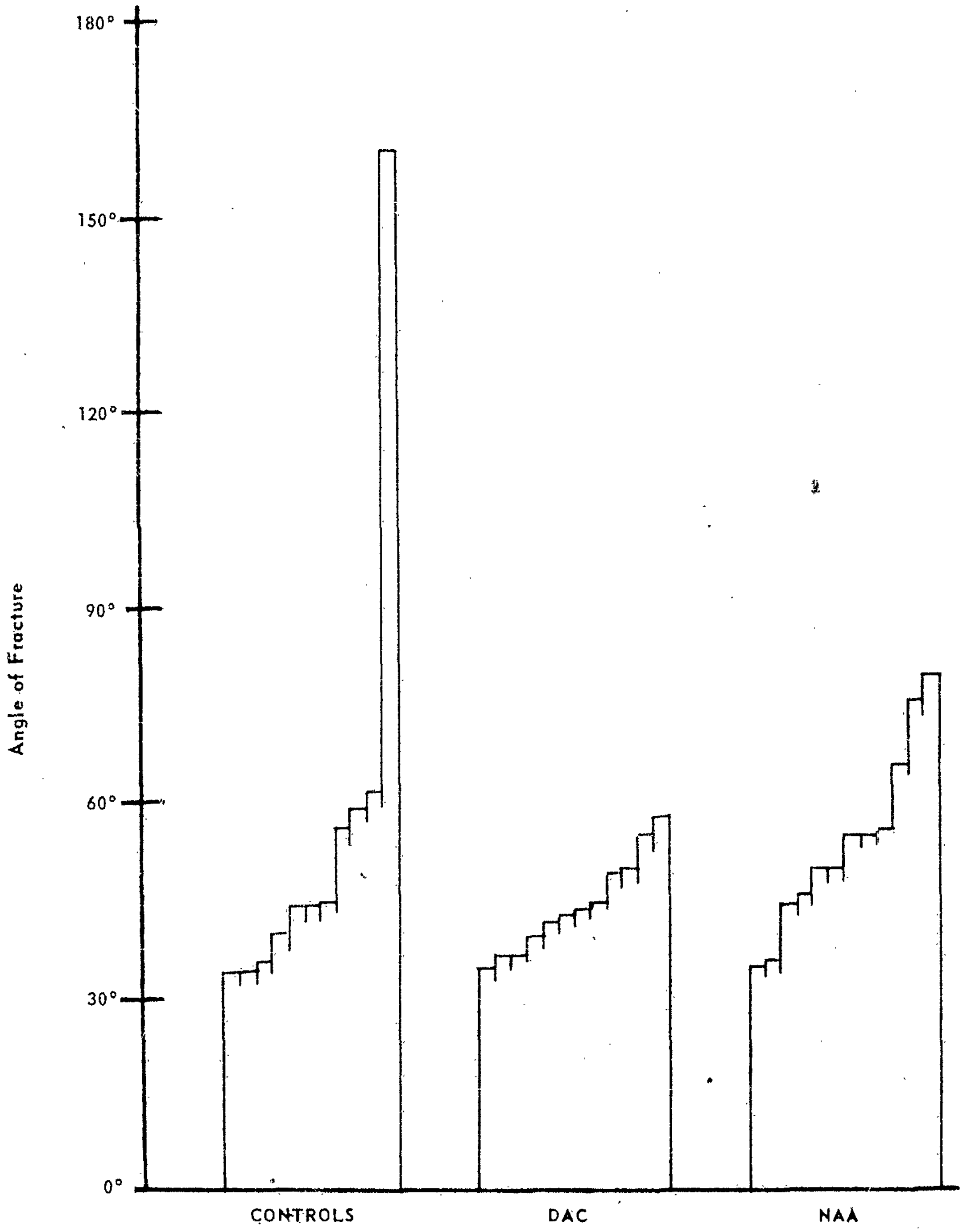
Graph 6. Phase I Torqued Bolt Test Results
(North American)



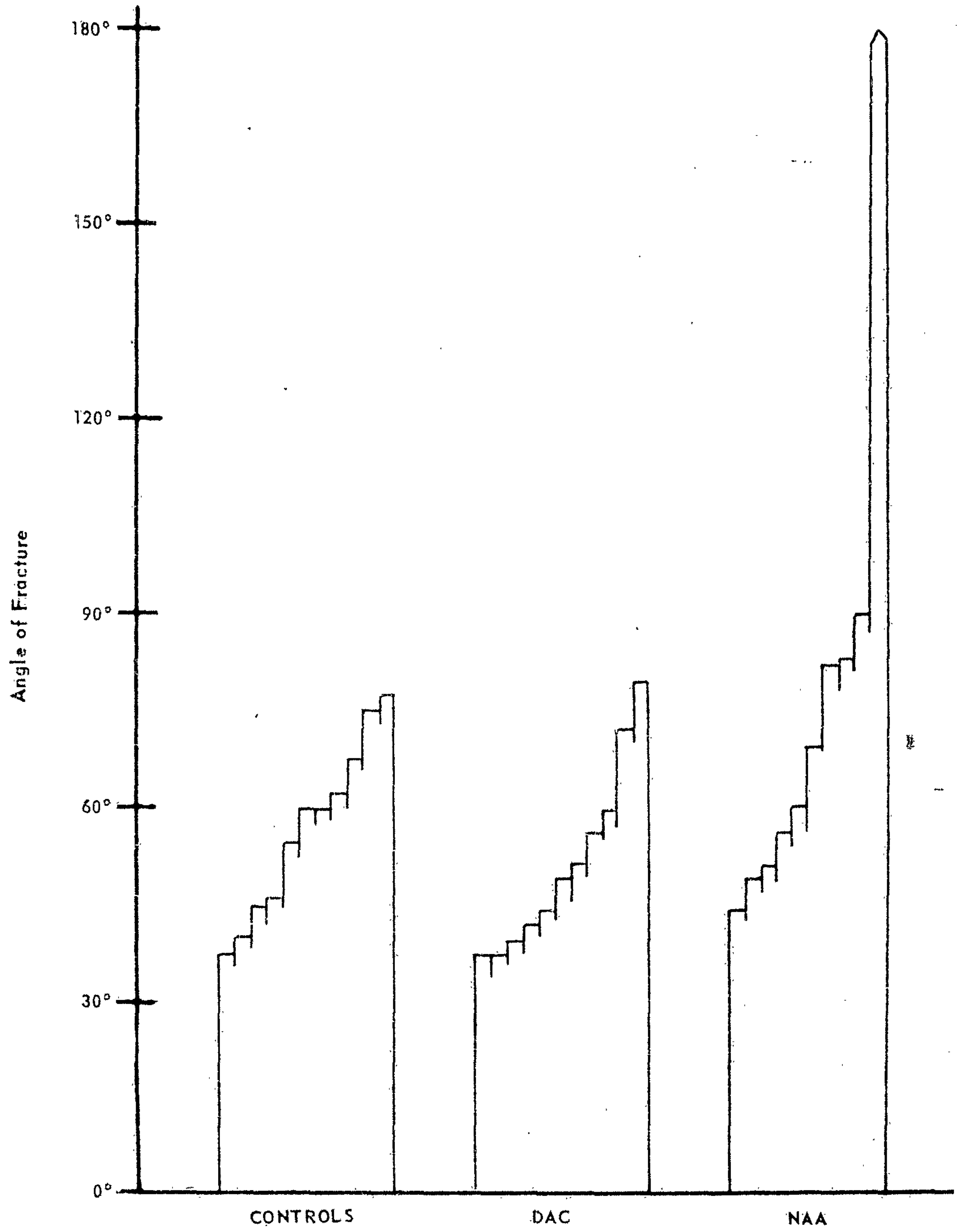
Graph 7. Phase II Constant-Strain-Rate Tensile Test Results (Convair)



Graph 8. Phase II Notched Tensile Test Results
(Mc Donnell)



Graph 9. Phase II Slow-Speed Bend Test Results
(Norair)



Graph 10. Phase II Intermittent Bend Test Results
(Norair)

6. REFERENCES

ARTC-WR-57-115	Questionnaire on Hydrogen Embrittlement Testing
ARTC-WR-57-130	Summary of Replies to Questionnaire on Hydrogen Embrittlement Testing
ARTC-58-12	Minutes of First Meeting of Panel W-95 "Standard Method for Evaluation of Susceptibility of Ferrous Metals to Hydrogen Embrittlement"
ARTC-58-94	U.S. Naval Research Laboratory Studies on Embrittlement and Crack Propagation
ARTC-58-167	Minutes of Second Meeting of Project W-95 "Standard Method for Evaluation of Susceptibility of Ferrous Metals to Hydrogen Embrittlement"
ARTC-59-42	ARTC Project W-95 "Standard Method for Evaluation of Susceptibility of Ferrous Metals to Hydrogen Embrittlement" - Naval Research Laboratory Report Regarding Nonembrittling Plating Solutions
ARTC-59-185	Minutes of Final Meeting of Project W-95 "Standard Method for Evaluation of Susceptibility of Ferrous Metals to Hydrogen Embrittlement"