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Report No. FAA-SS-72-68

Bo 87970

SST Technology Follow-On Program-Phase I

AD904766

TITANIUM 3A1-2.5V CW HYDRAULIC TUBING DEVELOPMENT

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D6-68268

October, 1972

(9) FINAL REPORT
Task 2

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Prepared for

(15) DOT-FA-SS-71-12

FEDERAL AVIATION ADMINISTRATION

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Citation Format: Full Citation (1F)

Accession Number:

AD0904766

Citation Status:

Active

Citation Classification:

Unclassified

Fields and Groups:

010309 - Civilian Aircraft
110602 - Fabrication Metallurgy
130700 - Hydraulic and Pneumatic Equipment

Corporate Author:

BOEING COMMERCIAL AIRPLANE CO SEATTLE WA

Unclassified Title:

(U) Titanium 3Al-2.5V CW Hydraulic Tubing Development.

Title Classification:

Unclassified

Descriptive Note:

Final rept. on Task 2,

Personal Author(s):

Harruff, G W
vanderVelden, J
Nelson, W G
Spurr, W
Quist, W

Report Date:

Oct 1972

Media Count:

150 Page(s)

Cost:

\$14.60

Contract Number:

DOT-FA-SS-71-12

Report Number(s):

D6-60260

FAA-SS-72-60

Monitor Acronym:

FAA-SS

Monitor Series:

72-60

Report Classification:

Unclassified

Supplementary Note:

Report on SST Technology Follow-On Program-Phase 1.

Descriptors:

(U) *HYDRAULIC EQUIPMENT, TITANIUM ALLOYS, PIPES, JET TRANSPORT AIRCRAFT, COLD WORKING, MECHANICAL PROPERTIES, SURFACE PROPERTIES, MICROSTRUCTURE, BENDING, MANUFACTURING, SURFACE ROUGHNESS, QUALITY CONTROL, FATIGUE(MECHANICS), SUPERSONIC AIRCRAFT, COMMERCIAL AIRCRAFT, SPECIFICATIONS, FLEXIBLE STRUCTURES, STRESS RELIEVING

Identifiers:

(U) SST TECHNOLOGY FOLLOW ON PROGRAM, SUPERSONIC TRANSPORTS, TITANIUM ALLOY 3AL 2.5V.

Identifier Classification:

Unclassified

Abstract:

(U) This report contains the fatigue, metallurgical, and bend test results on titanium alloy 3Al-2.5V cold worked and stress relieved tubing procured during the prototype supersonic transport test program, and the new texture-controlled tubing. The tubing procured for the prototype program was tested with three different inside-diameter finishes developed by Boeing, Grumman Aerospace, and McDonnell-Douglas. The texture-controlled tubing was developed during this program, and its requirements are defined in the new Boeing-proposed specification, which is included in this report. (Author)

Abstract Classification:

Unclassified

Distribution Limitation(s):

01 - APPROVED FOR PUBLIC RELEASE

Source Serial:

F

Source Code:

390145

Document Location:

DTIC AND NTIS

IAC Assigned Accession Number:

MCIC-087970

Change Authority:

ST-A FAA LTR, 26 APR 77



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DISTRICT	
13	

1. Report No. FAA-SS-72-60		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle SST TECHNOLOGY FOLLOW-ON PROGRAM, PHASE I— Titanium 3Al-2.5V CW Hydraulic Tubing Development			5. Report Date October 1972		
			6. Performing Organization Code		
7. Author(s) G. W. Harruff, J. vanderVelden, W. G. Nelson, W. Spurr, and W. Quist			8. Performing Organization Report No. D6-60260		
9. Performing Organization Name and Address The Boeing Company Commercial Airplane Group P. O. Box 3707 Seattle, Washington 98124			10. Work Unit No.		
			11. Contract or Grant No. DOT-FA-SS-71-12 ✓		
12. Sponsoring Agency Name and Address Federal Aviation Administration Supersonic Transport Office 800 Independence Avenue SW Washington, D. C. 20590			13. Type of Report and Period Covered Final Report, Task 6		
			14. Sponsoring Agency Code		
15. Supplementary Notes Other documents released: D6-60261, D6-60262, D6-60263 and D6-60264.					
16. Abstract This report contains the fatigue, metallurgical, and bend test results on titanium alloy 3Al-2.5V cold worked and stress relieved tubing procured during the prototype supersonic transport test program, and the new texture-controlled tubing. The tubing procured for the prototype program was tested with three different inside-diameter finishes developed by Boeing, Grumman Aerospace, and McDonnell-Douglas. The texture-controlled tubing was developed during this program, and its requirements are defined in the new Boeing-proposed specification, which is included in this report.					
17. Key Words Fatigue Flexure Supersonic Texture Tubing			18. Distribution Statement Approved for U.S. Government only. Distribution of this report outside the U.S. Government must have prior approval of the Supersonic Transport Office.		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 150	
				22. Price	

PREFACE

This is one of a series of final reports submitted under Department of Transportation contract DOT-FA-SS-71-12, task 6, dated June 30, 1971. The report was prepared by the Mechanical Systems Staff organization of The Boeing Company, Commercial Airplane Group, Seattle, Washington.

Test and development work was conducted to establish improved criteria for a proposed new specification for the procurement of improved titanium 3Al-2.5V cold worked and stress relieved tubing.

The success of this effort depended largely on the cooperation which was obtained from engineering personnel at various tubing and airframe manufacturers. This assistance is gratefully acknowledged.

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1.0 INTRODUCTION

Late in 1969, titanium alloy 3Al-2.5V cold worked and stress relieved tubing (Ti-3Al-2.5V CWSR) was selected for use in the hydraulic systems of the two SST prototype aircraft which at that time were nearing production. In 1-1/2 years of work with this new tubing, considerable progress was made in optimizing tube performance and specification controls to ensure reliable performance on the prototype aircraft. It was realized, however, that a number of questions and problems required solution before the tubing could be used for production aircraft. At the time of cancellation of the SST program the following items were in work or recognized as requiring work:

- Tube hollows—Variations in the surface finish, heat treat condition, and micro-structure of the starting stock contributed to variations in the final product. Controls and inspection requirements for the starting stock had to be developed and specified to ensure consistency and predictable performance of tubing.
- Tubing texture—It was suspected that differences in the amount of tube hollow diameter and wall reduction had a great effect on the properties of the tubing. Controlling tube material properties by longitudinal tensile and yield strength alone was believed to be inadequate. At the time there was no technique established to evaluate and control differences in titanium tubing texture.
- Ultrasonic inspection—Hydraulic impulse and flexure test failures of SST prototype tubing indicated the presence of defects which had passed unnoticed through various inspection procedures at both the tubing manufacturer and at Boeing. The defects were suspected to be closed cracks which would not give an echo in ultrasonic testing, or cracks oriented at inappropriate angles to the inspection probes, thereby giving a small echo.
- Finish requirements—Boeing specified chemical milling of the tubing outside diameter (OD) surface to eliminate defects which previously had caused test failures. At the time of the SST cancellation, fatigue cracking had also been noted to originate on the tubing inside diameter (ID) surface, thereby requiring consideration of new finish requirements for the ID as well as for the OD surface.

In view of other work with Ti-3Al-2.5V CWSR tubing which had started at Grumman and McDonnell-Douglas for the F-14 and F-15 aircraft, the following additional items were of interest:

- Different finish requirements—The Lockheed, Boeing, Grumman, McDonnell-Douglas, and North American tubing finish requirements all differ. All have been demonstrated to qualify for hydraulic system use, but no attempt had been made to compare the differences by appropriate tests and to develop a common standard.
- Tubing test and qualification—No commonly agreed upon criteria existed for the evaluation and qualification of hydraulic tubing such as those for hydraulic fittings and hose. New tubing such as 21Cr-6Ni-9Mn CRES and Ti-6Al-4V or Ti-3Al-2.5V were normally being tested with a fitting joint.

During DOT-FA-SS-71-12 task 6 (ref. 1) the following was accomplished:

- Industry and military coordination
- Reporting of SST tubing development up to the time of program cancellation
- Comparison of the SST and other Ti-3Al-2.5V tubing as used by various airframe manufacturers
- Evaluation of tubing with a controlled crystallographic texture
- Improvement of ultrasonic inspection methods
- Draft of a new specification with proposed new or improved criteria for callout by the military or industry.

Work for this program extended over a 9-month period and was divided into two parts. The work under Part I consisted of a review of tubing specifications from other airframe manufacturers, evaluation of four types of tubing, and selection of the one type found to be optimum in fatigue testing. Following this selection, specification criteria were drafted and tubing ordered for work under Part II. This work extended over a 6-month period. Part II consisted of further evaluation of the tubing and specification criteria. In addition, this tubing was used in qualification testing with welded and separable fittings (refs. 2, 3, 4). Part II work was also intended to demonstrate that tube manufacturers understood and complied with the new requirements, and that the new tubing performed satisfactorily in hydraulic performance testing.

2.0 SUMMARY

The following work has been accomplished during this program.

2.1 GENERAL

Existing specifications for Ti-3Al-2.5V cold worked and stress relieved tubing (CWSR) have been compiled and the approach to this program discussed and coordinated with the airframe and tubing manufacturers concerned. Progress and findings have been made known at industry meetings and have been useful to current programs such as F-14, F-15, and B-1, as well as Air Force contracts pertaining to titanium hydraulic fittings and tubing.

2.2 SELECTION OF OPTIMUM TUBING

Four types of tubing currently in use or being considered for use have been evaluated by fatigue testing (120° bend specimens) and by other performance tests.

Various types of Ti-3Al-2.5V CWSR tubing, tube hollows, and semi-finished tubes were evaluated metallurgically to develop a better understanding of the metallurgical factors governing tube performance. The materials were characterized for microstructure, crystallographic texture, surface condition, failure mode, and defect type. Microstructures were evaluated for grain size and morphology. Texture was evaluated by a computerized X-ray pole figure technique, color metallography, and strain ratio (R) measurements. Good correlation between the various techniques was observed. Scanning electron microscopy and macro examination were utilized in characterizing surface condition.

Ultrasonic inspection was improved by developing new standards to detect rejectable defects which are neither longitudinal nor transverse.

Fatigue testing of 120° bend specimens was found to be an excellent method to evaluate and compare the fatigue performance of various tubing types, and to duplicate typical failure modes as are being observed during service of hydraulic tubing.

Residual stresses in the tube such as may be induced by straightening have been limited to a maximum of 15 ksi. A test procedure is specified for this inspection.

The inside and outside finish requirement for the tubing was evaluated and altered to specify 32 RHR as a minimum. In addition the visual appearance was defined as a control of the surface finish. This finish requirement will necessitate the use of ultrasonically agitated internal drawing dies or similar advanced tube fabrication methods. Grit blasting and chemical milling are required for finishing the ID surface and chemical milling for the OD surface.

Criteria for tube hollows were defined on the basis of a survey of tubing and tube hollow manufacturers. These new specification requirements will eliminate unnecessary variations in hollow characteristics such that optimum tube fabrication practices can be standardized.

Quality assurance was provided by the introduction of ultrasonic, penetrant, and visual inspection requirements for the hollows. In addition, permissible defect levels, strength, and microstructural requirements have been defined.

A requirement for drawing of the tubing was specified, since this was observed to improve the tubing surface and open defects which otherwise can go undetected during ultrasonic inspection.

Qualification requirements have been specified for future evaluation and approval of tubing for hydraulic use, in the event that new tube fabrication methods are introduced which deviate from those presently specified.

2.3 PERFORMANCE OF THE NEW TUBING

Two tubing manufacturers, Bishop and Superior Tube Companies, fabricated tubing to the proposed new specification, with the exceptions noted in section 4.0.

Hydraulic impulse testing (80% at 450 F) indicated the superiority of the new tubing. Of 114 specimens made with tubing as originally purchased for SST use, 29 failed. Of 36 specimens made from tubing purchased to the new specification requirements, none failed during 200,000 cycles of impulse testing. The impulse testing is reported in references 2 and 3.

3.0 PART I—EVALUATION OF VARIOUS TUBING

3.1 GENERAL APPROACH

This program was intended to complete work for the SST prototype hydraulic tubing specification for Ti-3Al-2.5V cold worked and stress relieved (CWSR) titanium tubing. In addition, various tubing finishes and processing techniques were to be reviewed and evaluated to develop data for the selection of one standard tubing. Such standardization was regarded to be of mutual interest to manufacturers and users for reasons of cost and interchangeability. This work was programmed to fit with other tasks defined in the DOT/SST follow-on contract (ref. 1). The various tasks were combined into an efficient and economical overall test plan. The tubing work was divided into two parts.

Part I consisted of the following tasks:

- The industry was surveyed and active tubing specifications obtained. Existing differences were discussed to identify them as major or minor. Candidate materials or processes were chosen for testing.
- Four candidates were tested. Three of them differed only in the surface finishes: (1) as specified by Boeing for SST prototype use, (2) as intended by Grumman for the F-14, and (3) as specified by McDonnell-Douglas for the F-15. The tubing required for these tests was drawn from the SST tubing store. The tubing had been fabricated (rocker formed) by Zirtech (Zirconium Technology Corporation) to XBMS 7-234 and to the wall thicknesses specified by Boeing for 4150-psi hydraulic system use. Zirtech also reprocessed this SST tubing for use in this program to the grit blasting and chemical milling requirements of the Grumman specifications and the chemical milling requirements of the McDonnell-Douglas specifications. The fourth (4) candidate material was fabricated by Superior Tube Company as an example of tubing with an improved crystallographic texture.
- The fatigue tests of 120° tube bends were conducted in sizes 3/8 x .020 and 1 x .080 in. Specimens for the crystallographic-texture-controlled tubing could be made available only in the 3/8 x .020 size. More time than the available 3 months would have been required to fabricate and test different sizes and other textures.
- The four candidate materials were evaluated by metallurgical, formability, and fatigue testing. Special emphasis was placed on finding and evaluating various control methods for later inclusion in the specification.
- On the basis of the above-described work, a new specification was drafted and discussed with the tubing manufacturers involved.

Part II consisted of the following tasks, described in detail in section 4.

- Tubing was procured to the new specification and used in the fitting test program described in references 2, 3, and 4. Metallurgical, formability, and fatigue tests were

conducted to further evaluate and confirm the work done under part I, and to finalize the specification criteria.

- Fatigue tests of bend specimens were conducted in the pressure and return line sizes for 3/8- and 1-in. tubing. The tubing was used also in the qualification testing of fittings with tubing sizes and walls as indicated above, and 5/8 x .050 and 5/8 x .021 to investigate the tube performance for a 4150-psi Type III (-65° to 450° F) hydraulic system.

3.2 SURVEY OF EXISTING 3Al-2.5V TUBING SPECIFICATIONS

At the outset of this program the tubing and airframe manufacturers concerned were contacted and their cooperation invited. The response indicated a strong interest in the success of the program. The following company specifications and information were obtained:

- Lockheed, Georgia—STM08, Tubing, Titanium Hydraulic, Ti-3Al-2.5V, Rev. B, dated 11-18-68

This tubing is used in a portion of the high-pressure hydraulic system of several C-5 aircraft. It is cold worked and stress relieved, and used with flareless fittings having a swaged-on sleeve.

- Boeing—XBMS 7-234, Titanium 3Al-2.5V Seamless Tubing for Hydraulic Systems, Cold Worked and Stress Relieved, dated 10-7-70

As the finish requirement, chemical milling of the OD surface was specified. In addition, various polishing or grinding processes were recognized as type I, II, III, and IV prior to chemical milling. Type I was selected as the optimum performer based on fatigue testing. The specification also included a requirement to limit residual stresses caused by straightening.

At the time of the SST cancellation, test data indicated that chemical milling of the ID surface would be required, as well as a revision of ultrasonic inspection to control defects with an orientation neither longitudinal nor transverse.

- Grumman—GM 3107 Titanium 3Al-2.5V Tubing Seamless, Cold Worked and Stress Relieved, dated 9-4-70

Nearly identical specifications existed at Boeing and Grumman: Boeing BMS 7-203 and Grumman GM 3107. These two specifications were changed in 1970 to delete the shot peening requirement in an attempt to permit easier detection of defects in ultrasonic inspection. Deletion of peening of the outside and concern regarding the inside diameter necessitated later on the introduction of grit blasting and chemical milling as finish for the tubing.

This tubing was intended for use on the F-14. At the time of the survey, Grumman changed the F-14 hydraulic tubing to annealed in lieu of cold worked Ti-3Al-2.5V tubing. With that change, Grumman specified a new grit blasting plus chemical milling finish for the annealed tubing which was not shown in the specification for cold worked tubing. Grumman

staff personnel recommended that for the DOT/SST follow-on program their new grit blast plus chemically milled finish be tried for cold worked tubing. This recommendation was accepted.

- McDonnell-Douglas—MMS 1205, Titanium Seamless Tubing, Cold Worked and Stress Relieved, 3Al-2.5V, Aircraft Hydraulic System Preliminary Revision B, dated 9-8-71

Chemical milling of the inside and outside surfaces was specified for the surface finish of this tubing. Of special interest to the program was the prestressing treatment specified by McDonnell-Douglas after fittings are attached.

- North American STO 170 LB 0017—Titanium 3Al-2.5V Cold Worked and Stress Relieved Tubing, dated 10-12-70

This specification was drafted for B-1 use. As surface finish, a 32 RHR roughness limit is specified without specific processing requirements such as for chemical milling. This specification also contains a requirement for penetrant inspection.

Detailed differences between these specifications are listed in table 1.

The tubing evaluated in part I of this program is listed in table 2. The 1 x .080 and 3/8 x .020 in. sizes (numbered tube 1 through tube 6) were procured during the SST prototype test program and tested with three different ID finish processes. The first was in accordance with the Boeing Materials Specification, XBMS 7-234, Type I (ref. 5) used for the SST prototype. This surface finish is essentially as-processed, and only flash pickled, with no grit blasting or chemical milling specified. The second ID finish is that specified by McDonnell-Douglas, chemical milling (0.0005-in. surface removal) followed by pressurization to four times the working pressure for 30 seconds. The final ID treatment was that specified by Grumman Aerospace Corporation—a grit blast (0.0005 in. surface removal) followed by a 0.0005-in. chemical milling operation. The 3/8 x .020 size tubing (tubes 7 and 8) procured during the DOT/SST Technology Follow-On test program was made by Superior Tube Company per the specification XBMS 7-234, Type I, except that an attempt was made to optimize the crystallographic texture. Also, the ID was grit blasted and pickled. Prior to this finishing treatment the tubing had been drawn using an ultrasonically agitated mandrel die.

3.3 SURFACE CONDITION

The surface roughness on the OD and ID surfaces of tubes 1 through 6 was determined using a profilometer. The results are shown in table 3. These surface measurements indicate that the ID surface roughness is not improved by chemical milling alone; it is improved by grit blasting and subsequent chemical milling. The surface condition of the various tubes was studied further using the wide-field microscope and macrophotography. The 3/8 x .020-in. Zirtech tube OD surfaces displayed a severely pickled, rough appearance, as shown in figure 1a. The 3/8 x .020-in. Superior tubes displayed a much smoother OD surface than did the Zirtech tubes but did show residual sanding marks (see fig. 1b). The ID surface of the as-received SST tubing (tube 4, Zirtech) displayed a very rough and rutted appearance. The

TABLE 1.—COMPARISON OF TITANIUM 3Al-2.5V TUBE SPECIFICATIONS

A. Ti-3Al-2.5V Cold Worked and Stress Relieved

Company	Boeing	Grumman	McDonnell Douglas																														
Specification no.	XBMS 7-234, dated 10-7-70	GMPS 3107, dated 9-4-70	MMS 1205 (rev. B-prelim), dated 9-8-71																														
Tested for or used on	SST	F 14 prior to 9-15-70	F 15																														
Physical properties																																	
Longitudinal F _{tu}	125,000 psi min	125,000 psi min	(For tubing classification see F _{ty}) CWSR 70—85,000 min, 105,000 max CWSR 95—100,000 min, 120,000 max CWSR 105—125,000 min, 145,000 max																														
F _{ty} at 2% offset	105,000 psi min	105,000 psi min	Tubing classified as follows: CWSR 70—70,000 psi min yield CWSR 95—95,000 psi min yield CWSR 105—105,000 psi min yield																														
Elongation in 2 in. (%) min	10%	10%	CWSR 70—15.0% CWSR 95—13.0% CWSR 105—10.0%																														
Bending	3 x OD	5 x OD	3 x <i>o</i> b																														
Flattening	14 x nom WT	—																															
Circumferential Flaring	ASTM B 338, 1.2 x OD	MS 33584	MS 33584																														
Residual hoop stress	15,000 psi max	—	—																														
Surface finish and defects	ID RHR 63, OD RHR 32 Type I Chem mill 0.002 in. from OD surface, no abrasives Type II Cork belt polish and then chem mill 0.002 in. from OD surface, no abrasives. Type III Sand with 400 or finer grit and then chem mill 0.002 in. from OD surface Depth of defects shall be in conformance with class A-2 and B-3 standards per BAC 5439-2. Class A-2 (depth .002 in. by .060 in. long) for WT ≤ .046. Class B-3 (depth .003 in. by 125 in. long) for WT > .046.	ID RHR 63, OD RHR 32 When specified by purchase order shot peened per specification GSS 5310 <table><tr><th>Nom. WT (in.)</th><th>Max defect depth (in.)</th></tr><tr><td>Up to .030</td><td>0.002</td></tr><tr><td>.031 to .040</td><td>0.0025</td></tr><tr><td>.041 to .050</td><td>0.003</td></tr><tr><td>.051 to .066</td><td>0.004</td></tr><tr><td>.067 to .086</td><td>0.006</td></tr></table> All tubing shall be 100% eddy current inspected or ultrasonically inspected. A reference notch 1/8 in. long times applicable defect depth shall be used.	Nom. WT (in.)	Max defect depth (in.)	Up to .030	0.002	.031 to .040	0.0025	.041 to .050	0.003	.051 to .066	0.004	.067 to .086	0.006	ID RHR 63, OD RHR 32 After final reduction, tubing shall be pickled to remove a minimum of 0.002 in. from OD surface and a minimum of 0.001 inch from ID See  for surface conditioning prior to pickling Tubing shall meet the following ultrasonic inspection defect limits <table><tr><th>Nom. WT (in.)</th><th colspan="2">Max defect size, (in.)</th></tr><tr><th></th><th>Depth</th><th>Length</th></tr><tr><td>.045 and smaller</td><td>0.002</td><td>0.060</td></tr><tr><td>.046 thru .060</td><td>0.002</td><td>0.125</td></tr><tr><td>.061 thru .080</td><td>0.003</td><td>0.125</td></tr><tr><td>.081 thru .100</td><td>0.004</td><td>0.125</td></tr></table> Ultrasonic inspection per MCAIR P.S.21211.2, Class AA	Nom. WT (in.)	Max defect size, (in.)			Depth	Length	.045 and smaller	0.002	0.060	.046 thru .060	0.002	0.125	.061 thru .080	0.003	0.125	.081 thru .100	0.004	0.125
Nom. WT (in.)	Max defect depth (in.)																																
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.081 thru .100	0.004	0.125																															
Dimensional tolerances																																	
Straightness	0.025 in./ft and not more than 0.125 in any 5-ft length	0.025 in./ft and not more than 0.125 in. in any 5-ft length	0.090 in. maximum in any 3 ft length																														
Wall thickness	±7 1/2%	±10%	±10%																														
Diameter	<table><tr><th>Nom OD (in.)</th><th>Tolerance (in.)</th></tr><tr><td>0.188 to 0.499</td><td>+0.004—0.000</td></tr><tr><td>0.500 to 0.999</td><td>+0.005—0.000</td></tr><tr><td>1.000 to 1.499</td><td>+0.007—0.000</td></tr><tr><td>1.500 to 2.000</td><td>+0.010—0.000</td></tr></table>	Nom OD (in.)	Tolerance (in.)	0.188 to 0.499	+0.004—0.000	0.500 to 0.999	+0.005—0.000	1.000 to 1.499	+0.007—0.000	1.500 to 2.000	+0.010—0.000	<table><tr><th>OD (in.)</th><th>Tolerance (in.)</th></tr><tr><td>0.188 to 0.500 incl.</td><td>+0.004—0.000</td></tr><tr><td>0.501 to 1.500 incl.</td><td>+0.005—0.000</td></tr><tr><td>1.501 to 2.499 incl.</td><td>+0.006—0.000</td></tr></table>	OD (in.)	Tolerance (in.)	0.188 to 0.500 incl.	+0.004—0.000	0.501 to 1.500 incl.	+0.005—0.000	1.501 to 2.499 incl.	+0.006—0.000	<table><tr><th>OD (in.)</th><th>Tolerance (in.)</th></tr><tr><td>Up to 3/32</td><td>+0.002—0.000</td></tr><tr><td>3/32 to 2 1/2</td><td>+0.003—0.000</td></tr></table>	OD (in.)	Tolerance (in.)	Up to 3/32	+0.002—0.000	3/32 to 2 1/2	+0.003—0.000						
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3/32 to 2 1/2	+0.003—0.000																																
Ovality	Same as noted for diameter tolerances listed above	Same as noted for diameter tolerances listed above	Same as noted for diameter tolerances listed above																														

TABLE 1.—Continued
A. Ti-3Al-2.5V Cold Worked and Stress Relieved—Continued

Company	North American	Lockheed Georgia	Proposed Aerospace Material Specification																								
Specification no.	STO 170 LB 0017, dated 10-12-70	STM08-303, dated 11-18-68 (rev. B)	AMS 4944, coordination copy, dated January 7																								
Tested for or used on	B-1	C-5	—																								
Physical properties																											
Longitudinal																											
F_{tu}	125,000 psi min	1/4 and 3/8 tubes, 120,000 psi min Tube sizes over 3/8, 125,000 psi min	125,000 psi min																								
F_{ty} at 2% offset	105,000 psi min	1/4 and 3/8 tubes, 90,000 psi min Tube sizes over 3/8, 95,000 psi min	105,000 psi max																								
Elongation in 2 in. (%) min	10%	10%	10%																								
Bending	5 x OD	5 x OD	—																								
Flattening	12 x nom WT	12 x nom WT	—																								
Circumferential																											
Flaring	—	—	1.2 x OD																								
Residual hoop stress	—	—	—																								
Surface finish and defects	RHR 32 max as defined by ASA-B46.1  Light belt polishing permitted provided 0.003 in. is removed after polishing by chemical etching. Prior to ultrasonic all tubing penetrant inspected to MIL-I-6866 type I, method A. Defects on either inside or outside surfaces exceeding 5% of WT in depth or 0.002 in., whichever is greater, and 5/64 in. in length, as determined by ultrasonic inspection, shall be rejected.	Shot peened with cast steel shot per MIL-S-13165B Surface finish prior to peening: ID RHR 63 OD RHR 32 Sand blasting or vapor honing may be used on ID For maximum depth of discontinuities see 	External and internal surface imperfections such as handling marks, straightening marks, light mandrel and die marks, shallow pits, seams, scores, and scale pattern will not be considered injurious provided they are within following allowances: Surface finish: ID 63 RHR, OD 32 RHR <table><thead><tr><th>WT (in.)</th><th>Max defect depth (in.)</th></tr></thead><tbody><tr><td>Up to .030 incl.</td><td>0.002</td></tr><tr><td>.031 to .040 incl.</td><td>0.0025</td></tr><tr><td>.041 to .050 incl.</td><td>0.003</td></tr><tr><td>.051 to .066 incl.</td><td>0.004</td></tr><tr><td>.067 to .086 incl.</td><td>0.006</td></tr></tbody></table> Method of test shall be as agreed between purchaser and vendor	WT (in.)	Max defect depth (in.)	Up to .030 incl.	0.002	.031 to .040 incl.	0.0025	.041 to .050 incl.	0.003	.051 to .066 incl.	0.004	.067 to .086 incl.	0.006												
WT (in.)	Max defect depth (in.)																										
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.041 to .050 incl.	0.003																										
.051 to .066 incl.	0.004																										
.067 to .086 incl.	0.006																										
Dimensional tolerances																											
Straightness	0.075 in. max in any 3-ft length	0.090 in. max in 3 ft	—																								
Wall thickness	±10%	1/4 OD through 5/8 OD, ±10% 3/4 OD, 1 OD & 1 1/4 OD, ±.003	±10%																								
Diameter	<table><thead><tr><th>Nom OD (in.)</th><th>Tolerance (in.)</th></tr></thead><tbody><tr><td>0.250 thru 0.750</td><td>+0.003 -0.000</td></tr><tr><td>0.751 thru 1.250</td><td>+0.003 -0.001</td></tr><tr><td>0.251 thru 1.500</td><td>+0.004 -0.001</td></tr></tbody></table>	Nom OD (in.)	Tolerance (in.)	0.250 thru 0.750	+0.003 -0.000	0.751 thru 1.250	+0.003 -0.001	0.251 thru 1.500	+0.004 -0.001	<table><thead><tr><th>Nom OD (in.)</th><th>Tolerance (in.)</th></tr></thead><tbody><tr><td>0.188 to 0.500</td><td>+0.004 -0.000</td></tr><tr><td>0.501 to 1.500</td><td>+0.005 -0.000</td></tr><tr><td>1.501 to 2.500</td><td>+0.006 -0.000</td></tr></tbody></table>	Nom OD (in.)	Tolerance (in.)	0.188 to 0.500	+0.004 -0.000	0.501 to 1.500	+0.005 -0.000	1.501 to 2.500	+0.006 -0.000	<table><thead><tr><th>Nom OD (in.)</th><th>Tolerance (in.)</th></tr></thead><tbody><tr><td>0.188 to 0.500</td><td>+0.004 -0.004</td></tr><tr><td>0.500 to 1.000</td><td>+0.005 -0.005</td></tr><tr><td>1.000 to 1.500</td><td>+0.007 -0.007</td></tr></tbody></table>	Nom OD (in.)	Tolerance (in.)	0.188 to 0.500	+0.004 -0.004	0.500 to 1.000	+0.005 -0.005	1.000 to 1.500	+0.007 -0.007
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1.000 to 1.500	+0.007 -0.007																										
Ovality	Same as noted for diameter tolerance listed above.	Same as noted for diameter tolerances listed above.	—																								

TABLE 1.—Continued
B. Ti-3Al-2.5V Annealed

Company	Boeing	Grumman	Proposed Aerospace Material Specification																										
Specification no.	BMS 7-203B, dated 11-10-70	GM 3118, dated 5-4-71	AMS 4943																										
Tested for or used on	SST and 747	F-14	—																										
Physical properties																													
Longitudinal																													
F_{tu}	90,000 psi min	90,000 psi min 110,000 psi max	90,000 psi min																										
F_{ty} at 2% offset	74,000 psi min	75,000 psi min 95,000 psi max	75,000 psi max																										
Elongation in 2 in. (%)	15% min	15%	15%																										
Bending	2 x OD	3 x OD	—																										
Flattening	—		—																										
Flaring	—	1.4 x OD	—																										
Residual hoop stress	—	—	—																										
Surface finish and defects	ID RHR 63, OD RHR 32 Grinding of surface is not acceptable. Sanding, buffing, or polishing with a soft backing is acceptable. A minimum of 0.002 in. shall be removed by chemical milling from OD surface after sanding, polishing, and buffing. <table><tr><td><u>Nom WT (in.)</u></td><td><u>Max defect depth (in.)</u></td></tr><tr><td>Up to .060</td><td>0.002</td></tr><tr><td>.061 to .080</td><td>0.003</td></tr><tr><td>.081 to .100</td><td>0.004</td></tr><tr><td>.101 to .120</td><td>0.005</td></tr><tr><td>.121 and over</td><td>0.006</td></tr></table> 	<u>Nom WT (in.)</u>	<u>Max defect depth (in.)</u>	Up to .060	0.002	.061 to .080	0.003	.081 to .100	0.004	.101 to .120	0.005	.121 and over	0.006	ID RHR 63, OD RHR 32 Tube OD shall show a uniformly pickled surface finish (minimum of 0.0005 in. per surface shall have been chemically removed as a finishing operation). Soft belt polishing prior to pickling operation is permissible, but all traces of polishing marks shall be removed by subsequent pickle. Tube ID shall show a uniform matte finish and shall be achieved by grit blasting followed by a subsequent pickling operation to remove a minimum of 0.0005 in. per surface <table><tr><td><u>Nom WT (in.)</u></td><td><u>Max defect depth (in.)</u></td></tr><tr><td>Up to .060</td><td>0.002</td></tr><tr><td>.061 to .080</td><td>0.003</td></tr><tr><td>.081 to .100</td><td>0.004</td></tr></table> (a)	<u>Nom WT (in.)</u>	<u>Max defect depth (in.)</u>	Up to .060	0.002	.061 to .080	0.003	.081 to .100	0.004	"External and internal surface imperfections such as handling marks, straightening marks, light mandrel and die marks, shallow pits, seams, scores and scale pattern will not be considered injurious provided the imperfections are removable within the tolerances specified herein for wall thickness." No RHR requirements were noted. No ultrasonic inspection was specified.						
<u>Nom WT (in.)</u>	<u>Max defect depth (in.)</u>																												
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Straightness	0.025 in./ft and not more than 0.125 in. in any 5-ft length	0.025 in./ft and not more than 0.125 in. in any 5-ft length.	—																										
Wall thickness	±10%	±10%	±10%																										
Diameter	<table><tr><td><u>Nom OD (in.)</u></td><td><u>Tolerance (in.)</u></td></tr><tr><td>0.188 to 0.499</td><td>+0.004 -0.000</td></tr><tr><td>0.500 to 0.999</td><td>+0.005 -0.000</td></tr><tr><td>1.000 to 1.499</td><td>+0.007 -0.000</td></tr><tr><td>1.500 to 2.000</td><td>+0.010 -0.000</td></tr></table>	<u>Nom OD (in.)</u>	<u>Tolerance (in.)</u>	0.188 to 0.499	+0.004 -0.000	0.500 to 0.999	+0.005 -0.000	1.000 to 1.499	+0.007 -0.000	1.500 to 2.000	+0.010 -0.000	<table><tr><td><u>Nom OD (in.)</u></td><td><u>Tolerance (in.)</u></td></tr><tr><td>0.188 to 0.500</td><td>+0.004 -0.000</td></tr><tr><td>0.501 to 1.500</td><td>+0.005 -0.000</td></tr><tr><td>1.501 to 2.500</td><td>+0.006 -0.000</td></tr></table>	<u>Nom OD (in.)</u>	<u>Tolerance (in.)</u>	0.188 to 0.500	+0.004 -0.000	0.501 to 1.500	+0.005 -0.000	1.501 to 2.500	+0.006 -0.000	<table><tr><td><u>Nom OD (in.)</u></td><td><u>Tolerance (in.)</u></td></tr><tr><td>0.188 to 0.500</td><td>+0.004 -0.004</td></tr><tr><td>0.500 to 1.000</td><td>+0.005 -0.005</td></tr><tr><td>1.000 to 1.500</td><td>+0.006 -0.006</td></tr></table>	<u>Nom OD (in.)</u>	<u>Tolerance (in.)</u>	0.188 to 0.500	+0.004 -0.004	0.500 to 1.000	+0.005 -0.005	1.000 to 1.500	+0.006 -0.006
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Ovality	Same as noted for diameter tolerances listed above.	Same as noted for diameter tolerances listed above.	—																										

*Tubing ultrasonically inspected with standards having a reference notch 1/8 in. long +5%, 0.010 wide and a depth as specified for the cold worked tubing.

TABLE 1.—Concluded

1 Flattening Tests (McDonnell-Douglas)

Specimens of the full section of the tube not less than two inches in length shall be cut from tubes selected in accordance with the sampling plan. The tube specimens shall be flattened between parallel plates under a gradual load applied perpendicularly to the longitudinal axis until the distance between the plates is not greater than that specified in the table below. After examination of the outside surfaces, the samples shall be split longitudinally and the inside surfaces examined. The inside and outside surfaces shall be free from cracks, tears, breaks or opened die or polishing marks when examined at 3 to 5 x magnification.

Flattening Factors

Outside diameter to wall thickness ratio, OD/t	Distance between plates where t = wall thickness
10 or less	7t
11 to 16	12t
17 to 30	15t
31 to 50	17t

2 Surface Conditioning Prior to Pickling (McDonnell-Douglas)

Intermediate mechanical conditioning prior to final pickling is permissible within the following limits:

- Centerless grinding of the outside surfaces is not acceptable.
- Light belt polishing or buffing of the outside diameter surfaces is permissible with a grit size of 400 or less.
- Light grit blasting of the inside diameter surfaces is permissible with a grit size of 100 or less.
- Belt polishing, buffing and grit blasting operations are not acceptable after final pickling.

3 Depth of Discontinuities (Lockheed-Georgia)

The maximum depth of individual discontinuities shall not exceed the limits specified below. The specified limits are applicable only to discontinuities removable without violating the OD and wall thickness tolerances specified.

Depth of Discontinuities

Nom wall thickness (in.)	Max depth of discontinuities (in.)
.020 and under	10% of nominal wall thickness or .001 whichever is greater.
.021 through .030	.002
.031 through .040	.0025
.041 through .050	.003
.051 through .066	.004
.067 through .085	.006

Discontinuities having a depth equal to or less than the limits specified shall be removed from the exterior surfaces of the tubing, except that discontinuities, having large root radii plainly visible to the unaided eye and whose surfaces blend smoothly into the normal tubing surface, need not be removed. Removal shall be accomplished by light belt polishing and buffing; grit blasting or centerless grinding with hard wheels shall not be used.

Note: No ultrasonic inspection was specified. Some eddy current inspection was done by the tube manufacturer for their own satisfaction.

4 Maximum Depth of Defects (Boeing)

A defect on the outside surface of tubing may be removed by sanding, polishing, and buffing prior to chemical milling as applicable, to bring the defect into conformance with the allowable noted defect requirements, providing the finished tubing remains within dimensional tolerance in the areas from which the defect was removed.

Inspection of Finished Tubing (Boeing)

Finished tubing shall be inspected for inside and outside defects per the requirements of BAC 5439-2. Depth of the standard notch shall be in conformance with the maximum defect limits shown. Length of the standard shall be 0.060 for wall thickness less than 0.046 inch and shall be 0.125 inch for wall thickness 0.046 or greater.

5 Reverse Flattening Test (Grumman)

A representative sample of tubes from each lot shall be subjected to a reverse flattening test to examine the ID surface condition. Specimens approximately 3" long shall be sectioned longitudinally along the diameter and one half flattened between parallel plates until the distance between the plate is essentially equal to the wall thickness of the tube sample. The flattened sample shall then be examined under fluorescent lighting at 30x magnification. Evidence of ID imperfections (see GAC supplied standards) shall be cause for provisional rejection of the lot.

6 (North American)

The surface requirements are presently being revised to have the ID RHR 63 and the OD RHR 32.

TABLE 2.—TUBING TESTED FOR PART I

Tube no.	Tube size OD and WT (in.)	Manufacturer and heat number	Tubing specification and ID finish requirements
1	1 x .080	Reactive Metals, Inc. Niles, Ohio HT304450-03	XBMS 7-234 ^a
2	1 x .080	Reactive Metals, Inc. Niles, Ohio HT 304450-03	XBMS 7-234 ^a , except the ID pickled ^b to remove 0.0005 in. from each surface. Note: This ID finishing process is used by McDonnell-Douglas Airplane Division, Sept. 1971.
3	1 x .080	Reactive Metals, Inc. Niles, Ohio HT 304450-03	XBMS 7-234 ^a , except the ID was grit blasted (size 60 to 120 grit) to remove 0.0005 to 0.0010 in. from each ID surface. After grit blast, the ID was pickled ^b to remove 0.0005 in. from each surface. Note: This ID finishing process is used by Grumman Aerospace Corporation, Sept. 1971
4	3/8 x .020	Zirconium Technology Albany, Oregon BF 10059	XBMS 7-234 ^a
5	3/8 x .020	Zirconium Technology Albany, Oregon BF 10059	XBMS 7-234 ^a , except the ID was pickled ^b to remove 0.0005 in. from each surface. Note: This ID finishing process is used by McDonnell-Douglas Airplane Company.
6	3/8 x .020	Zirconium Technology Albany, Oregon BF 10059	XBMS 7-234 ^a , except the ID was grit blasted (size 60 to 120 grit) to remove 0.0005 to 0.0010 in. from each ID surface. After grit blast, the ID was pickled ^b to remove 0.0005 in. from each surface. Note: This ID finishing process is used for Grumman Aerospace Corp for annealed tubing.
7	3/8 x .020	Superior Tube Norristown, Pa. HT 304450	XBMS 7-234, except with special crystallographic texture. In addition, the ID was grit blasted and pickled. The metal removal was approximately 0.0005 in. for each operation.
8	^c 5/8 x .040	Superior Tube Norristown, Pa.	Same as tube 7

^aAs processed for the SST prototype airplane.

^bThe composition of the pickling solution is:

60 gal water

15 gal nitric acid

2 gal hydrofluoric acid

^cNonstandard size, used only for metallurgical analysis

chemical milling of this surface (tube 5, Zirtech) showed some improvement. Further improvement was evident in tubes that had been grit blasted prior to chemical milling (tube 6). The ID surface of the Superior tubing (tube 7) showed the same appearance as tube 6 (fig. 2).

TABLE 3.—SURFACE ROUGHNESS OF TUBES

Tube no. ^a	Tube size (in.)	RHR Value	
		OD surface	ID surface
1	1 x .080	15	60
2	1 x .080	20	60
3	1 x .080	17	30
4	3/8 x .020	65	^b 50
5	3/8 x .020	60	^b 50
6	3/8 x .020	65	^b 40
7	3/8 x .020	10	20
8	5/8 x .040	14	18

^aSee table 2 for manufacturer, specification, and ID finish

^bThe quantitative accuracy may have been affected by probe malfunction.

Scanning electron micrographs were taken on the ID surface of tubes 4 and 6 to determine the difference between as-processed, and grit blasted and chemically milled surfaces. The results, shown in figures 3 and 4, illustrate the improved finish resulting from the grit blasting and chemical milling treatment. These effects are particularly noticeable when the electron beam is oriented in the longitudinal (or axial) direction of the tube.

The 1 x .080 in. tubes all displayed approximately the same OD surface. Under visual examination at 10 times magnification similar pits, nicks, and scratches were visible which in high-stress fatigue testing tend to become origins for fatigue cracking. The chemical milling and grit blasting plus chemical milling treatments of the ID resulted in progressive improvements over the as-received finish. The ID surface of the 1 x .080 in. tubing did not show ruts and similar gross defects as had been observed in visual inspection of the 3/8 x .020 in. as-received tubing (tube 4).

3.4 MICROSTRUCTURE

The microstructure and surface roughness of tubes 1 through 6 was photographed at 500X. The Ti-3Al-2.5V tubes possessed a fine, equiaxed structure and showed considerable cold work in the transverse direction (fig. 5 and 6). In these photographs it may also be noted that the ID surface condition of the tubes appeared to improve considerably for the grit blasted and chemically milled condition but did not differ noticeably between the chemically milled and the as-processed tubing.

Color anodizing of titanium has been used by Boeing over the past several years as a method of studying crystallographic texture and texture banding. With this method it is possible to access the preferred crystallographic texture of titanium. The method is based on the observation that grains with a basal texture do not develop an oxide layer during anodizing as quickly as do grains with other orientations. This technique has been used with considerable success on plate and forgings to evaluate texture banding, but has not been previously attempted for tubing. Experimentation for this program indicated that:

- The tubing is not texture-banded (i.e., the microstructure did not contain banded regions of similarly oriented grains.)
- The grain size and orientations found were not sufficiently different for a texture analysis by color anodizing. The grain sizes tend to be too small, and crystals of similar orientation are too well dispersed.

3.5 RESIDUAL STRESS

The residual stresses in tubes 1, 4, 7, and 8 were measured using the method outlined in XBMS 7-234A (appendix A). Several additional samples were also analyzed with these tubes to provide additional information regarding the scatter obtained (see table 4).

The materials specification calls for a maximum stress of ± 15.0 ksi; thus, most tubes meet the required values. Tubes 8, (B), and (E) were above the desired values but were not used extensively during the present investigation. High residual stress values are thought to be caused by excessive straightening and may result in a degradation of fatigue properties.

TABLE 4.—RESIDUAL STRESS IN TUBES

Tube no.	Tube size (in.)	Residual stress (ksi)	Manufacturer	Heat no.
1	1 x .080	13.4	Reactive Metals	HT304450-03
4	3/8 x .020	-5.5	Zirtech	BF10059
7	3/8 x .020	14.3	Superior	HT304450
8	5/8 x .040	19.9	Superior	HT304450
(B)	3/8 x .030	26.3	Zirtech	BF10050
(E)	5/8 x .021	35.8	Zirtech	BF07058
(F)	5/8 x .050	-4.3	Zirtech	BF07058
(D)	1 x .033	-0.6	Reactive Metals	HT294804-23
(G)	1 x .033	-1.2	Reactive Metals	HT294804-24
(H)	1 x .033	4.2	Reactive Metals	HT304042-22

^a See table 2 for specification and finish requirements.

The residual stress in tubes 2 and 3, noted in table 2, should have the same value as those for tube 1.

The residual stress in tubes 5 and 6, noted in table 2, should have the same value as those for tube 4.

^b Samples selected from random tubes with additional wall thicknesses, sizes, and heats.

3.6 TUBING TEXTURE

3.6.1 Metallurgical Considerations

The mechanical and physical properties of many hexagonal-close-packed materials can be varied over broad ranges by the control of crystallographic texture. In seamless tubing applications, texture control has been applied in zirconium tubing technology to control the deleterious effects of hydride precipitates. Similarly, burst strengths and forming characteristics are improved by a favorable orientation of basal planes. The control of crystallographic texture in titanium tubing has not been made an integral part of tubing manufacturing technology, although preliminary evidence indicates that substantial improvements in many important properties could be obtained for titanium tubing.

The deformation characteristics of titanium are such that forming treatments produce an anisotropic texture. Judicious control of the metal working and annealing will result in particular textures being developed. In the manufacture of seamless titanium tubing it has been found that texture will usually vary between circumferential and radial orientations of the basal plane poles of the titanium unit cell (fig. 7). Severely textured material will normally be found to have one of these two basic textures. Investigations performed to date on zirconium and titanium tubing have demonstrated that the radial texture will cause an optimization of most properties important to aircraft hydraulic tubing. The radial texture affects the tubing properties as follows:

- It minimizes wall thinning during bending. Diameter reduction is the deformation mode.
- It maximizes the biaxial strength of the tube (circumferential and axial). This gives improved burst strengths.
- It maximizes the fracture resistance for flaws normal to the tube surface.
- It improves the fatigue resistance of tubes by increasing the biaxial strength of the tube, and by minimizing wall thinning in bends.

The circumferential texture results in properties almost the exact opposite of the above. Deformation is by wall thinning rather than by diameter reduction, and the circumferential strength is maximized (which minimizes toughness for defects oriented parallel to the axial directions).

The preferred radial texture in tubes is developed by manufacturing the tubes from controlled starting stock, such that a large degree of wall reduction takes place compared to the amount of diameter reduction. This value is called the T-ratio and is given as follows:

$$\text{T-ratio} = \frac{W/W_o}{OD/OD_o}$$

where:

W = Wall thickness of tube

W_o = Wall thickness of hollow

OD = Outside diameter of tube

OD_o = Outside diameter of hollow

High T-ratios (greater than 1.0) tend to give radial textures. Low T-ratios tend toward the circumferential crystallographic texture.

The actual texture produced in a tube can be measured by several different methods. The most accurate method available is X-ray diffraction, where the actual orientation of basal planes is measured and plotted as a stereographic projection pole figure plot. Unfortunately this technique is time consuming, relatively expensive, and requires special equipment, and therefore does not lend itself well to production applications. Several other methods, including hardness measurements and special metallographic techniques, are also available to measure texture in titanium tubes. However, the fastest and most straightforward technique appears to be direct measurement of the degree of wall and diameter reduction associated with the tensile testing of a tube. The advantage of this technique is that it utilizes two of the basic mechanical properties affected most by texture variations. The values derived from this test are called R-ratios and are determined as indicated in figure 8. High R-ratios indicate the desired radial texture (little wall thinning and relatively large diameter reduction) and low R-ratios the circumferential texture.

T-ratios and R-ratios generally move in concert; high T-ratios during the manufacture of a tube will be reflected in high R-ratios during the testing of the tube, and vice versa. This phenomenon has been observed experimentally in zirconium alloys and titanium alloys.

3.6.2 R-Ratio and Pole Figure Data

Crystallographic texture studies were performed on all tubes tabulated in the residual stress study (table 3) to relate manufacturing methods, tube size, and texture to the resulting mechanical and fatigue properties. The texture of each tube was determined by X-ray diffraction techniques and by mechanical test (R values). The X-ray diffraction results are shown in figures 9 through 18.

The X-ray texture evaluations indicate that the higher the ratio of wall reduction to diameter reduction during manufacture, the more advantageous is the resulting texture of the tube. The most desirable texture is considered to be that represented by basal plane poles perpendicular to the surface of tube; i.e., radial texture. For this case, burst strength is improved, deformation is by diameter reduction rather than wall reduction, fracture toughness is improved for flaws oriented in the axial direction, and fatigue properties are optimized. Considering the presently used tube fabrication techniques it is observed that thin-walled, large-diameter tubes tend to have the best texture and heavy-walled small-diameter tubes the worst.

Tubes manufactured by Zirtech and Reactive Metals, Inc. (RMI) are produced by tube-reducing mills (Pilger mills) whereas Superior used tube drawing techniques. The pole figure analysis indicated that the 3/8 x .020 in. Superior tubing had a better texture than did the 3/8 x .020 in. Zirtech product.

R-ratio measurements were made from fractured tube tensile specimens. Measurements were taken in conformance with Boeing Materials Specification XBMS 7-234A (appendix A). This ratio involves a measurement of the degree of wall thinning and diameter reduction after a tensile test. This method specifies "after test" measurements to be made midway between the fracture surface and the beginning of the neck-down region (see fig. 8). R values were derived for tubes 1 through 7 and the results are shown in table 5. The R-ratios established in this manner have a qualitative correlation with the pole figure plots shown in figures 9 through 18. In the 3/8-in.-diameter samples the crystallographic texture of the Superior tube was better than for the Zirtech. The 1-in. diameter RMI tube also displayed a favorable crystallographic texture.

TABLE 5.—STRAIN RATIO OF VARIOUS TUBES TESTED IN PART I

Tube no. ^a	Tube size (in.)	Strain ratio, R ^b	Manufacturer	Heat no.
^c 1	1 x .080	^d 0.70	Reactive Metals	HT304450-03
^c 1	1 x .080	^d 1.115	Reactive Metals	HT304450-03
^c 1	1 x .080	^e 0.78 & 0.92	Reactive Metals	HT304450-03
^f 4	3/8 x .020	^c 0.402	Zirtech	BF10059
4	3/8 x .020	^c 0.508	Zirtech	BF10059
7	3/8 x .020	^c 0.730	Superior	304450
7	3/8 x .020	^c 0.940	Superior	304450

^aSee table 2 for specification and finish requirements.

$$^bR = L_n(OD_f/OD_o) \div L_n(W_f/W_o)$$

^cTubes 2 and 3, as noted in table 2, are identical to tube 1, except for ID surface finish.

^dBoeing measurement method:

All measurements were made with a micrometer.

The final dimensions were measured approximately halfway between the fracture surface and the point where uniform elongation ends.

^eSuperior Tube Company measurement methods (sample sent to Superior)

The 0.92 value was determined by using a vitagage for the measurements.

The 0.78 value was determined by using a micrometer for the measurements.

The same vitagage calibration setting was used for measuring the dimensions before and after the test. The final measurements were taken about 0.25 in. from the fracture.

^fTubes 5 and 6, as noted in table 2, are identical to tube 4, except for ID surface finish.

3.7 TUBE BENDING AND FLATTENING TESTS

Bending and flattening tests were performed to compare the formability of the rocker-formed standard tube with the new texture-controlled tube. The tests were also intended to evaluate whether bending and/or flattening were meaningful specification controls. The work was conducted in the three 3/8-, 5/8- and 1-in. sizes and for the tube fabrication methods being considered. The bends were made to 2, 2.5, and 3 times diameter bend radius and to a 120° angle. The springback, thinning, and flattening behavior were compared. The flattening tests were performed by flattening 3-in.-long straight sections to various dimensions, such as 16, 14, 10, and 8 times the tubing wall thickness. Flattening tests were performed on the pressure and return lines in the 3/8-, 5/8-, and 1-in. sizes made by different manufacturers and are described in section 5.1.

3.8 ROTARY FLEXURE TESTS

3.8.1 Preparation and Inspection of Test Specimens

The tube sizes tested in rotary flexure were the 3/8 x .020 and 1 x .080 return and pressure lines, respectively. Prior to forming, all tubing was ultrasonically inspected, with certified standards per BAC 5439-2 (ref. 5) for longitudinal, transverse, and herringbone defects. All tubing used in these tests met the requirements.

Specimens were formed with 120° bends using a 3D bend radius (three times the tube diameter). The bending equipment and forming characteristics are described in section 5.0. After forming, the tubes were penetrant inspected for cracks per BAC 5423 (ref. 6) and found to be acceptable.

All specimens were checked for ovality, and these values are shown in table 6.

3.8.2 Stress Application and Flexure Test Geometry

The stress application for tubes formed with 120° bends are shown in appendix B. All stresses were determined by mathematical analyses, based upon deflection and pressure.

The geometry selected for the 3/8 x .020 and 1 x .080 rotary test specimens was very similar (3D bend radius and 120° bend, as shown on figs. 19 and 20), and conventional engineering bending theory when applied to these specimens would indicate similar stress distributions, σ_{ml} and σ_{mc} , for both types of specimens. Pressure values were calculated depending upon deflection to obtain the desired stress. Application of the analysis to both types of specimens indicates that internal stress distribution in the walls of the tubing is quite different in the 1-in. tubing from that of the 3/8-in. tubing. For the 1-in. tubing, the maximum stress exists at $\phi = 270^\circ$ on the outer surface of the tube wall and is longitudinally oriented, whereas for the 3/8-in. tubing, the maximum stress exists at $\phi = 0^\circ$ or 180° on the inner surface of the tube wall and is circumferentially oriented.

TABLE 6.—FLEXURE TEST RESULTS FOR BENT TUBES, PART I

Specimen no.	Tube size, OD and WT (in.)	Special finish process	Maximum ovality in bend (%)	Deflection, single amplitude, δ_{SA}	Press (psi)	No. of cycles	Failure (deg)		Longitudinal ^a stress at failure		R_{long}	Circumferential ^a stress at failure		R_{long}	Failure analysis	
							$\theta(a)$	$\phi(a)$	σ_{max} (psi)	σ_{min} (psi)	σ_{min}	σ_{max} (psi)	σ_{min} (psi)	σ_{min}	Origin	Mode
											σ_{max}			σ_{max}		
16PB-B1	1 x .080 ↓	— ↓	1.50	0.64	4150	698,340	42	270	38,720	-14,900	-0.385	—	—	—	OD; abrasion and pit	Trans
16PB-B2			1.90	0.875	5770	86,130	65	270	58,300	-25,100	-0.430	—	—	—	OD; pit or scratch	Trans
16PB-B3			1.60	0.64	4150	271,920	113	270	40,620	-16,800	-0.414	—	—	—	OD; gouge	Trans
16PB-B4			2.10	0.875	5770	115,275	80	180	—	—	—	65,500	1100	0.0168	ID	Long
16PB-B5			2.00	0.725	4780	391,975	83	0	—	—	—	55,200	0	0	ID	Long
16PB-B6			2.20	0.725	4780	98 x 10 ⁶	No failure		^b 49,340	^b -21,860	-0.444	—	—	—	—	—
16PB-B7			1.70	0.725	4780	99,180	110	270	48,740	-21,260	-0.436	—	—	—	OD; small pit	Trans
16PB-B8			1.60	0.875	5770	68,730	106	270	59,000	-25,600	-0.435	—	—	—	OD; small pit	Trans
16PB-G1	1 x .080 ↓	(c) ↓	1.90	0.64	4150	256,470	108	270	40,820	-16,980	-0.415	—	—	—	OD; pit	Trans
16PB-G2			2.50	0.64	4150	146,230	110	270	40,720	-16,880	-0.414	—	—	—	OD; gouge	Trans
16PB-G3			2.40	0.725	4780	203,580	97	180	—	—	—	55,200	0	0	ID	Long
16PB-G4			2.20	0.725	4780	229,680	96	270	49,340	-21,860	-0.444	—	—	—	OD; long scratch	Trans
16PB-G5			2.10	0.725	4780	167,040	26	270	43,840	-16,360	-0.374	—	—	—	OD; pit	Trans
16PB-G6			2.00	0.875	5770	87,652	116	270	58,300	-25,100	-0.480	—	—	—	OD; small scratch	Trans
16PB-G7			2.00	0.875	5770	61,552	18	270	49,400	-16,200	-0.329	—	—	—	OD; crease	Trans
16PB-G8			2.20	0.875	5770	91,350	114	270	58,600	-25,400	-0.434	—	—	—	OD	Trans
16PB-M1	1 x .080 ↓	(d) ↓	1.80	0.64	4150	129,780	72	270	40,920	-17,080	-0.417	—	—	—	OD; gouge	Trans
16PB-M2			1.70	0.64	4150	10 x 10 ⁶	No failure		^b 41,320	^b -17,480	-0.424	—	—	—	—	—
16PB-M3			2.00	0.725	4780	103,530	55	270	46,540	-20,060	-0.430	—	—	—	OD; gouge	Trans
16PB-M4			2.30	0.725	4780	74,820	41	270	45,940	-18,460	-0.402	—	—	—	OD; scratch	Trans
16PB-M5			2.30	0.725	4780	77,865	70	270	48,740	-21,260	-0.436	—	—	—	OD; pit	Trans
16PB-M6			1.80	0.875	5770	118,755	103	270	59,200	-26,000	-0.439	—	—	—	OD; small pit	Trans
16PB-M7			2.00	0.875	5770	57,420	89	270	59,200	-26,000	-0.439	—	—	—	OD; pit	Trans
16PB-M8			1.90	0.875	5770	63,075	101	270	59,200	-26,000	-0.439	—	—	—	OD; gouge	Trans
6RB-B1	3/8 x .020 ↓	— ↓	3.20	0.52	2680	94,620	76	0	—	—	—	45,600	2,000	0.044	ID	Long
6RB-B2			3.20	0.52	2680	139,440	76	0	—	—	—	45,600	2,000	0.044	ID	Long
6RB-B3			3.20	0.59	3080	82,170	43	180	—	—	—	50,400	4,400	0.087	ID	Long
6RB-B4			3.47	0.59	3080	74,700	32	0	—	—	—	51,400	3,400	0.067	ID	Long
6RB-B5			3.20	0.59	3080	74,700	71	0	—	—	—	51,200	3,600	0.070	ID	Long
6RB-B6			2.94	0.71	3730	39,840	81	180	—	—	—	60,600	5,800	0.096	ID	Long
6RB-B7			2.94	0.71	3730	34,860	61	180	—	—	—	60,200	6,200	0.103	ID	Long
6RB-B8			3.20	0.71	3730	34,860	49	0	—	—	—	59,800	6,600	0.110	ID	Long

TABLE 6.—Concluded

Specimen no.	Tube size, OD and WT (in.)	Special finish process	Maximum ovality in bend (%)	Deflection, single, amplitude, δ_{SA}	Press (psi)	No. of cycles	Failure (deg)		Longitudinal ^a stress at failure		R_{long}	Circumferential ^a stress at failure		R_{long}	Failure analysis			
							θ (a)	ϕ (a)	σ_{max} (psi)	σ_{min} (psi)		$\frac{\sigma_{min}}{\sigma_{max}}$	σ_{max} (psi)		σ_{min} (psi)	$\frac{\sigma_{min}}{\sigma_{max}}$	Origin	Mode
6RB-G1	3/8 x .020	(c)	3.47	0.52	2680	2,858,520	Specimen not valid; tube broke off in center of bend										(e)	Long
6RB-G2			3.20	0.52	2680	4,163,820	71	0	—	—	—	45,600	2,000	0.044				
6RB-G3			3.20	0.59	3080	378,480	59	180	—	—	—	50,900	3,900	0.077				
6RB-G4			3.47	0.59	3080	388,440	75	0	—	—	—	50,900	3,900	0.077				
6RB-G5			2.94	0.59	3080	398,400	50	0	—	—	—	50,600	4,200	0.083				
6RB-G6			3.20	0.71	3730	80,510	71	180	—	—	—	60,400	6,000	0.099				
6RB-G7			2.94	0.71	3730	88,810	71	0	—	—	—	60,400	6,000	0.099				
6RB-G8			3.20	0.71	3730	73,870	68	0	—	—	—	60,400	6,000	0.099				
6RB-M1	3/8 x .020	(d)	2.67	0.52	2680	614,200	60	0	—	—	—	45,400	2,200	0.048	(e)	Long		
6RB-M2			2.94	0.52	2680	10×10^6	No failure		—	—	—	^b 45,800	^b 1,800	0.039	—	—		
6RB-M3			3.20	0.59	3080	10×10^6	No failure		—	—	—	^b 51,400	^b 3,400	0.066	—	—		
6RB-M4			2.94	0.59	3080	1,094,006	60	0	—	—	—	50,900	3,900	0.077	(e)	Long		
6RB-M5			3.20	0.59	3080	300,460	73	180	—	—	—	51,300	3,600	0.070	ID	Long		
6RB-M6			2.67	0.71	3730	56,440	77	180	—	—	—	60,600	5,800	0.096	ID	Long		
6RB-M7			3.20	0.71	3730	36,520	49	340	—	—	—	59,800	6,600	0.110	ID	Long		
6RB-M8			2.94	0.71	3730	127,820	78	0	—	—	—	60,500	5,900	0.098	ID	Long		
6RB-1	3/8 x .020	(f)	3.20	0.52	2680	10×10^6	No failure		—	—	—	^b 45,800	^b 1,800	0.039	—	—		
6RB-2			2.65	0.52	2680	10×10^6	No failure		—	—	—	^b 45,800	^b 1,800	0.039	—	—		
6RB-3			2.65	0.59	3080	10×10^6	No failure		—	—	—	^b 51,400	^b 1,800	0.066	—	—		
6RB-4			2.94	0.59	3080	10×10^6	No failure		—	—	—	^b 51,400	^b 1,800	0.066	—	—		
6RB-5			3.20	0.59	3080	10×10^6	No failure		—	—	—	^b 51,400	^b 1,800	0.066	—	—		
6RB-6			2.94	0.71	3730	647,400	83	180	—	—	—	60,600	5,800	0.096	ID	Long		
6RB-7			2.94	0.71	3730	112,050	60	180	—	—	—	60,200	6,200	0.103	ID	Long		
6RB-8			3.20	0.71	3730	154,380	36	180	—	—	—	59,300	7,100	0.120	ID	Long		

Note: All specimens were fabricated to specification XBMS 7-234

^aSee appendix B for stress formula and nomenclature

^bAssume max stress location at $\theta = 90^\circ$ and $\phi = 0^\circ$ or 180°

^cGrumman finish process

- o Tube ID grit blasted (60-120 grit) to remove 0.0005 to 0.0010 in. from each ID surface
- o After grit blast, ID was pickled to remove 0.0005 in. from each surface

^dMcDonnell-Douglas process

- o Tube ID pickled to remove 0.0005 in. from each surface
- o Tube pressurized to 21,000 psi for 30 sec prior to flexure testing

^eSpecimens not analyzed

^fTubing with texture control

3.8.3 Test Procedure and Results

3.8.3.1 Proof Pressure Tests

Prior to flexure testing, each specimen was subjected to a proof pressure test for 5 minutes at the values shown below. Any leakage or permanent deformation in the tube constituted a failure. If leakage occurred in the hydraulic fittings, the fitting was repaired or replaced. All specimens met this requirement satisfactorily.

Tube Size, OD and WT (in.)	Proof Pressure at Room Temperature (psig)
3/8 x .020	4150
1 x .080	8300

3.8.3.2 Pressurization Test

Prior to flexure testing, the test specimens with the grit blast and chemically milled ID finish (3/8 x .020 6RB-M1 to 6RB-M8 and 1 x .080 16PB-M1 to 16PB-M8 in table 6) were subjected to the pressurization test. This test is required by McDonnell-Douglas for all tube assemblies prior to installation in the airplane. Each tube assembly is pressurized to four times the working pressure for 30 seconds. McDonnell-Douglas reports that the pressurization test is helpful in detecting poor-quality tubing and defective fittings.

The 3/8 x .020 specimens were pressurized to 13,500 psi for 30 seconds. The 13,500 psi was based on the following:

$$P_B = \frac{K F_{tu} \times 2t}{OD - 1.4t} \quad (1)$$

where:

P_B = Burst pressure

K = $0.6 + 0.4 (F_{ty}/F_{tu})$

F_{ty} = Minimum yield strength of tubing at room temperature (psi)

F_{tu} = Minimum tensile strength of tubing at room temperature (psi)

t = Wall thickness

OD = Outside diameter (in.)

$$\begin{aligned}
 P_B &= \frac{\left[0.6 + 0.4 \left(\frac{105,000}{125,000} \right) \right] (125,000)(2)(.020)}{.375 - 1.4 (.020)} \\
 &= 13,500 \text{ psi}
 \end{aligned}$$

The .020-in. wall thickness was the minimum thickness specified for the SST prototype. The Lamé formula shown below was used for sizing the prototype tubing and gave a P_B of 14,100 psi; however, the conservative value of 13,500 psi was used for the pressurization test.

$$\text{Lamé formula } P_B = F_{tu} \frac{OD^2 - ID^2}{OD^2 + ID^2} \quad (2)$$

where ID is the inside diameter (in.) and P_B , F_{tu} and OD are as listed for the Boeing formula above.

The 1 x .080 specimens were pressurized to 21,000 psi for 30 seconds. The 21,000-psi value was obtained using equation 1, as follows:

$$P_B = \frac{\left[0.6 + 0.4 \left(\frac{105,000}{125,000} \right) \right] (125,000)(2)(.080)}{1.0 - 1.4 (.080)}$$

$$= 21,000 \text{ psi}$$

The .080 wall thickness was determined by the Lamé formula (eq. 2) for an operating temperature of 450 F. Since all testing on this program (Task 6) was at room temperature, the burst pressure was calculated using room temperature mechanical properties. The Lamé formula showed the burst pressure to be 21,500 psi; however, the conservative value of 21,000 psi was used for the pressurization test. Results from the pressurization test showed no leakage and no significant change in the tube ovality after depressurization.

3.8.3.3 Flexure Tests

The flexure tests on the 1 x .080 and 3/8 x .020 specimens were conducted at different deflections and pressures for the characteristic curves. The stress application and flexure test geometry are defined in section 3.8.2.

The centering and deflection setting procedures for the rotary flexure equipment defined in ARP 1185 (ref. 7) were used where applicable. However, this ARP was written for straight tubes with specified lengths and required changes for tubes with bends, as follows:

- The tightening of the clamp near the tail stock was critical and required several adjustments to the head stock to obtain the required deflection.
- The application of pressure may affect the deflection setting. The specimen should be pressurized to the working pressure, then depressurized, and a final check made on the deflection.
- The 1 x .080 specimens were tested at 1030 and 435 rpm. The faster speed of 1030 rpm was found to be satisfactory and gave no dynamic problems.
- The 3/8 x .020 specimens were all tested at 835 rpm.

Photographs of the 1 x .080 and 3/8 x .020 in. test specimens are shown in figures 21 and 22.

For the 1 x .080 specimens, the predicted mode of failure was a transverse crack, due to longitudinal stress, originating at the outside of the tube at $\theta = 90^\circ$ and $\phi = 270^\circ$. Of 24 specimens tested (three different configurations), 19 failures occurred as predicted, with the transverse cracks originating on the outside diameter of the tube. On three specimens, the failures occurred due to longitudinal cracks originating on the inside diameter of the tube. On the remaining two specimens, failures did not occur after 9.8×10^6 and 10×10^6 cycles.

The test data for the 1 x .080 specimens showing deflection, pressure, total cycles, failure analysis (if applicable), calculated stresses and stress ratio ($R = \sigma_{\min}/\sigma_{\max}$) are shown in table 6. Stress values for specimens that failed are calculated at the point of failure, whereas if no failure occurred the value is calculated for the maximum at $\theta = 90^\circ$ and $\phi = 270^\circ$ in the bend. The curves showing deflection versus cycles and longitudinal stress versus cycles are shown in figures 34 and 35 (section 5.0). These curves show the 21 test specimens, including the two specimens that did not fail. The three specimens that failed because of longitudinal cracks on the inside diameter could not be directly compared and were not plotted; however, the circumferential stresses at the point of failure are shown for reference on the data sheets.

For the 3/8 x .020 specimens, the predicted mode of failure was a longitudinal crack due to circumferential stress, which originated at the inside surface of the tube at $\theta = 90^\circ$ and $\phi = 0^\circ$ or 180° . Of 32 specimens tested (four different configurations), 24 failures occurred as predicted, with longitudinal cracks originating on the inside diameter of the tube. On one specimen, the tube fractured in the bend before the fail-safe device stopped the test. The cyclic life for this specimen is not considered valid. Of the remaining seven specimens, no failure occurred after 10×10^6 cycles.

The test data for the 3/8 x .020 specimens showing deflection, pressure, total cycles, failure analysis (if applicable), calculated stress, and stress ratio ($R = \sigma_{\min}/\sigma_{\max}$) are shown in table 6. The specimens that did not fail are also shown, with the maximum circumferential stress value obtained in the bend. The curves showing deflection vs cycles and circumferential stress vs cycles are shown in figures 36 and 37 (section 5.0).

Test results for the three ID finish configurations of the 1 x .080 tube specimens made from tubing procured during the SST program per XBMS 7-234 showed no significant difference. The failure analysis showed that failures on 19 of 22 specimens originated on the outside diameter. Therefore, the special (Grumman, McDonnell-Douglas) ID finishes did not improve the fatigue life over the as-received (Boeing) finish. Closeup photos of flexure fatigue cracks are shown in figures 23 and 24.

Test results for the four configurations of the 3/8 x .020 tube specimens showed that the Superior tubing per XBMS 7-234 with texture control had the best fatigue life. The results on tubing procured during the SST program per XBMS 7-234 showed ID failures and that improving the ID finish per the Grumman and McDonnell-Douglas ID requirements significantly improved the fatigue life over the as-received Boeing finish. Based on the part I test results, the texture-controlled tubing showed the best fatigue life and was used for subsequent tests in part II.

4.0 PART II—EVALUATION OF IMPROVED TUBING (Procured per Specification XBMS 7-234A)

Part II of this program was to evaluate the metallurgical characteristics of the new 3/8 x .020, 3/8 x .030, 5/8 x .021, 5/8 x .050, 1 x .033, and 1 x .080 tube sizes, and the fatigue characteristics of the 3/8 x .020 and 1 x .080 sizes procured per the proposed specification XBMS 7-234A (appendix A). The tubes evaluated are detailed in table 7. The tubes were evaluated as a function of manufacturer, surface condition, tube size, and crystallographic texture.

*TABLE 7.—Ti-3Al-2.5V CWSR TUBES PROCURED
FOR PART II PER BMS 7-234A*

Tube no.	Tube size, OD and WT (in.)	Manufacturer	Heat no.	Lot no.
1	3/8 x .020	Superior	304450-03	1
2	3/8 x .030	Superior	304450-03	1
3	5/8 x .021	Superior	304450-03	1
4	5/8 x .050	Superior	304450-03	1
5	10 x .033	Bishop	704511-06	1-1
6	10 x .080	Bishop	704511-06	1-1

The 3/8 and 5/8 tube sizes were manufactured by Superior Tube Company, using the 1 x .080 tubing made by Reactive Metals, Inc. for the SST program as the starting stock (tube hollows). Prior to manufacturing by Superior, the 1 x .080 starting stock was ultrasonically inspected and met the requirements of BAC 5439-2 (refs 8 and 9) for longitudinal, transverse, and herringbone defects.

The 1 x .033 and 1 x .080 tube sizes were manufactured by Bishop Tube Company using stock (tube hollows) procured from Reactive Metals, Inc.

Because of time limitations in the program, certain requirements for starting stock (tube hollows) were waived, and the Reactive Metals starting stock used for the 1 x .033 and 1 x .080 tubing was accepted on a best-effort basis. The basic new provisions of the specification were fourfold:

- Increased quality of tube hollows through more stringent defect allowances and quality control requirements
- Specified tube processing methods

- Required improved surface finishes
- Required specific degree of preferred crystallographic texture

4.1 SURFACE CONDITION

The surface roughness on the OD and ID surfaces of tubes 1 through 6 was determined using a profilometer. Boeing material specification XBMS 7-234A calls for the final tube reduction to be by drawing and prohibits the use of sanding or grinding operations on the OD surfaces following the final drawing operation. The OD surface is then chemically milled 0.002 in. and the ID surface is grit blasted (~ 0.0005 in.) and chemically milled (~ 0.0005 in.). The surface roughness of the various tubes was found to be as shown in table 8 and figure 25.

*TABLE 8.—SURFACE ROUGHNESS VALUES OF
Ti-3Al-2.5V CWSR TUBING*

Tube no.	RHR roughness value ranges			
	OD surface		ID surface	
	Manufacturer	Boeing	Manufacturer	Boeing
1	12-17	18-25	25-25	21-27
2	10-11	11-13	17-20	18-25
3	13-16	15-18	20-21	20-25
4	10-17	16-21	25-25	21-25
5	20-24	9-14	12-20	13-18
6	15-25	12-15	10-20	16-22

The surface roughness of all tubes was considerably better than that normally observed for Ti-3Al-2.5V tubing procured over the past several years. XBMS 7-234A stipulates that an RHR value of 32 on the ID and OD surfaces shall not be exceeded. As shown in table 8, these limits were easily met.

Examination of OD surfaces with a wide-field microscope revealed relatively coarse circumferential sanding marks on all tubing except the 1 x .033 size, however. These sanding marks (striker marks in some cases) apparently survived the final reduction process as well as the 0.002 in. chemical milling treatment, which was not anticipated when XBMS 7-234 was being revised, and which is in conflict with the intent of the revised specification. Sanding marks of this type have previously been noted to act as points of origin for fatigue cracks and are considered to be unacceptable for the OD surface finish.

The ID finish of all tubes appeared smooth and free from surface irregularities. After examination of the OD surface finish, 25 ft of the 1 x .080 tubing was returned to Bishop Tube Company for additional chemical milling to remove the sanding marks. Bishop removed approximately 0.0005 to 0.0010 in. from the OD and improved the surface; however, there was still some evidence of sanding marks. Photographs of the tubing as received and after additional chemical milling are shown in figure 26. (The photographs are of different pieces of tubing.)

4.2 MICROSTRUCTURE

The microstructures of the subject tubes were examined and are shown in figure 27. All tubes possessed a relatively fine, equiaxed, alpha-beta morphology, but tubes 1 and 5 displayed a somewhat larger grain size. A relatively high-temperature anneal in the alpha-beta (~1600° F) prior to final drawing might produce this increase in grain size. All tubes were judged to have acceptable microstructures.

4.3 RESIDUAL STRESS

The residual hoop stresses in the six different tube sizes were measured using the method outlined in XBMS 7-234A. The results of this investigation are shown in table 9.

**TABLE 9.—RESIDUAL STRESS MEASUREMENTS FOR
Ti-3Al-2.5V CWSR TUBING**

Tube no.	Tube size, OD and WT (in.)	Manufacturer	Residual stress (ksi)
1	3/8 x .020	Superior	+7.1
2	3/8 x .030	Superior	+11.0
3	5/8 x .021	Superior	+5.8
4	5/8 x .050	Superior	+13.5
5	1 x .033	Bishop	+7.2
6	1 x .080	Bishop	+25.5

The specification requirement for residual stresses is ± 15.0 ksi maximum; thus, all tubes except number 6 met the required limits. The experimental nature of these lots of material and a tight schedule required that they be procured on a best-effort basis, so the high residual stress value found for tube 6 was not considered cause for rejection. High residual stress values might be expected to occasionally cause premature fatigue failures for some modes of stressing.

4.4 TEXTURE STUDIES

Crystallographic texture studies were performed on the subject tubes using a computerized X-ray pole figure technique and a tensile test technique. The X-ray diffraction results are shown in figures 28 through 33 and in table 10. The results of the pole figures were in accordance with previous observations. As tube diameter increased and wall thickness decreased the texture tended toward the desired radial orientation of basal plane poles. Conversely, small-diameter, thick-walled tubes tended to possess a circumferential texture of basal plane poles. Table 10 shows the ϕ_p angle of basal planes for each tube; the 1 x .033 tube has the smallest angle and the 5/8 x .050 tube the largest.

Note: The ϕ_p angle is the angle between a true radial texture of basal plane (0°) and the actual centroid of high intensity basal plane poles along the $270^\circ \alpha$ axis.

TABLE 10.—CRYSTALLOGRAPHIC TEXTURE MEASUREMENTS FOR
Ti-3Al-2.5V CWSR TUBING

Tube no.	Tube size, OD and WT (in.)	Manufacturer	ϕ_p angle ^b (°)	R-ratio ^a	
				Boeing ^c	Manufacturer
1	3/8 x .020	Superior	52	0.49	^d 0.74
2	3/8 x .030	Superior	62	0.50	^d 0.47
3	5/8 x .021	Superior	32	2.80	^d 2.40
4	5/8 x .050	Superior	63	0.33	^d 0.44
5	1 x .033	Bishop	37	0.91	^e 1.54
6	1 x .080	Bishop	52	0.31	^e 0.56

$$^a R = L_n(OD_f/OD_o) \div L_n(W_f/W_o)$$

See XBMS 7-234A (appendix A) for an explanation of terms.

^bSee figure 28 for example

^dSuperior Measurement Method:

Approximately 20 measurements were made with a micrometer for each value and averaged. The final dimensions on tested specimens were measured approximately 0.25 in. from the fracture. Prior to measuring the final dimensions, the rough edge at the fracture was cut off with a hack saw, lightly filed, and the ID lightly reamed to remove burrs.

^eBishop Measurement Method:

Several measurements were made for each value and averaged. The final dimensions were measured about 0.25 in. near the uniform elongation section.

^cBoeing Measurement Method:

All measurements were made with a micrometer. The final dimensions were measured approximately halfway between the fracture surface and the point where uniform elongation ends. The fractured edge was cut off, lightly filed, and surfaces deburred.

The R values determined at Boeing and by the tube suppliers are also shown in table 10. The R values qualitatively correlate well with the pole figure results (high R values corresponding to low ϕ_p and vice-versa) but a rather large scatter is sometimes noted between the Boeing and supplier R value determinations. This circumstance is considered to be due to variations in making the required measurements and is expected to improve considerably as data are accumulated and procedures refined.

4.5 TUBE BENDING AND FLATTENING TESTS

Tube bending and flattening tests were conducted on various tubes as defined in section 3.7. Test results on bending and flattening are given in section 5.0.

4.6 ROTARY FLEXURE TESTS

4.6.1 Preparation and Inspection of Tube Specimens

The preparation and inspection of the 1 x .080 and 3/8 x .020 pressure and return line sizes are the same as defined in part I, except that no penetrant inspection was conducted in part II. The penetrant test was discontinued since no indications for defects were noted in the work performed in part I.

4.6.2 Stress Application and Flexure Test Geometry

The stress application and flexure test geometry are the same as defined in part I (sec. 3.8.2).

4.6.3 Test Procedure and Results

4.6.3.1 Proof Pressure Tests

The proof pressure test procedure is the same as defined in section 3.8.3.1. All specimens met this requirement.

4.6.3.2 Flexure Tests

The flexure tests on the 1 x .080 and 3/8 x .020 specimens, made per specification XBMS 7-234A, were conducted at different deflections and pressures to establish the characteristic curves. The values were in the same range as those used in part I so that a direct comparison could be made.

The centering and deflection setting procedures for the rotary flexure test equipment are the same as defined in section 3.8.3.3. All 1 x .080 specimens were tested at 435 rpm.

For the 1 x .080 specimens, the predicted mode of failure was a transverse crack due to longitudinal stress originating at the outside of the tube at $\theta = 90^\circ$ and $\phi = 270^\circ$ in the bend. Of the 1 x .080 tubing made by Bishop Tube Company, four specimens which showed transverse striker marks were initially tested. Test results on these specimens (16 PBT-1 through

-4) showed transverse cracks and low fatigue life. After evaluating these results, a small quantity of the tubing was returned to Bishop for additional chemical milling to remove the striker marks.

Bishop removed approximately .001 in. from the OD and improved the surface; however, there was still some evidence of the striker marks. Three new specimens (16 PBT-5 through -7) were tested. Test results showed improvement in fatigue life over tubing not being retreated by additional chemical milling at Bishop.

The test data for the 1 x .080 specimens showing deflection, pressure, total cycles, failure analysis (if applicable), and calculated longitudinal stress are shown in table 11. The stress value is calculated at the point of failure for specimens that failed, whereas if no failure occurred the value is the maximum at $\theta = 90^\circ$ and $\phi = 270^\circ$ in the bend. Curves showing deflection versus cycles and longitudinal stress versus cycles are shown in section 5.0.

For the 3/8 x .020 specimens, the predicted mode of failure was a longitudinal crack due to circumferential stress, originating at the inside surface of the tube at $\theta = 90^\circ$ and at $\phi = 0^\circ$ or 180° . Of the eight specimens tested, six failures occurred as predicted, with longitudinal cracks originating on the ID of the tube. On the remaining two specimens no failures occurred after 10×10^6 cycles.

The test data for the 3/8 x .020 specimens showing deflection, pressure, total cycles, failure analysis (if applicable), and calculated circumferential stress are shown in table 11. Stress values are calculated at the point of failure for the specimens that failed, whereas if no failure occurred the value is the maximum at $\theta = 90^\circ$ and $\phi = 0^\circ$ or 180° in the bend. Curves showing deflection versus cycles and circumferential stress versus cycles are shown in section 5.0.

TABLE 11.—FLEXURE TEST RESULTS FOR BENT TUBES, PART II

Specimen no.	Tube size, OD and WT (in.)	Special finish process	Maximum ovality in bend (%)	Deflection, single amplitude, δ_{SA}	Press (psi)	No. of cycles	Failure		Longitudinal ^a stress at failure		R_{long} $\frac{\sigma_{min}}{\sigma_{max}}$	Circumferential ^a stress at failure		R_{long} $\frac{\sigma_{min}}{\sigma_{max}}$	Failure analysis	
							θ (a)	ϕ (a)	σ_{max} (psi)	σ_{min} (psi)		σ_{max} (psi)	σ_{min} (psi)		Origin	Mode
6RST-1	3/8 x .020 ↓	—	3.47	0.52	2680	10 x 10 ⁶	No failure	—	—	—	—	b45,800	b1,800	0.039	—	—
6RST-2		—	3.20	0.59	3080	10 x 10 ⁶	No failure	—	—	—	—	b51,400	b3,400	0.066	—	—
6RST-3		—	3.47	0.71	3730	112,050	71	0	—	—	—	60,400	6,000	0.099	ID; general surface cond	Long
6RST-4		—	2.90	0.675	3540	146,910	21	0	—	—	—	55,900	7,100	0.127	↓	Long
6RST-5		—	3.20	0.675	3540	137,000	38	0	—	—	—	56,750	6,250	0.110	↓	Long
6RST-6		—	3.20	0.800	4200	67,230	21	180	—	—	—	65,000	9,900	0.150	↓	Long
6RST-7		—	2.90	0.800	4200	49,800	50	180	—	—	—	66,600	8,200	0.123	↓	Long
6RST-8		—	3.20	0.800	4200	52,290	38	180	—	—	—	66,000	8,800	0.133	↓	Long
16PBT-1	1 x .080 ↓	—	2.20	0.64	4150	199,230	c78 21	c270 270	29,950	-10,050	-0.335	—	—	—	OD; residual grind mark	Trans
16PBT-2		—	2.20	0.725	4780	56,115	102	270	38,850	-15,950	-0.410	—	—	—	OD; small scuff mark	Trans
16PBT-3		—	2.50	0.875	5770	33,930	61	270	45,200	-17,800	-0.384	—	—	—	OD; elongated indentation	Trans
16PBT-4		—	2.20	0.725	4780	67,860	91	270	37,150	-14,250	-0.384	—	—	—	OD; long deep scratch	Trans
16PBT-5		(d)	3.00	0.64	4150	1,983,600	No failure	—	40,320	-16,500	-0.382	—	—	—	—	—
16PBT-6		(d)	2.60	0.725	4780	81,780	91	180	48,100	-20,700	-0.420	—	—	—	ID	45 to neutral axis
16PBT-7		(d)	2.40	0.875	5770	64,815	10	270	49,600	-16,400	-0.330	—	—	—	OD; small scratch	Trans

Note: All specimens were fabricated to specification XBMS 7-234A.

^aSee appendix B for stress formula and nomenclature

^bAssume maximum stress location at $\theta = 90^\circ$ and $\phi = 0^\circ$ or 180°

^cBoth failures occurred simultaneously

^dAdditional chemical milling to OD surface (0.0005 to 0.0010 in.) done by Bishop

5.0 DISCUSSION OF TEST RESULTS—PARTS I AND II

This section describes the results of tests on the various tubes conducted in parts I and II, including bending and flattening, mechanical properties, and characteristic curves showing deflection versus cycles. Each test is discussed separately.

5.1 BENDING AND FLATTENING TESTS

Bending and flattening tests were conducted on various tubes to determine the formability characteristics. Many of the tubes used are manufactured to the previous specifications BMS 7-203 and XBMS 7-234 and were not used for the fatigue tests, but were tested for comparison only.

5.1.1 Bend Tests

The bend criteria for the 3D bend specimens formed to 120° bends are shown in table 12. The criteria include the type of bender, springback (degrees), and the minimum clamp length. The results show no significant difference in the springback when comparing the same size tube made by different manufacturers and to different specifications.

TABLE 12.—BEND CRITERIA FOR THREE-DIMENSIONAL 120° BENDS

Nominal tube diameter (in.)	Nominal tube wall thickness (in.)	Actual wall thickness (in.)	Specification	Manufacturer	Type bender	Springback (deg)	Minimum clamp length ^a (in.)
3/8	.020	.021	XBMS 7-234	Zirtech	Leonard PB	11	0.75
3/8	.030	.030			Leonard PB	11.5	0.75
5/8	.021	.0225			Leonard 162-HYD	10	1.25
5/8	.050	.051			Leonard 162-HYD	12	1.25
1	.080	.080	XBMS 7-203A XBMS 7-234A	Reactive Metals Reactive Metals Superior	Pines 1-1/2	14	2.00
1	.033	.034			Pines 1-1/2	10	2.00
3/8	.020	.020			Leonard PB	10.5	0.75
3/8	.030	.0305			Leonard PB	11	0.75
5/8	.021	.022		Bishop Bishop	Leonard 162-HYD	9	1.25
5/8	.050	.051			Leonard 162-HYD	11	1.25
1	.033	0.034			Pines 1-1/2	10.5	2.00
1	.080	(b)			Pines 1-1/2	14	2.00

Note: Manufacturing permits a maximum thinout of 10%.

Maximum ovality 3% permitted on bends

^aAlso minimum distance between bends

^bWall thickness varied 0.005 in.

The results of bend tests conducted with various size bend blocks are shown in table 13. The comparison was made by evaluating the maximum bend ovality and bend thinout or reduction. Only one specimen for each size bend block was used; a better comparison could be made with more specimens.

The 1 x .080 tubes were made by two manufacturers to different specifications. The results did not show significant differences. Both types fractured using the 2.00-in. bend radius block.

The 1 x .033 tubes were made by two manufacturers to different specifications. The results were similar. Both types fractured using the 2.00- and 2.50-in. bend radius blocks.

The 5/8 x .050 tubes were made by two different manufacturers. The results were similar. Both types fractured using the 1.25- and 1.50-in. bend blocks.

The 5/8 x .021 tubes were made by two different manufacturers. The results were similar, and both types fractured using the 1.25-in. bend block.

The 3/8 x .030 tubes were made by Superior Tube Company per the initial specification XBMS 7-234 except for crystallographic texture control and to the new proposed specification XBMS 7-234A. The results show a tube fracture on the XBMS 7-234A tubing with a bend radius block of 0.750 in., whereas the XBMS 7-234 tubing did not fracture. The tube per specification XBMS 7-234A showed less bend thinout on the 0.933 and 1.000 bend radius blocks.

The four types of 3/8 x .020 tubes were made by two suppliers to different specifications. Results varied, and tube fractures occurred on three specimens formed with the 0.75-in. radius block. The best results were obtained on the Superior Tube per specification XBMS 7-234 with texture control, where no fracture occurred with the 0.75-in. radius block. The lowest percentage ovality occurred with the Superior XBMS 7-234A tubing.

In summary, the results show the Superior 3/8 x .020 texture-controlled tubing per the new specification XBMS 7-234A and the XBMS 7-234 tubing procured for part I had the best formability.

5.1.2 Flattening Tests

The flattening tests were conducted to determine ductility. Results are shown in table 14. In most cases, the same tubes were used as for the bend tests. All tests were conducted per the procedure in the new proposed specification XBMS 7-234A.

The 1 x .080 tubes were made by three manufacturers. Reactive Metals and Zirtech fabricated to the same specification, and Bishop to the new specification XBMS 7-234A. Results show the Bishop tube to be the most satisfactory at 8t; however, 10t is considered the acceptable value.

TABLE 13.—BEND TEST RESULTS

Nominal tube size OD and WT (in.)	Average tube OD (in.)	Average tube WT (in.)	Manufacturer	Specification	Heat and lot no.	Tool bend radius (in.)	Max bend ovality (%)	Max bend thinout (%)
1 x .080	1.001	.0770	Reactive Metals	XBMS 7-234	304450-03	2.000	Tube fracture	Tube fracture
1 x .080	1.001	.0770	Reactive Metals	XBMS 7-234	304450-03	2.500	3.00	5.20
1 x .080	1.001	.0770	Reactive Metals	XBMS 7-234	304450-03	3.000	3.00	6.50
1 x .080	1.001	.0790	Bishop	XBMS 7-234A	704511-06	2.000	Tube fracture	Tube fracture
1 x .080	1.001	.0790	Bishop	XBMS 7-234A	704511-06	2.50	2.80	7.90
1 x .080	1.001	.0790	Bishop	XBMS 7-234A	704511-06	3.000	3.00	6.30
1 x .033	1.002	.0320	Reactive Metals	XBMS 7-203A	2094804-24	2.000	Tube fracture	Tube fracture
1 x .033	1.002	.0320	Reactive Metals	XBMS 7-203A	2094804-24	2.500	Tube fracture	Tube fracture
1 x .033	1.002	.0320	Reactive Metals	XBMS 7-203A	2094804-24	3.000	.50	1.50
1 x .033	1.002	.0325	Bishop	XBMS 7-234A	704511-06	2.000	Tube fracture	Tube fracture
1 x .033	1.002	.0325	Bishop	XBMS 7-234A	704511-06	2.500	Tube fracture	Tube fracture
1 x .033	1.002	.0325	Bishop	XBMS 7-234A	704511-06	3.000	.70	3.00
5/8 x .050	.625	.0500	Superior	XBMS 7-234A	304450-03	1.250	Tube fracture	Tube fracture
5/8 x .050	.625	.0500	Superior	XBMS 7-234A	304450-03	1.500	Tube fracture	Tube fracture
5/8 x .050	.625	.0500	Superior	XBMS 7-234A	304450-03	1.750	2.05	8.00
5/8 x .050	.625	.0500	Superior	XBMS 7-234A	304450-03	2.000	1.40	6.00
5/8 x .050	.625	.0490	Zirtech	XBMS 7-234	BF07058	1.250	Tube fracture	Tube fracture
5/8 x .050	.625	.0490	Zirtech	XBMS 7-234	BF07058	1.500	Tube fracture	Tube fracture
5/8 x .050	.625	.0490	Zirtech	XBMS 7-234	BF07058	1.750	2.00	7.30
5/8 x .050	.625	.0490	Zirtech	XBMS 7-234	BF07058	2.000	1.90	6.10
5/8 x .021	.625	.0205	Superior	XBMS 7-234A	304450-03	1.250	Tube fracture	Tube fracture
5/8 x .021	.625	.0205	Superior	XBMS 7-234A	304450-03	1.500	.80	2.30
5/8 x .021	.625	.0205	Superior	XBMS 7-234A	304450-03	1.750	1.00	4.80

TABLE 13.—Concluded

Nominal tube size OD and WT (in.)	Average tube OD (in.)	Average tube WT (in.)	Manufacturer	Specification	Heat and lot no.	Tool bend radius (in.)	Max bend ovality (%)	Max bend thinout (%)
5/8 x .021	.625	.0215	Zirtech	XBMS 7-234	BF07058	1.250	Tube fracture	Tube fracture
5/8 x .021	.625	.0215	Zirtech	XBMS 7-234	BF07058	1.500	.30	6.90
5/8 x .021	.625	.0215	Zirtech	XBMS 7-234	BF07058	1.750	1.50	4.60
3/8 x .030	.377	.0300	Superior	XBMS 7-234A	304450-03	0.750	Tube fracture	Tube fracture
3/8 x .030	.377	.0300	Superior	XBMS 7-234A	304450-03	0.933	3.20	6.70
3/8 x .030	.377	.0300	Superior	XBMS 7-234A	304450-03	1.000	2.70	5.00
3/8 x .030	.376	.0295	Superior	XBMS 7-234	303118-15	0.750	4.80	6.70
3/8 x .030	.376	.0295	Superior	XBMS 7-234	303118-15	0.933	3.20	10.00
3/8 x .030	.376	.0295	Superior	XBMS 7-234	303118-15	1.000	2.70	10.00
3/8 x .020	.377	.0205	Superior	XBMS 7-234A	304450-03	0.750	Tube fracture	Tube fracture
3/8 x .020	.377	.0205	Superior	XBMS 7-234A	304450-03	0.933	1.80	4.80
3/8 x .020	.377	.0205	Superior	XBMS 7-234A	304450-03	1.000	1.80	5.00
3/8 x .020	.376	.0210	Zirtech	XBMS 7-234	BF10059	0.750	Tube fracture	Tube fracture
3/8 x .020	.376	.0210	Zirtech	XBMS 7-234	BF10059	0.933	2.40	4.30
3/8 x .020	.376	.0210	Zirtech	XBMS 7-234	BF10059	1.000	2.10	4.00
3/8 x .020	.376	.0205	Zirtech ^a	XBMS 7-234	BF10059	0.750	Tube fracture	Tube fracture
3/8 x .020	.376	.0205	Zirtech ^a	XBMS 7-234	BF10059	0.933	3.20	2.40
3/8 x .020	.376	.0205	Zirtech ^a	XBMS 7-234	BF10059	1.000	2.60	8.50
3/8 x .020	.376	.0200	Superior	^b XBMS 7-234	304450	0.750	4.80	9.50
3/8 x .020	.376	.0200	Superior	^b XBMS 7-234	304450	0.933	2.90	7.50

^aTube ID grit blasted and chemically milled per Grumman requirements

^bTubing has crystallographic texture control

TABLE 14.—FLATTENING TEST RESULTS

Nominal tube size, OD and WT (in.)	Manufacturer	Specification	Heat and lot no.	OD to wall thickness ratio, OD/t (ref)	Distance between plates ^a	16t	14t	12t	10t	8t	Remarks
1 x .080	Reactive Metals	XBMS 7-234	304450-03	12.5	12t = 0.96	—	—	0.96 in. OD-S ID-S	0.80 in. OD-OP ID-S	0.64 in. OD-S ID-S	Good surfaces. Tube showed satisfactory results at 8t.
1 x .080	Zirtech	XBMS 7-234	BC9014032-125R	12.5	12t = 0.96	—	—	0.96 in. OD-S ID-OP	0.80 in. OD-S ID-S	0.64 in. OD-CC ID-CC	OD had bright surface. ID had stains after vacuum annealing. Tube showed satisfactory results at 10t.
1 x .080	Bishop	XBMS 7-234A	704511-06	12.5	12t = 0.96	—	—	0.96 in. OD-S ID-S	0.80 in. OD-S ID-S	0.64 in. OD-S ID-S	Good surface but had striker marks. Tube showed satisfactory results at 10t.
1 x .033	Reactive Metals	XBMS 7-203A	294804-24	30.3	15t = 0.495	0.53 in. OD-S ID-S	0.46 in. OD-S ID-S	0.40 in. OD-CC ID-CC	0.33 in. OD-CC ID-CC	—	ID had heavy chemical milling. OD had good surface, but had fine sand marks. Tube showed satisfactory results at 14t.
1 x .033	Bishop	XBMS 7-234A	704511-06	30.3	15t = 0.495	0.53 in. OD-OP ID-S	0.46 in. OD-S ID-S	0.40 in. OD-CC ID-C&OP	0.33 in. OD-CC ID-C	—	OD and ID had heavy chemical milling. Tube showed satisfactory results at 14 t.
5/8 x .050	Zirtech	XBMS 7-234	BF07058	12.5	12t = 0.60	—	—	0.60 in. OD-S ID-S	0.50 in. OD-S ID-OP	0.40 in. OD-CC ID-CC	Average surfaces. Tube showed satisfactory results at 10t.
5/8 x .050	Superior	XBMS 7-234A	304450-03	12.5	12t = 0.60	—	—	0.60 in. OD-S ID-S	0.50 in. OD-S ID-S	0.40 in. OD-S ID-S	Brighter and smoother surface than 5/8 x .050 Zirtech. Tube showed satisfactory results at 8t.
5/8 x .021	Zirtech	XBMS 7-234	BF07058	29.8	15t = 0.315	0.33 in. OD-C ID-C	0.29 in. OD-C ID-C	0.25 in. OD-CC ID-CC	0.21 in. OD-OP&C ID-C	—	Surfaces showed heavy chemical milling. Tube was unsatisfactory at 16t.
5/8 x .021	Superior	XBMS 7-234A	304450-03	29.8	15t = 0.315	0.33 in. OD-S ID-S	0.29 in. OD-S ID-S	0.25 in. OD-S ID-S	0.21 in. OD-OP ID-S	—	Good surfaces with fine sanding marks on OD. Tube showed satisfactory results at 10t.
3/8 x .020	Zirtech	XBMS 7-234	BF10059	18.75	15t = 0.30	0.32 in. OD-S ID-S	0.28 in. OD-S ID-S	0.24 in. OD-C ID-C	0.20 in. OD-CC ID-CC	—	Good ID surface. Tube showed satisfactory results at 14t.
3/8 x .020	Zirtech	^b XBMS 7-234	BF10059	18.75	15t = 0.30	0.32 in. OD-S ID-S	0.28 in. OD-S ID-S	0.24 in. OD-S ID-S	0.20 in. OD-CC ID-S	—	Heavy chemical milling on OD. ID showed fabrication marks. Tube showed satisfactory results at 12t.
3/8 x .020	Superior	^c XBMS 7-234	304450	18.75	15t = 0.30	0.32 in. OD-S ID-S	0.28 in. OD-S ID-S	0.24 in. OD-S ID-S	0.20 in. OD-S ID-S	—	Good surfaces. Tube showed satisfactory results at 10t.
3/8 x .020	Superior	XBMS 7-234A	304450-03	18.75	15t = 0.30	0.32 in. OD-S ID-S	0.28 in. OD-S ID-S	0.24 in. OD-S ID-S	0.20 in. OD-S ID-S	—	Good surfaces with fine sand marks on OD. Tube showed satisfactory results at 10t.
3/8 x .030	Superior	XBMS 7-234A	304450-03	12.5	12t = 0.36	—	—	0.36 in. OD-S ID-S	0.30 in. OD-S ID-S	0.24 in. OD-CC ID-CC	Good surfaces with very fine sand marks on OD. Tube showed satisfactory results at 10t.

^aRequirement of paragraph 6.8

^bTube ID grit blasted and chemically milled per Grumman requirements

^cTubing has crystallographic texture control

OD = outside diameter
ID = inside diameter
OP = orange peel appearance
C = cracked one side
cc = cracked both sides
s = satisfactory
t = wall thickness (in.)

The 1 x .033 tubes were made by two manufacturers and to different specifications. Results showed the Bishop tubing per XBMS 7-234A to be the best; however, both are satisfactory at 14t, the acceptable value being 15t.

The 5/8 x .050 tubes were made by two manufacturers and to different specifications. Results show that Superior Tubing per specification XBMS 7-234A gave satisfactory results at 8t. The Zirtech tubing was also satisfactory at only 10t, the acceptable value being 12t.

The 5/8 x .021 tubes were made by two suppliers and to different specifications. Results show that the Superior tubing per XBMS 7-234A was satisfactory at 10t, whereas the Zirtech tubing per XBMS 7-234 was unsatisfactory at 16t. The acceptable value is 15t.

The four types of 3/8 x .020 tubes were made by two suppliers and to different specifications. Results show both Superior tubes per XBMS 7-234 with texture control and per XBMS 7-234A to be the most satisfactory at 10t. The Zirtech tubes per XBMS 7-234 were satisfactory at 12t and 14t only. The acceptable value is 15t.

The 3/8 x .030 tube had limited quantities and only one size was tested. The Superior tube per XBMS 7-234A showed satisfactory results at 10t, the acceptable value being 12t.

In summary, the results show that the texture-controlled tubing to the new proposed specification (XBMS 7-234A) has the best formability.

5.2 MECHANICAL PROPERTIES OF VARIOUS Ti-3Al-2.5V (CWSR) TUBES

The mechanical properties of various Ti-3Al-2.5V cold worked and stress relieved (CWSR) tubes were determined for design use and comparison between manufacturers. Tests were conducted on 1 x .080, 1 x .033, 5/8 x .050, 3/8 x .030, and 3/8 x .020 in. tube sizes. All sizes were tested at room temperature, and, in addition, the 5/8 x .050 and 3/8 x .030 were tested at 450°F. Complete test results are shown in table 15.

Evaluation of the mechanical properties, based upon two tests in each size, shows good correlation on the ultimate tensile strength (F_{tu}) and yield strength (F_{ty}) at 0.2% offset. Average room temperature values for F_{tu} were 123,250 psi to 126,400 psi and for F_{ty} were 106,100 psi to 111,200 psi. The specification minimum requirements for F_{tu} and F_{ty} were 125,000 psi and 105,000 psi respectively. The 450°F values for F_{tu} were 97,900 psi to 100,150 psi and for F_{ty} were 83,150 psi to 85,100 psi.

The modulus of elasticity values showed some variation when comparing two tubes of the same heat number and also the tubes made by different manufacturers. Average room temperature values were 13.25×10^6 . For accurate calculations the specific modulus of elasticity value for the tube being tested or analyzed should be determined by tensile tests per ASTM procedure E8-68.

TABLE 15.—MECHANICAL PROPERTIES OF VARIOUS Ti-3Al-2.5V (CWSR) TUBES AT RT AND 450° F

Specimen	Manufacturer	Heat no.	Lot no.	Specification	Length (in.)	OD (in.)	ID (in.)	Area (in. ²)	Test temp. (°F)	Ultimate strength, F _{tu} (ksi)	Avg F _{tu}	Yield strength, F _{ty} (ksi)	Avg f _{ty}	Modulus of elasticity, E (psi x 10 ⁶)	Avg E
1	Zirtech	BF10059	—	XBMS 7-234	7.25	0.3772	0.3338	0.0242	72	125.2	125.3	110.3	110.5	13.8	14.0
2	Zirtech	BF10059	—	XBMS 7-234	↓	0.3772	0.3341	0.0241	72	125.4	125.3	110.7	110.5	14.2	14.0
3	Superior	304450	—	^a XBMS 7-234	↓	0.3781	0.3368	0.232	78	124.3	123.25	108.3	107.25	15.6	14.85
4	↓	304450	—	^a XBMS 7-234	↓	0.3781	0.3364	0.0235	↓	122.2	123.25	106.2	107.25	14.1	14.85
5	↓	304450-03	1	XBMS 7-234A	↓	0.3778	0.3338	0.0246	↓	123.1	124.25	108.7	1.094	13.3	13.25
6	↓	↓	↓	↓	↓	0.3778	0.3342	0.0244	↓	125.4	124.25	110.1	1.094	13.2	13.25
7	↓	↓	↓	↓	↓	0.3775	0.3338	0.0244	450	97.7	97.9	83.1	83.15	12.1	12.5
8	↓	↓	↓	↓	↓	0.3775	0.3342	0.0242	450	98.1	97.9	83.2	83.15	12.9	12.5
9-2	↓	↓	↓	↓	↓	0.3782	0.3248	0.0345	78	132.0	131.85	115.3	116.05	14.0	13.95
10	↓	↓	↓	↓	7.25	0.3784	0.3148	0.0346	72	131.7	131.85	116.8	116.05	13.9	13.95
11	↓	↓	↓	↓	9.00	0.6285	0.5248	0.0939	450	99.2	100.15	84.3	85.1	11.7	11.35
12	↓	↓	↓	↓	9.00	0.6280	0.5249	0.0928	450	101.1	100.15	85.9	85.1	11.0	11.35
13	Bishop	704511-06	1-1	↓	11.70	1.0050	0.9378	0.1026	80	127.5	126.3	111.8	111.2	15.6	14.9
14	Bishop	704511-06	1-1	↓	11.70	1.0045	0.9358	0.1047	80	125.1	126.3	110.6	111.2	14.2	14.9
15	Reactive Metals	304450-03	—	XBMS 7-234	11.30	1.0052	0.8394	0.2402	82	123.8	126.4	103.9	104.65	14.1	14.5
16	Reactive Metals	304450-03	—	XBMS 7-234	↓	1.0055	0.8428	0.2362	↓	129.0	126.4	105.4	104.65	14.9	14.5
17	Bishop	704511-06	—	XBMS 7-234A	↓	1.0020	0.8464	0.2258	↓	124.6	125.35	105.4	106.1	14.7	14.9
18	Bishop	704511-06	—	XBMS 7-234A	↓	1.0025	0.8462	0.2269	↓	126.1	125.35	106.8	106.1	15.1	14.9

^aTubing has crystallographic texture control

5.3 CHARACTERISTIC CURVES OF DEFLECTION VERSUS CYCLES AND STRESS VERSUS CYCLES FOR 1 x .080 SPECIMENS

The 1 x .080 characteristic curves for parts I and II showing deflection versus cycles and stress versus cycles were constructed from the rotary flexure test results in tables 6 and 11, and are shown in figures 34 and 35, respectively. The test results from parts I and II are shown on the same figure so a direct comparison can be made.

The deflection versus cycle curve shows the deflection (double amplitude) used for the tests and cycles to failure or a maximum of 10^7 cycles if no failure occurred. The stress versus cycle curve shows the calculated longitudinal stress at the point of failure and cycles. If no failure occurred the stress was calculated for the maximum stress at $\theta = 90^\circ$ and $\phi = 270^\circ$ in the bend.

The deflection and stress curves indicate similar results. The Boeing tubing procured during the prototype SST program and the same tubing with the inside diameter finished per the Grumman and McDonnell-Douglas specifications showed no significant difference because the majority of failures originated on the OD surface, and therefore the improved ID finish would not increase the fatigue life.

The Bishop tubing tested in part II made to the new specification XBMS 7-234A did not give the expected fatigue life, but this was to be expected because of transverse sanding "striker" marks on the OD surface.

After evaluating these test results, 25 ft of tubing was returned to Bishop for additional chemical milling to improve the outside surface. Upon return to Boeing, the tubing surface was re-examined and was found to be improved, but still contained some sanding marks (see fig. 25). The flexure tests on this tubing showed some improvement, but the tubing did not meet the performance expected for texture-controlled and properly finished tubing. Additional chemical milling would have improved the OD surface, but could not be done in time for this program. Bishop reported that these marks originated with the hollows used and that experimentation with different chemical milling techniques is required to optimize this finishing method. It is on the basis of this experience that a pictorial requirement was added to the specification.

In addition to the surface condition, the poor tube texture indicated in table 10 and in the pole figures also likely contributed to the poor fatigue performance of this tubing. The R-ratio of 0.31 for the Bishop 1 x .080 tubing was considerably lower than for the RMI 1 x .080 tubing tested during part I ($R = 0.7$ to 1.15).

The stress ratios for fatigue testing ranged from minimum of $R = 0.330$ to $R = 0.420$ (appendix B). This range is considered essentially constant and results in a good S-N curve.

5.4 CHARACTERISTIC CURVES OF DEFLECTION VS CYCLES AND STRESS VS CYCLES FOR 3/8 X .020 SPECIMENS

The 3/8 x .020 characteristic curves for parts I and II showing deflection vs cycles and stress vs cycles were constructed from the rotary flexure test results in tables 6 and 11, and are shown in figures 36 and 37. The test results from parts I and II are shown on the same figure so a direct comparison can be made.

The deflection vs cycle curve shows the deflection (double amplitude) used for the tests and cycles to failure or a maximum of 10^7 cycles if no failure occurred. The stress versus cycle curve shows the calculated circumferential stress at the point of failure and the number of cycles. If no failure occurred, the stress was calculated for the maximum stress at $\theta = 90^\circ$ and $\phi = 0^\circ$ in the bend.

The tests conducted in part I were on the Boeing tubing procured during the prototype SST program and the same tubing with the inside diameter finished per the Grumman and McDonnell-Douglas specifications. The tubes made per the Grumman specification, which specified grit blasting and chemical milling on the ID surface, showed a significant improvement in fatigue life over the as-processed tubing, as did the pressure-tested tubing. In addition, the Superior tubing made per XBMS 7-234 with crystallographic texture control was evaluated, and results showed better fatigue properties than for the Boeing tubing with the ID reworked to the Grumman specification. The Superior tubing ID had been grit blasted and chemically milled.

The tube failures originated on the ID surface and in the neutral axis as predicted by the stress analysis (appendix B). The outside surfaces showed some sanding marks, which were not considered serious to this test because the failures were predicted to originate on the ID. Based on the results in part I the new proposed specification XBMS 7-234A with the crystallographic texture control was used for part II.

The tests conducted in part II (specimens 6RST-1 through -8) showed good fatigue life, but slightly lower than that of the texture-controlled tubing tested in part I. The comparison of the pole figure results for parts I and II shown in figures 6 and 7, respectively, shows that the tubing used for part I had better texture. The texture difference was also demonstrated in the R-ratio values for the respective tubes. The tubing of part I has R values ranging from 0.73 to 0.94, whereas the tubing with the lower fatigue performance had an R value of 0.49.

The fatigue stress ratios ranged from a minimum of $R = 0.039$ to $R = 0.150$. This range is considered essentially constant and results in a good S-N curve.

6.0 CONCLUSIONS

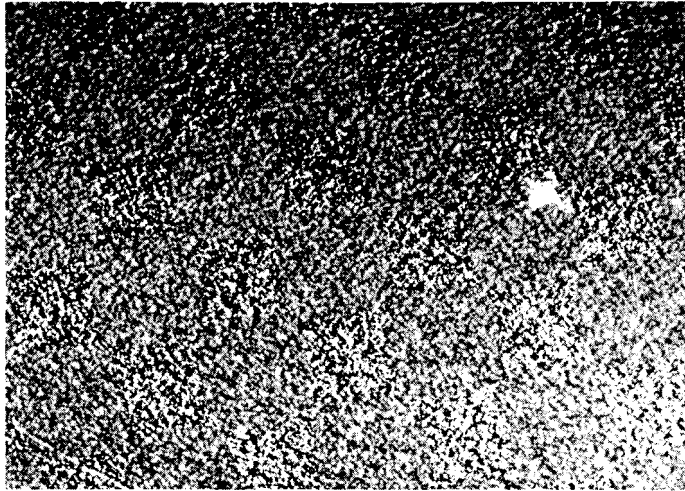
1. The data indicate that the new requirements of ultrasonic inspection, surface finish, and crystallographic texture for titanium 3Al-2.5V CWSR tubing ensure an improved and reliable performance in hydraulic flexure and impulse testing of tubing bends and tube-fitting assemblies. The incorporation of more stringent controls on tubing starting stock is also expected to result in an improved and consistent quality product.
2. Fatigue testing of 120° bends and impulse testing at 450° proved to be a good method to evaluate different tubing textures and surface finishes.
3. Color anodizing and formability tests were not found to be sensitive criteria for inspection of tubing texture.
4. Basal plane pole figures and R-ratio data were found to be good methods for analysis and inspection of tubing texture. The R-ratio measurements were affected, however, by the equipment and operating technique used and will require continued improvement and refinement.
5. Requirements for chemical milling and RHR surface finish alone were not sufficient to ensure a good surface. Until chemical milling or other surface finishing methods are further developed, a pictorial surface finish requirement will be needed.
6. The texture developed in Ti-3Al-2.5V tubing can be generally correlated to the ratio of diameter reduction to wall reduction.

7.0 RECOMMENDATIONS

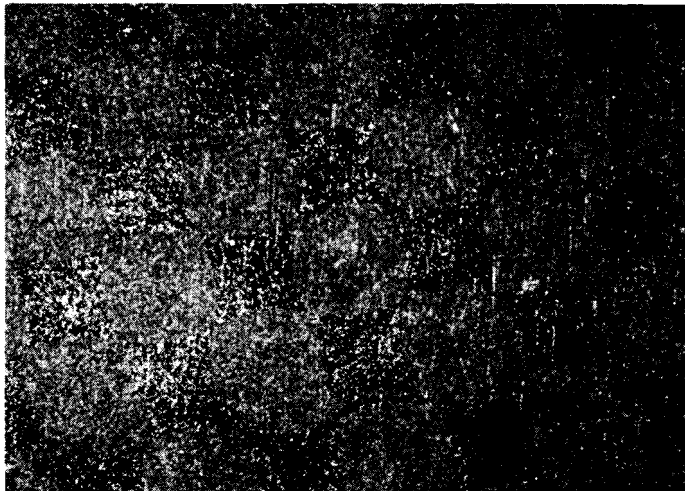
1. To achieve the same texture (R-ratio) in various tube sizes, 5/8 x .021 and 5/8 x .050 in. for example, different starting stock would be used to achieve the same degree of metal working. This is indicated by the good performance and R-ratio of thin-walled tubing compared to the poorer performance and R-ratio for heavy-walled tubing in the 3/8-in. tubing tested.
2. The techniques and tools for measuring the R-ratio of tubing texture require further development.
3. The optimum tubing texture and texture control should be established by systematic study and test. Fatigue properties should be determined for tubes with markedly different textures, and the effects of annealing cycles, reduction ratios, drawing, rolling, and extruding evaluated to quantitatively determine their effects on texture development.
4. The efficiency of ultrasonic inspection and/or other NDT methods should be improved.
5. The chemical milling techniques should be evaluated and optimized.
6. The degree of additional optimization of titanium tubing by shot peening should be established and the effects of residual stresses in the tubing further evaluated.
7. The above-mentioned recommendations for further work should not delay the acceptance of the new specification criteria by the industry and the military services. It is recommended that the proposed specification (appendix A) be the basis for a military specification for hydraulic tubing.

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3. *SST Technology Follow-On Program—Phase I, Reconnectable Titanium Fittings with Weld-Attached Sleeves for the Hydraulic System*, Boeing document D6-60262, October 1972.
4. *SST Technology Follow-On Program—Phase I, Repair Fittings and Repair Techniques for the Titanium Hydraulic Tubing*, Boeing document D6-60264, October 1972.
5. Boeing Specification XBMS 7-234, "Titanium 3Al-2.5V Seamless Tubing for Hydraulic Systems, Cold Worked and Stress Relieved."
6. Boeing Specification BAC 5423, "Penetrant Methods of Inspection."
7. Boeing Specification ARP 1185, "Flexure Testing of Hydraulic Tubing Joints and Fittings."
8. Boeing Specification BAC 5439-2, "Ultrasonic Inspection of Tubing."
9. *SST Technology Follow-On Program—Phase I, Titanium Alloy 6Al-4V and 3Al-2.5V Hydraulic Tubing*, Boeing document D6-60205.



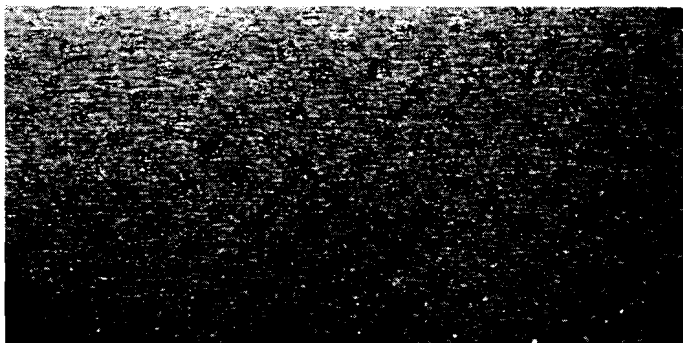
(a) Rough Surface of Tubes 4, 5, and 6 (20X)



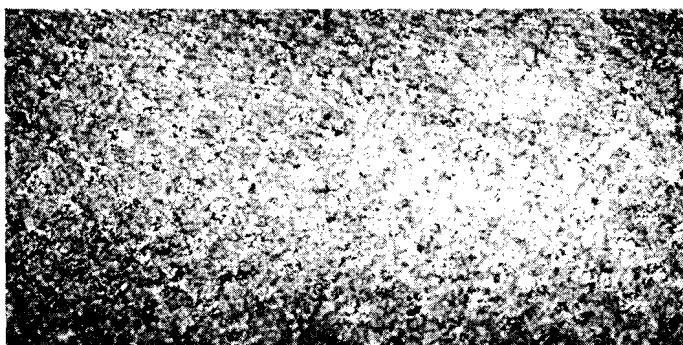
(b) Smooth Surface of Tube 7 (Superior) (20X)

See table 2 for tube description

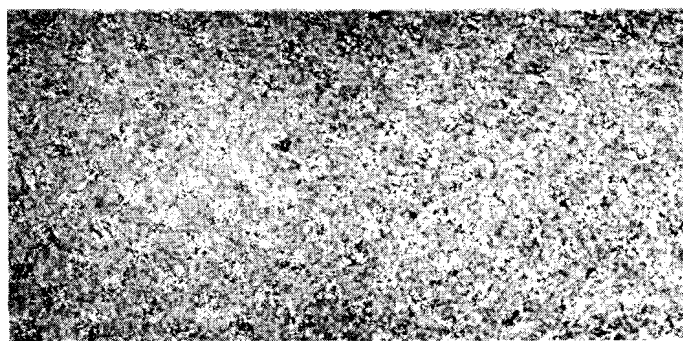
FIGURE 1.—TYPICAL 3Al-2.5V CWSR TITANIUM TUBE SURFACE CONDITION



Tube 4 (Zirtech)
As Received Surface
Condition (Detergent
Clean + "Flash Pickle")
(20X)

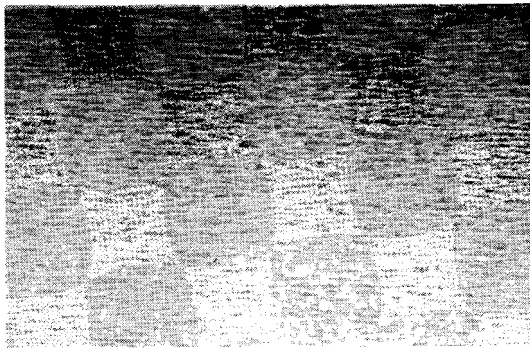


Tube 6 (Zirtech)
Grit Blast + Chem Mill
(20X)

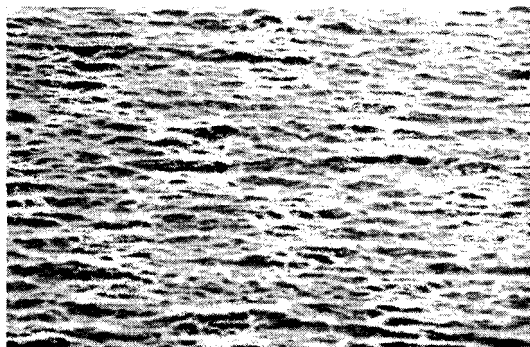


Tube 7 (Superior)
Grit Blast + Chem Mill
(20X)

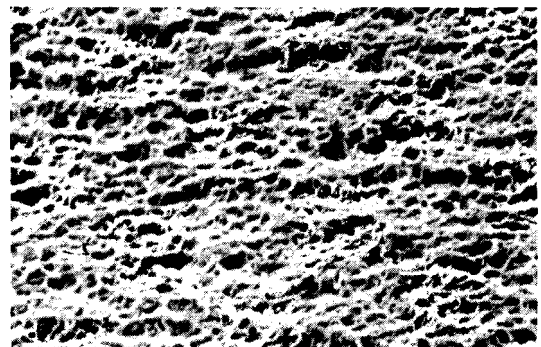
*FIGURE 2.—SURFACE CONDITION OF THE 3Al-2.5V CWSR TITANIUM TUBING
AFTER SPECIAL FINISHING*



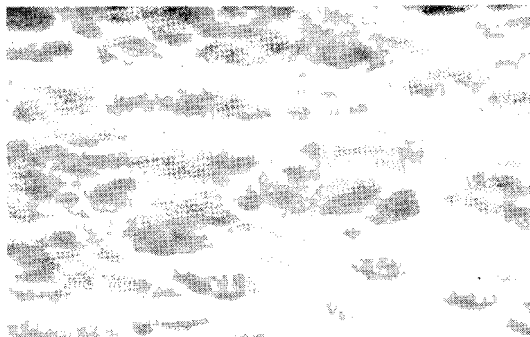
(a) Transverse Beam Direction (60X)



(b) Transverse Beam Direction (240X)



(c) Longitudinal Beam Direction (260X)



(d) Transverse Beam Direction (1200X)

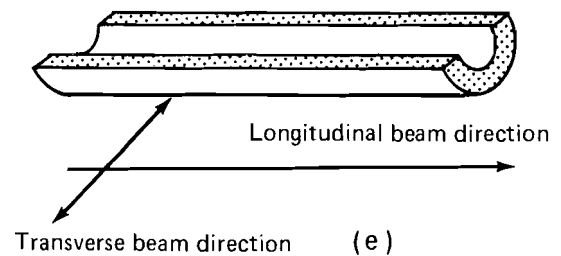
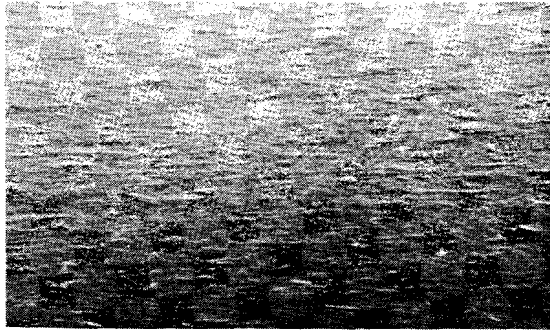
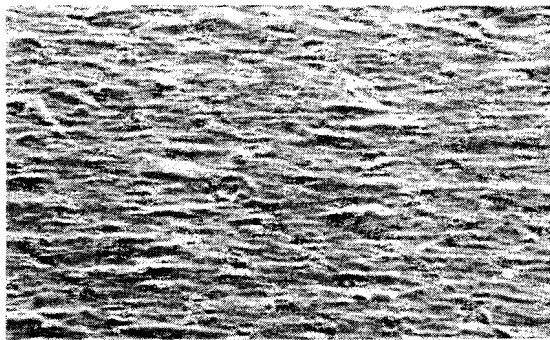


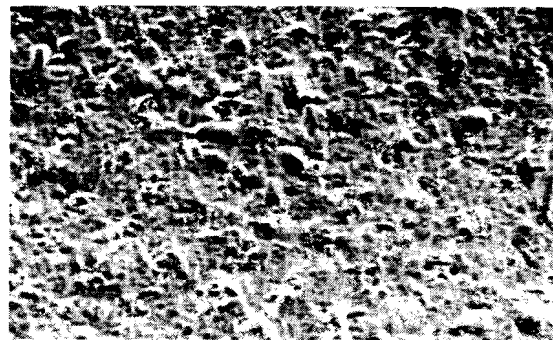
*FIGURE 3.—SCANNING ELECTRON MICROGRAPHS OF ID SURFACE OF
TUBE 4—AS-PROCESSED SURFACE FINISH*



(a) Transverse Beam Direction (60X)



(b) Transverse Beam Direction (240X)



(c) Longitudinal Beam Direction (260X)



(d) Transverse Beam Direction (1200X)

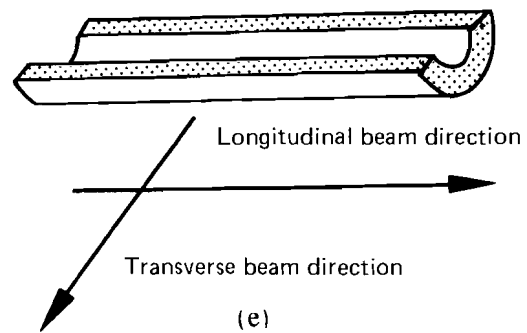
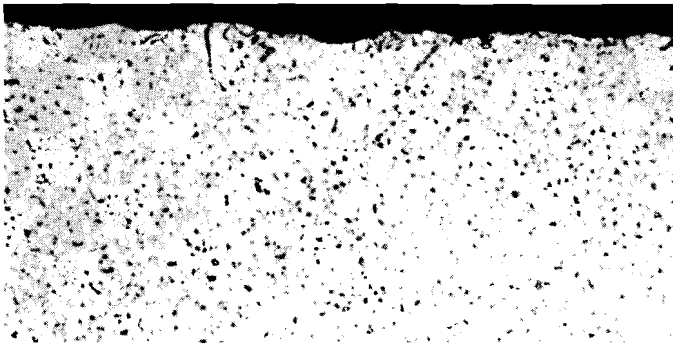
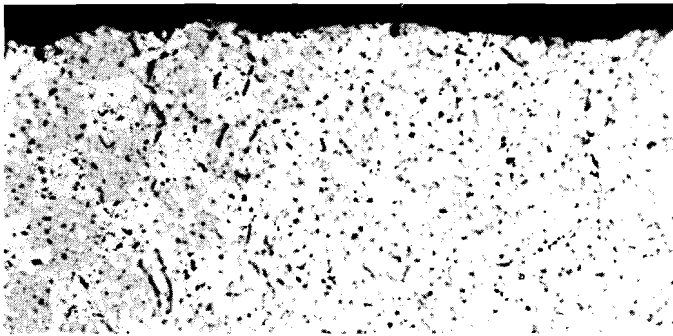


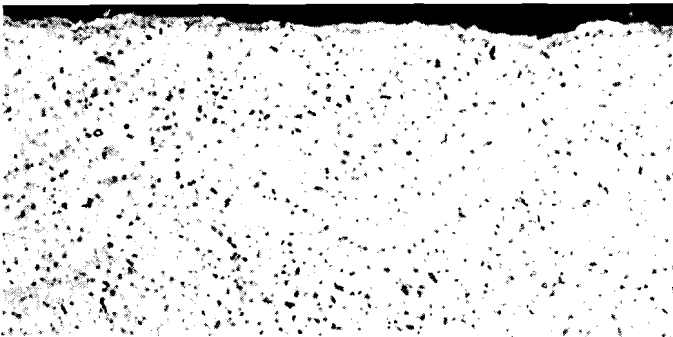
*FIGURE 4.—SCANNING ELECTRON MICROGRAPHS OF ID SURFACE OF TUBE 6
AFTER SPECIAL FINISHING*



(a) Tube 1—Transverse Section

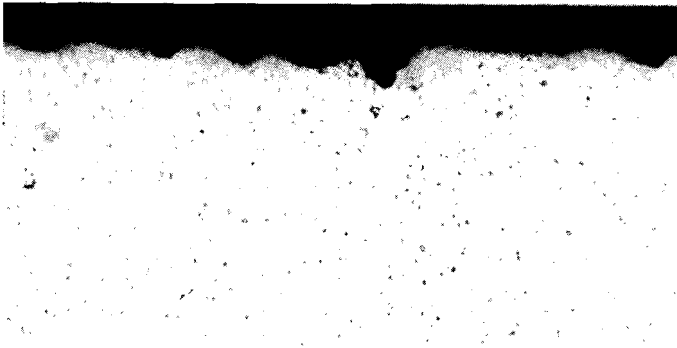


(b) Tube 2—Transverse Section

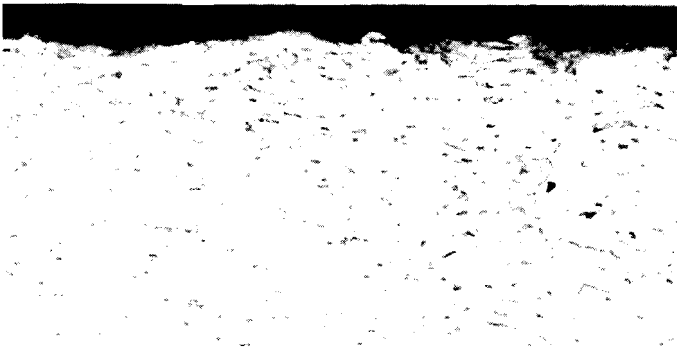


(c) Tube 3—Transverse Section

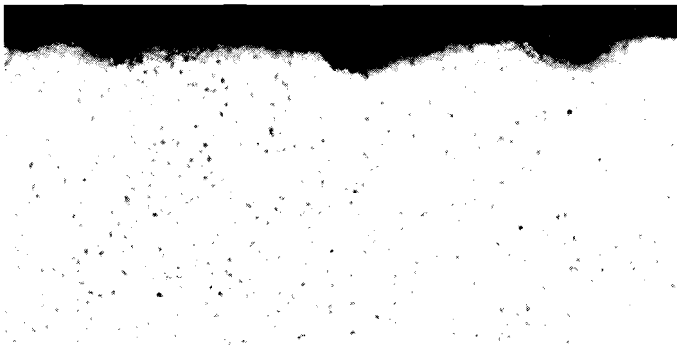
FIGURE 5.—PHOTOMICROGRAPHS SHOWING SECTIONS AND SURFACE OF TYPICAL AND SPECIALLY FINISHED TITANIUM TUBING, 3/8 SIZE, TUBES 1, 2, AND 3 (500X)



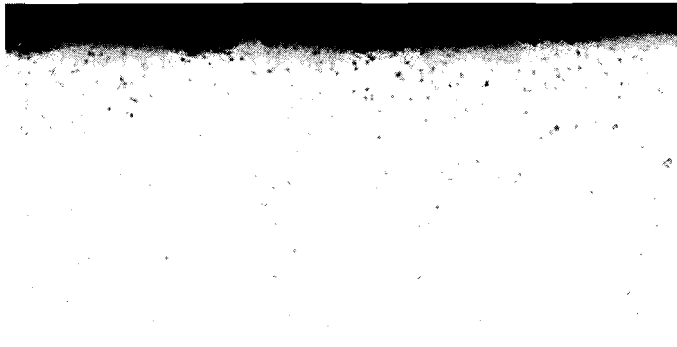
Tube 4—Transverse Section



Tube 4—Longitudinal Section



Tube 5—Transverse Section

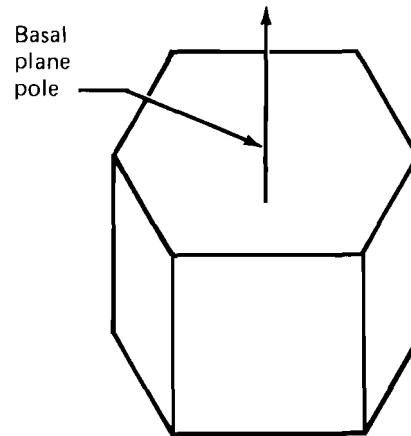


Tube 6—Transverse Section

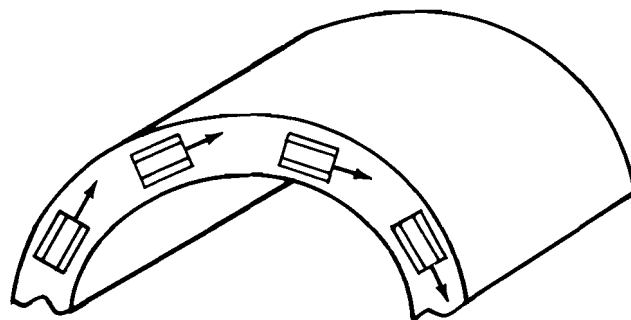
FIGURE 6.—PHOTOMICROGRAPH SHOWING SECTIONS AND SURFACE OF TYPICAL AND SPECIALLY FINISHED TITANIUM TUBING, 3/8 SIZE, TUBES 4, 5, AND 6 (500X)

Unit Cell of Titanium

Hexagonal close-packed structure

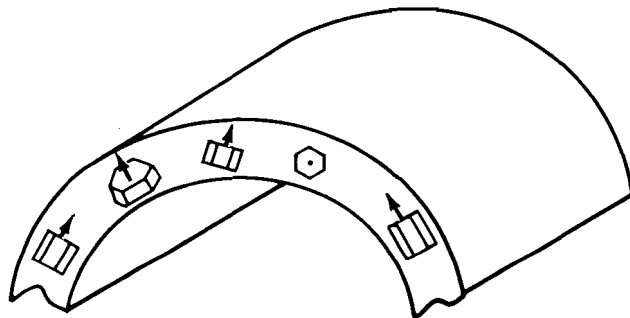


Circumferential
Texture of Basal Plane
Poles



Cross-section through a tube

Random Texture of Basal
Plane Poles



Radial Texture of
Basal Plane Poles

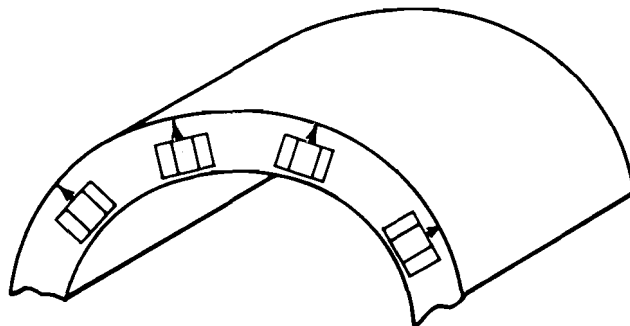


FIGURE 7.—CRYSTALLOGRAPHIC TEXTURE IN TITANIUM TUBES

$$R = L_n (OD_f/OD_o) \div L_n (W_f/W_o)$$

Where: R = strain ratio
 L_n = natural log
 f = final dimension, after testing
 o = original dimension, before testing
 OD = outside diameter (average of several measurements)
 W = wall thickness (average of at least four measurements around circumference)

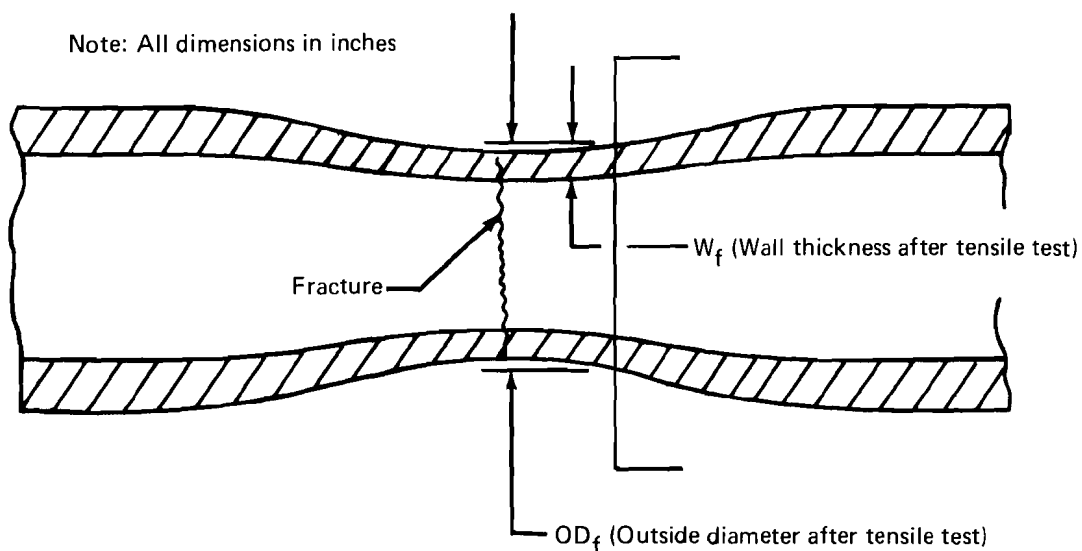
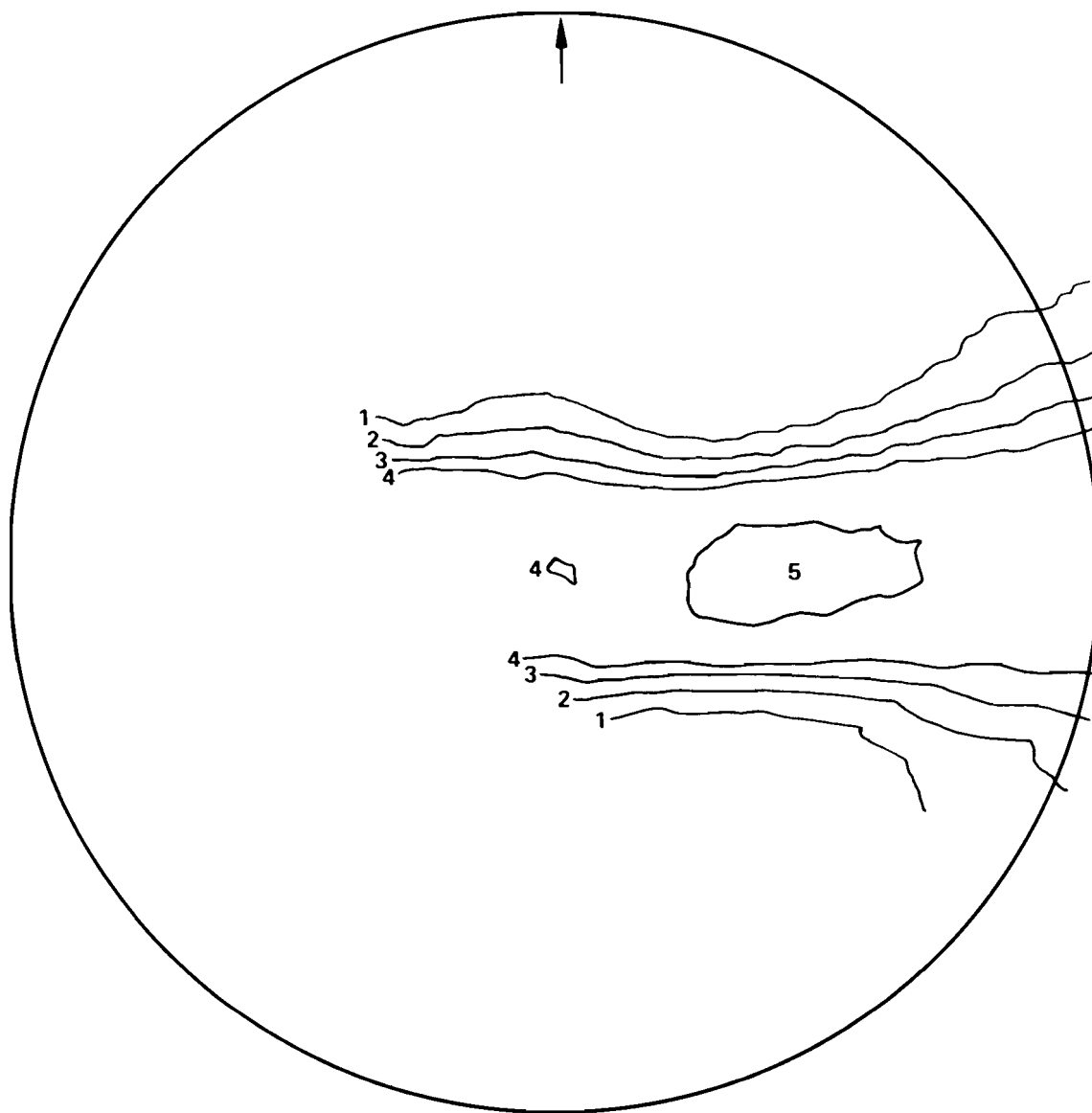
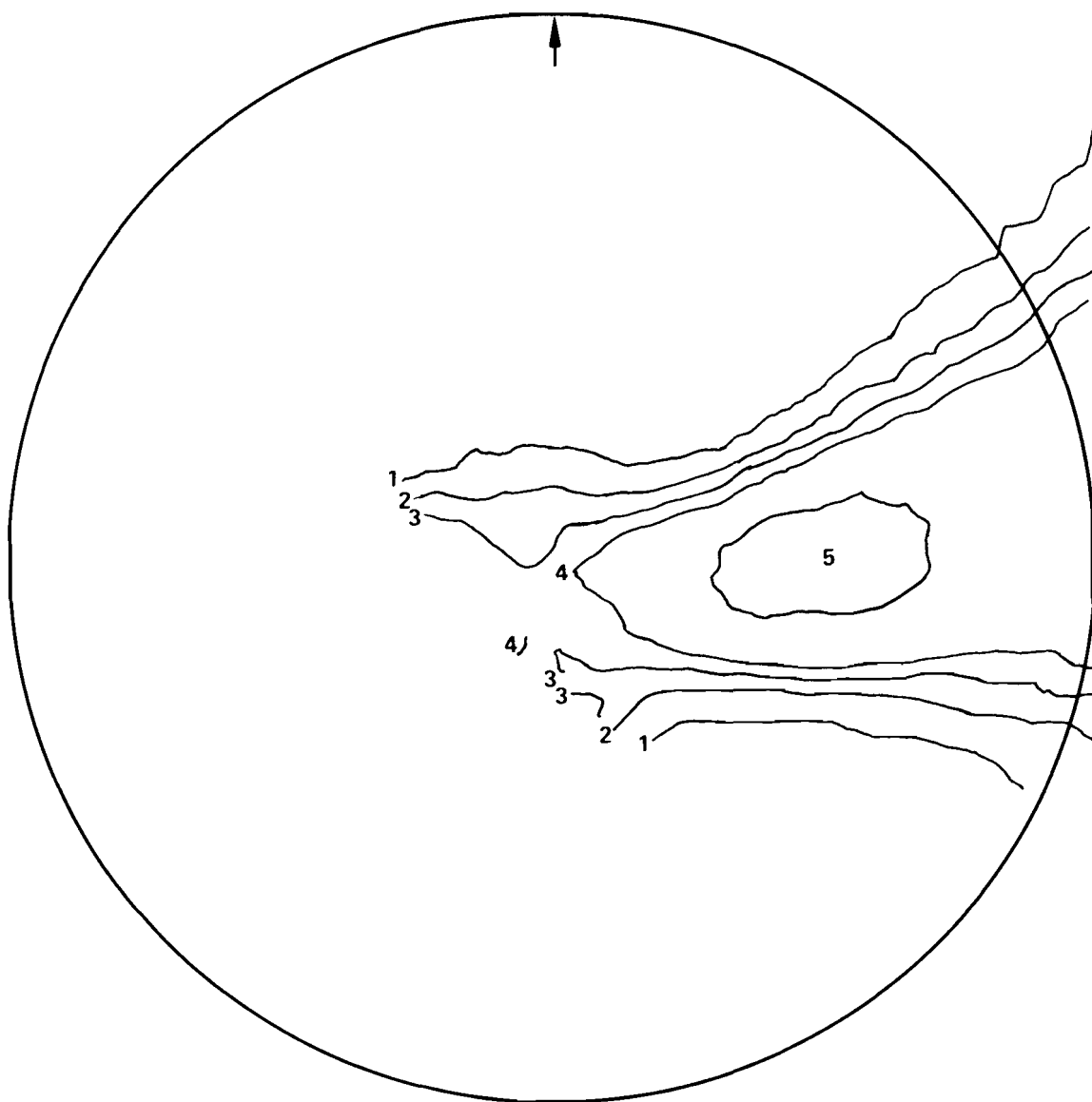


FIGURE 8.—METHOD FOR MEASURING STRAIN RATIO "R"



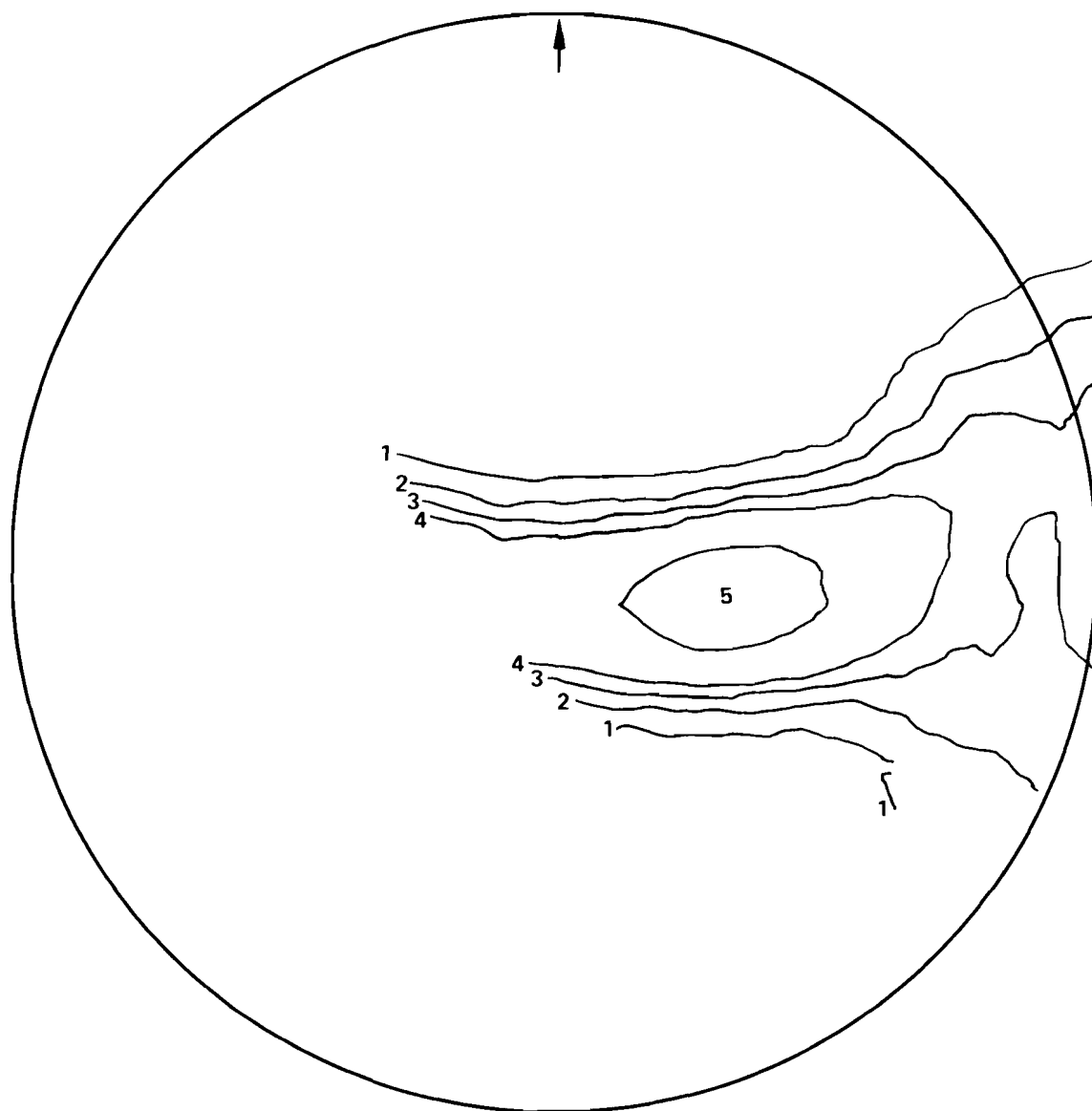
Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 9.—BASAL PLANE POLE FIGURE FOR 1 X .080 IN. RMI TUBE
(TUBE 1 PER TABLE 4)



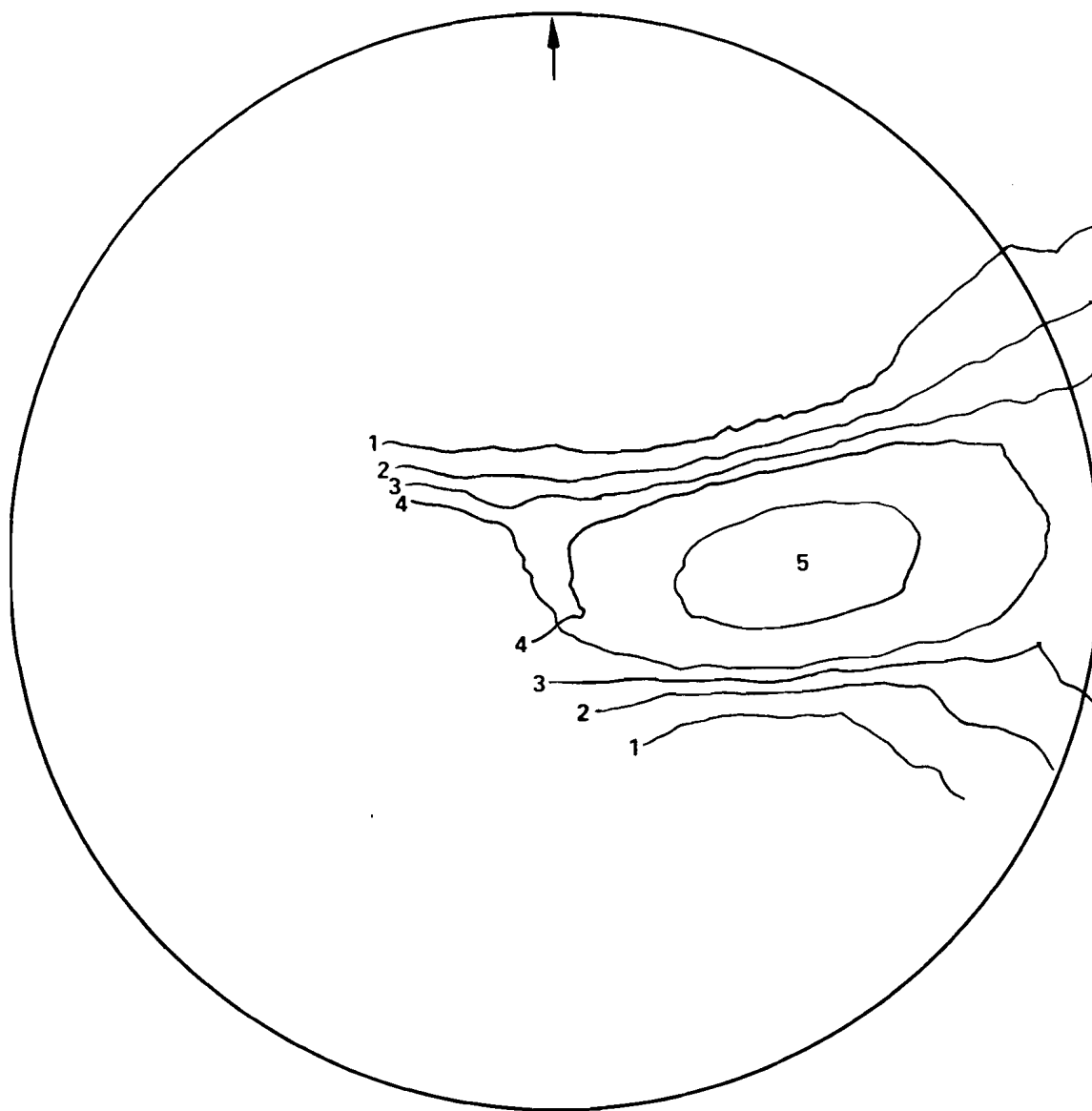
Contour lines	1	2	3	4	5
Times random X-ray intensity	.5	1.0	1.5	2.0	4.0

FIGURE 10.—BASAL PLANE POLE FIGURE FOR 3/8 X .020 IN. ZIRTECH
TUBE (TUBE 4 PER TABLE 4)



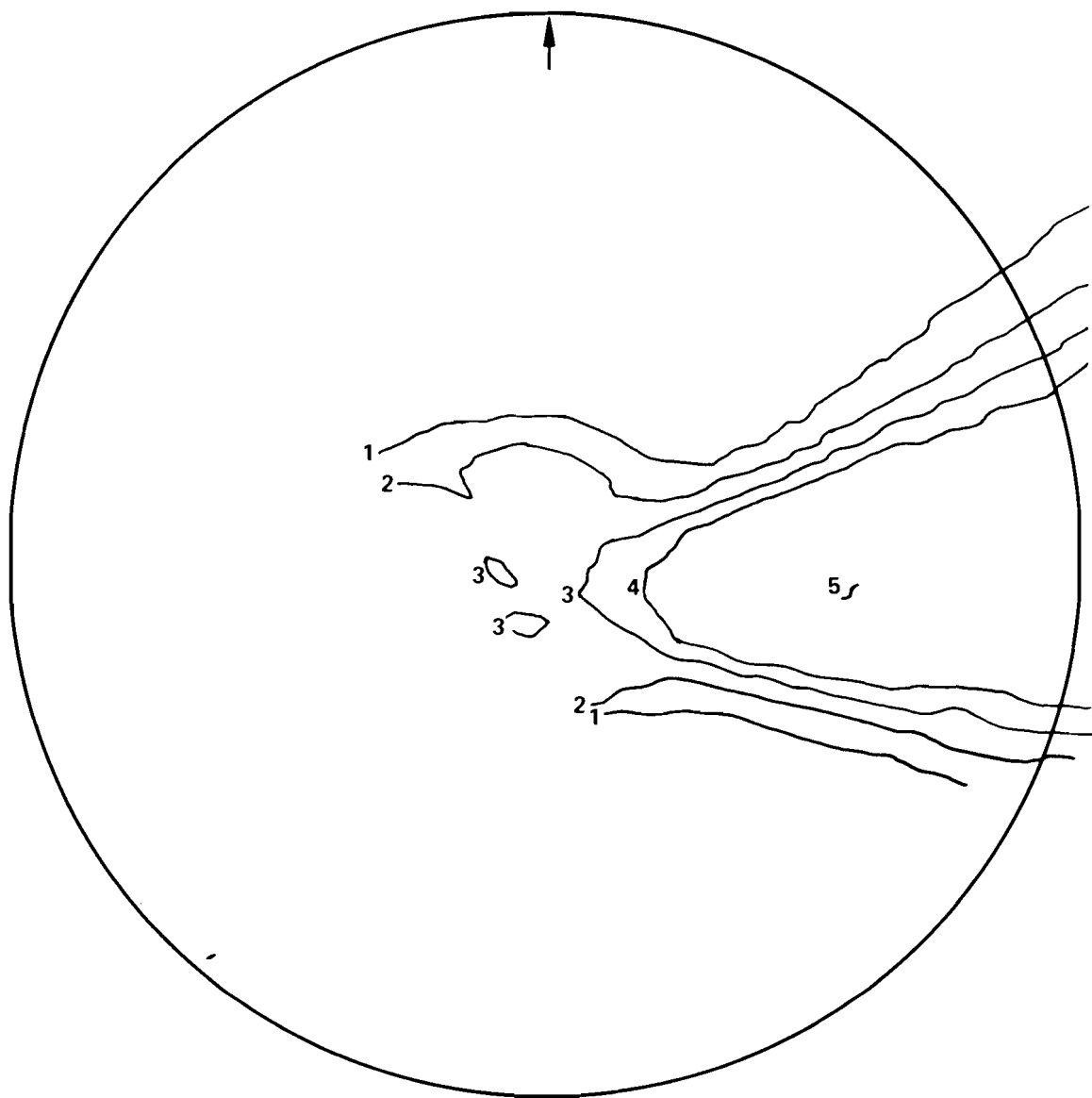
Contour lines	1	2	3	4	5
Times random X-ray intensity	.5	1.0	1.5	2.0	4.0

FIGURE 11.—BASAL PLANE POLE FOR 3/8 X .020 IN. SUPERIOR TUBE
(TUBE 7 PER TABLE 4)



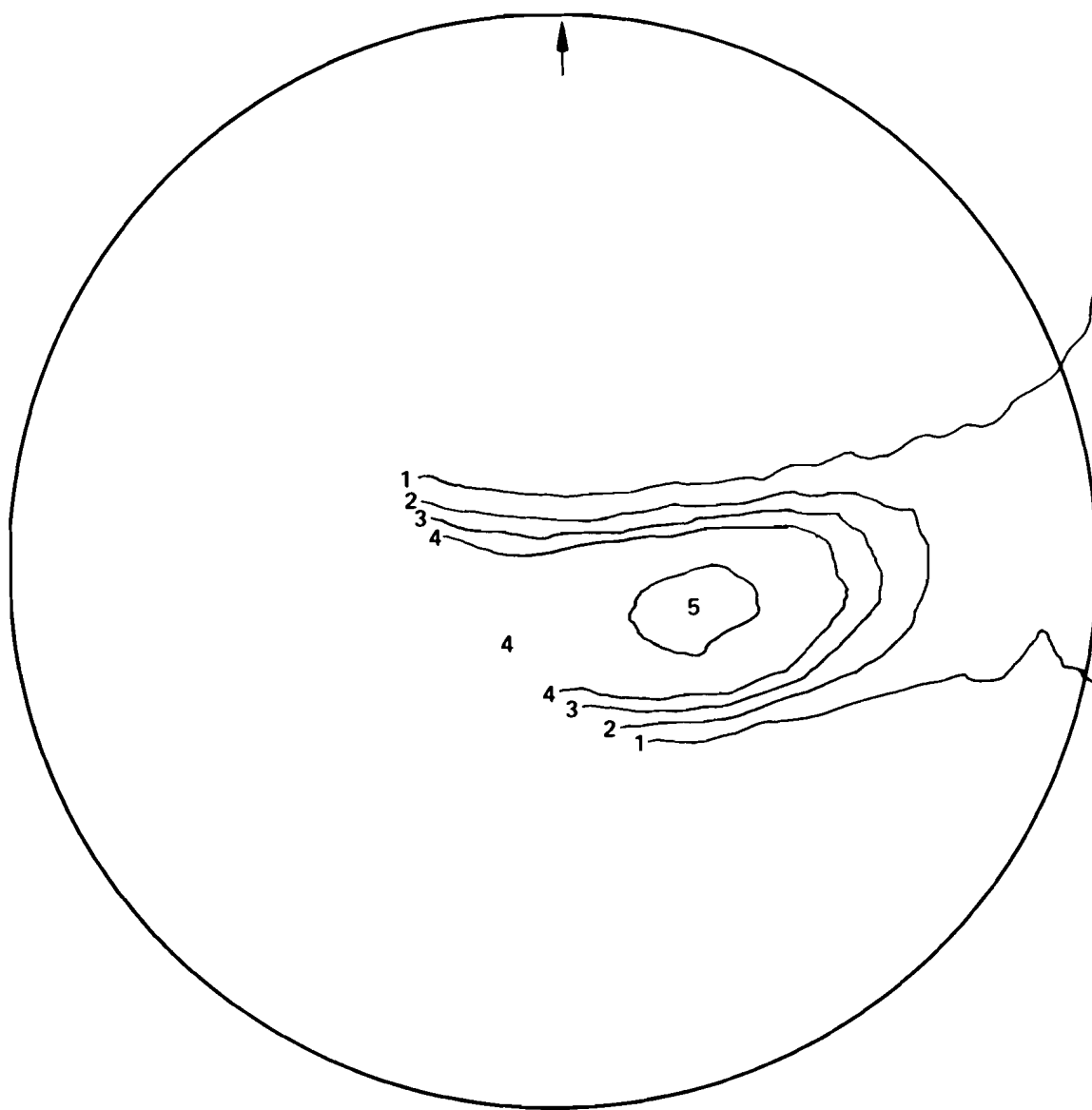
Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 12.—BASAL PLANE POLE FIGURE FOR 5/8 X .040 IN. SUPERIOR TUBE
(TUBE 8 PER TABLE 4)



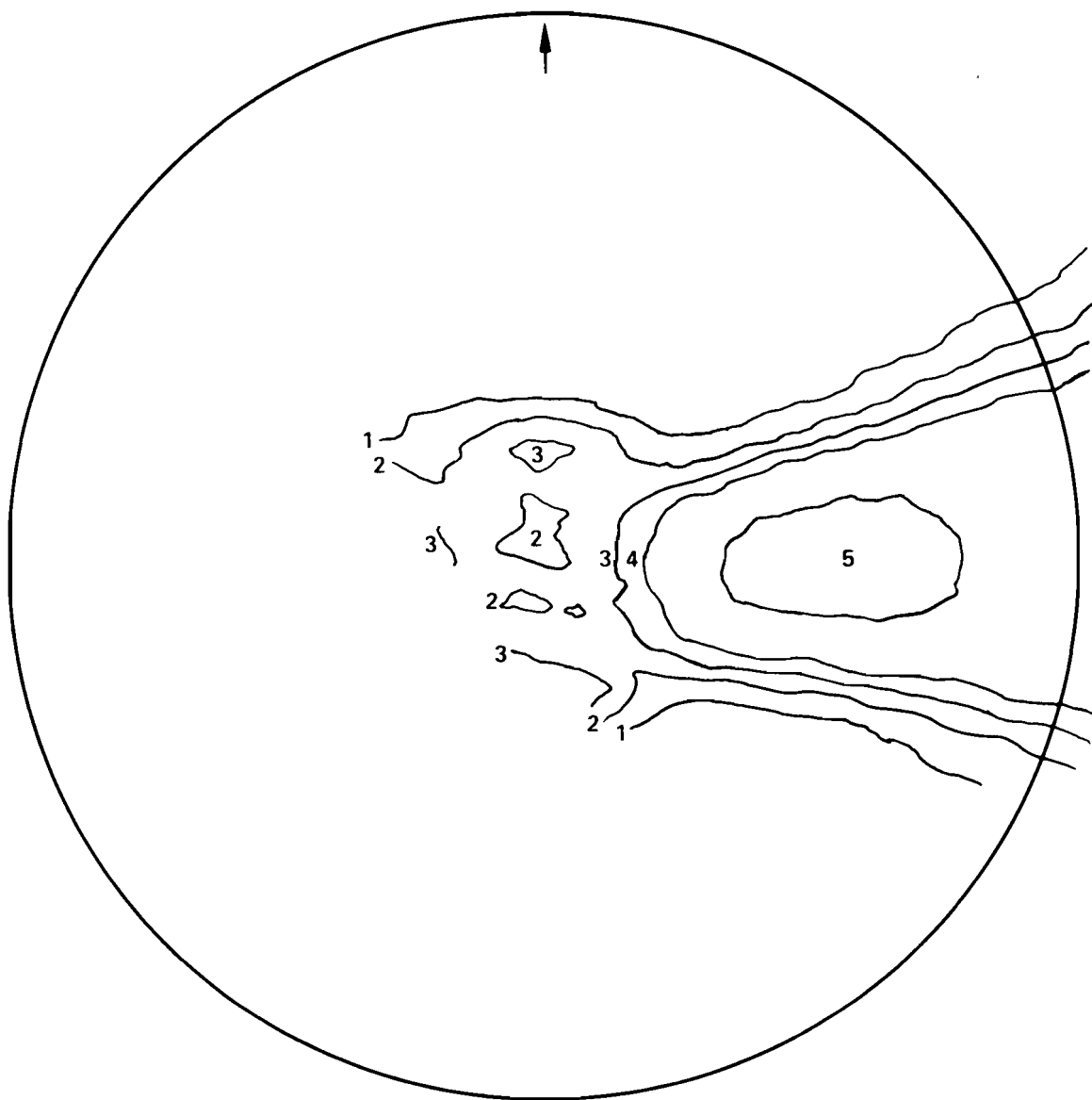
Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 13.—BASAL PLANE POLE FIGURE FOR 3/8 X .030 IN. ZIRTECH TUBE
(TUBE 8(B) PER TABLE 2)



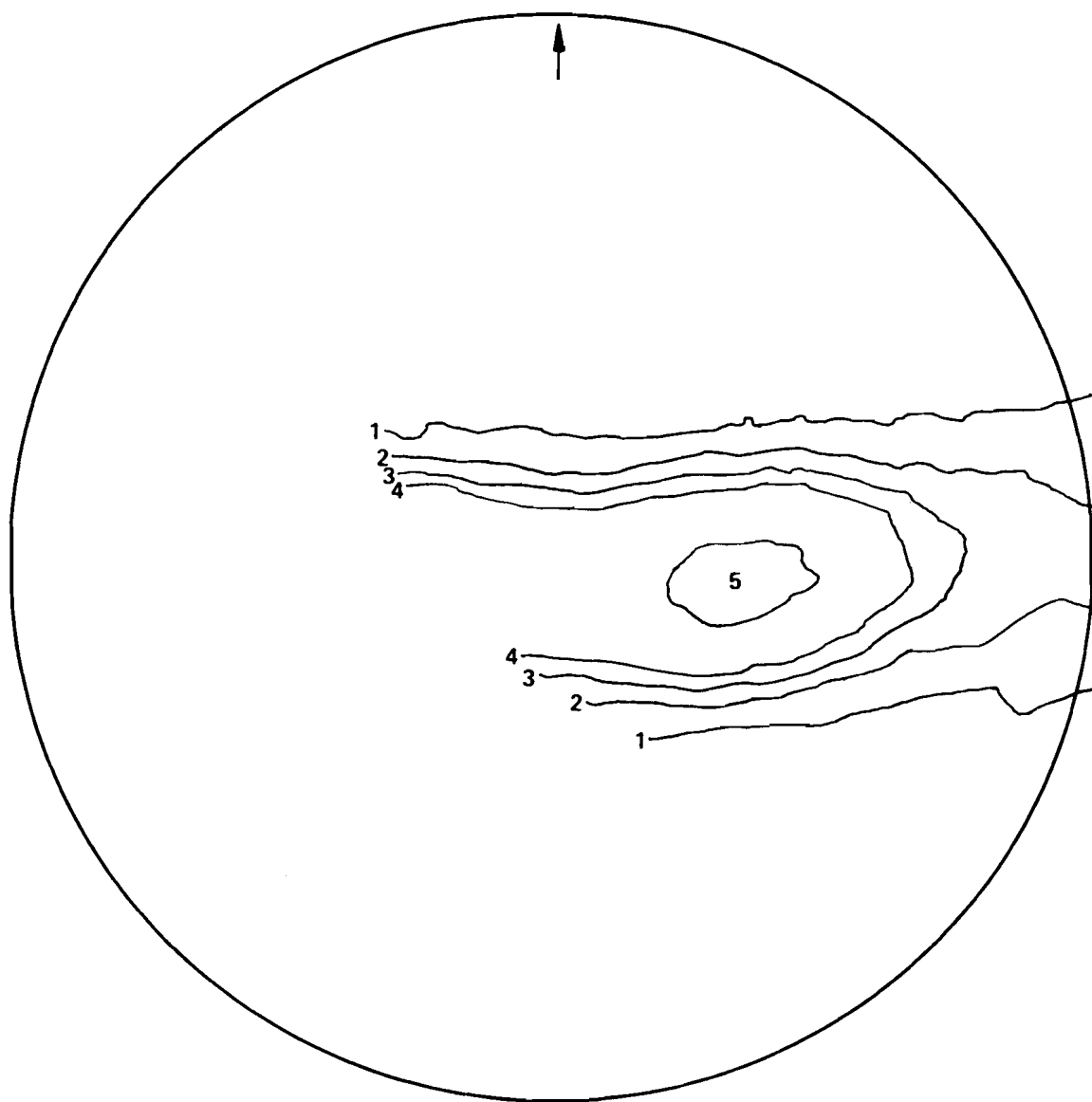
Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 14.—BASAL PLANE POLE FIGURE FOR 5/8 X .021 IN. ZIRTECH TUBE
(TUBE E PER TABLE 4)



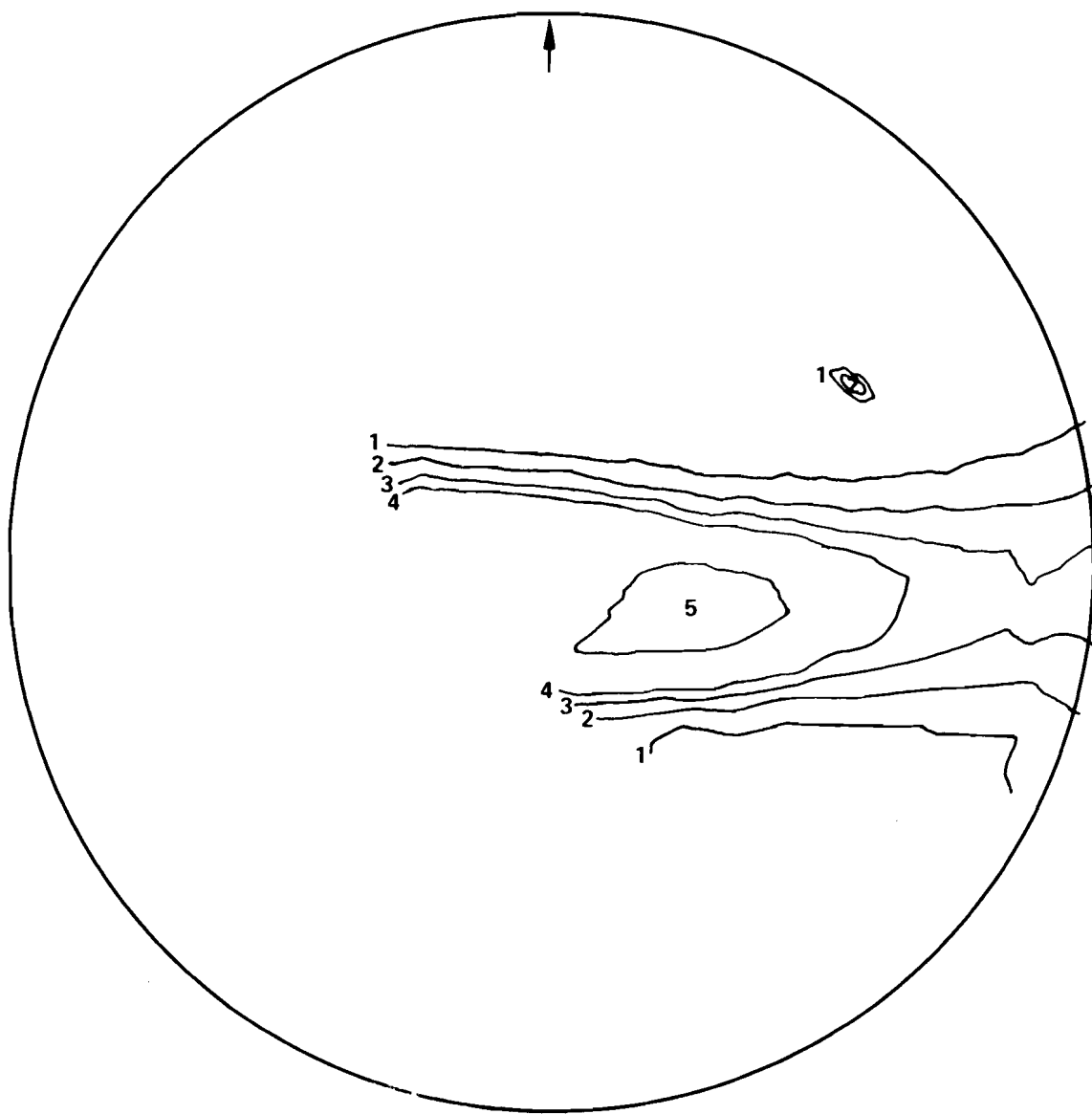
Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 15.—BASAL PLANE POLE FIGURE FOR 5/8 X .050 IN. ZIRTECH TUBE
(TUBE F PER TABLE 4)



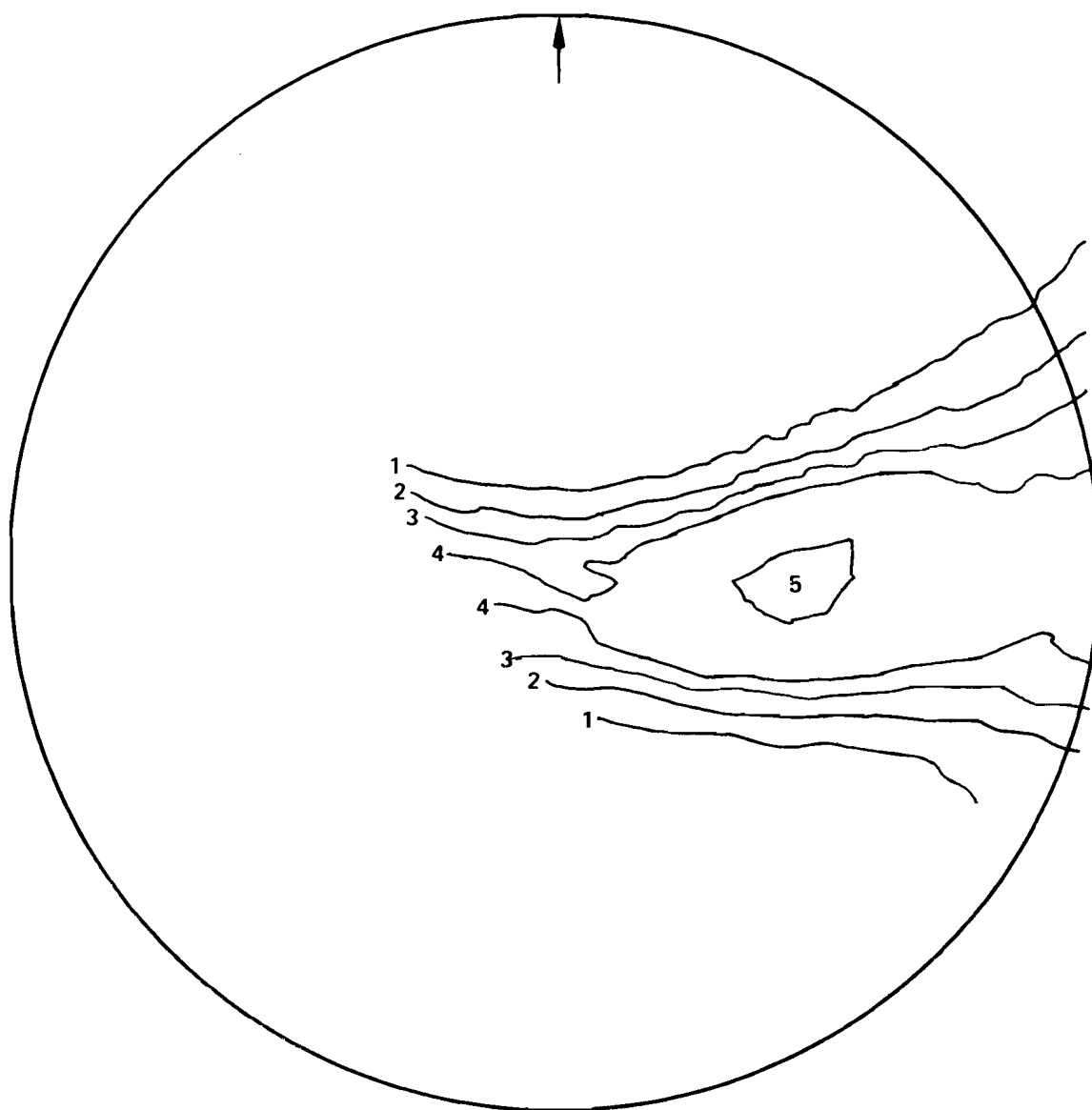
Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 16.—BASAL PLANE POLE FIGURE FOR 1 X .033 IN. RMI TUBE
(TUBE D PER TABLE 4)



Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 17.—BASAL PLANE POLE FIGURE FOR 1 X .033 IN. RMI TUBE
(TUBE G PER TABLE 4)



Contour lines	1	2	3	4	5
Times random X-ray intensity	.5	1.0	1.5	2.0	4.0

FIGURE 18.—BASAL PLANE POLE FIGURE FOR 1 X .033 IN. RM1 TUBE
(TUBE H PER TABLE 4)

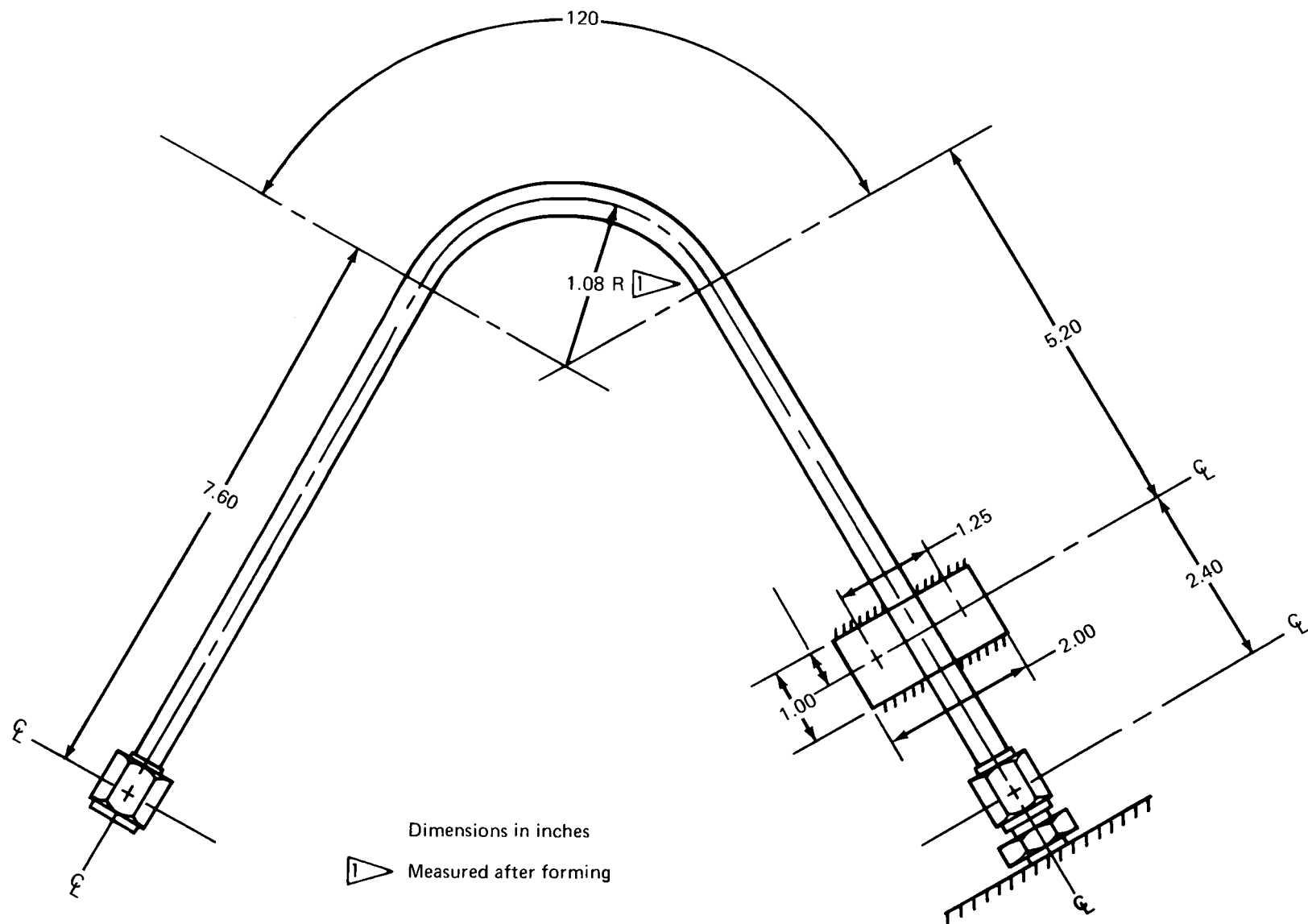


FIGURE 19.—DIMENSIONS FOR 3/8-IN. BENT TUBE SPECIMEN

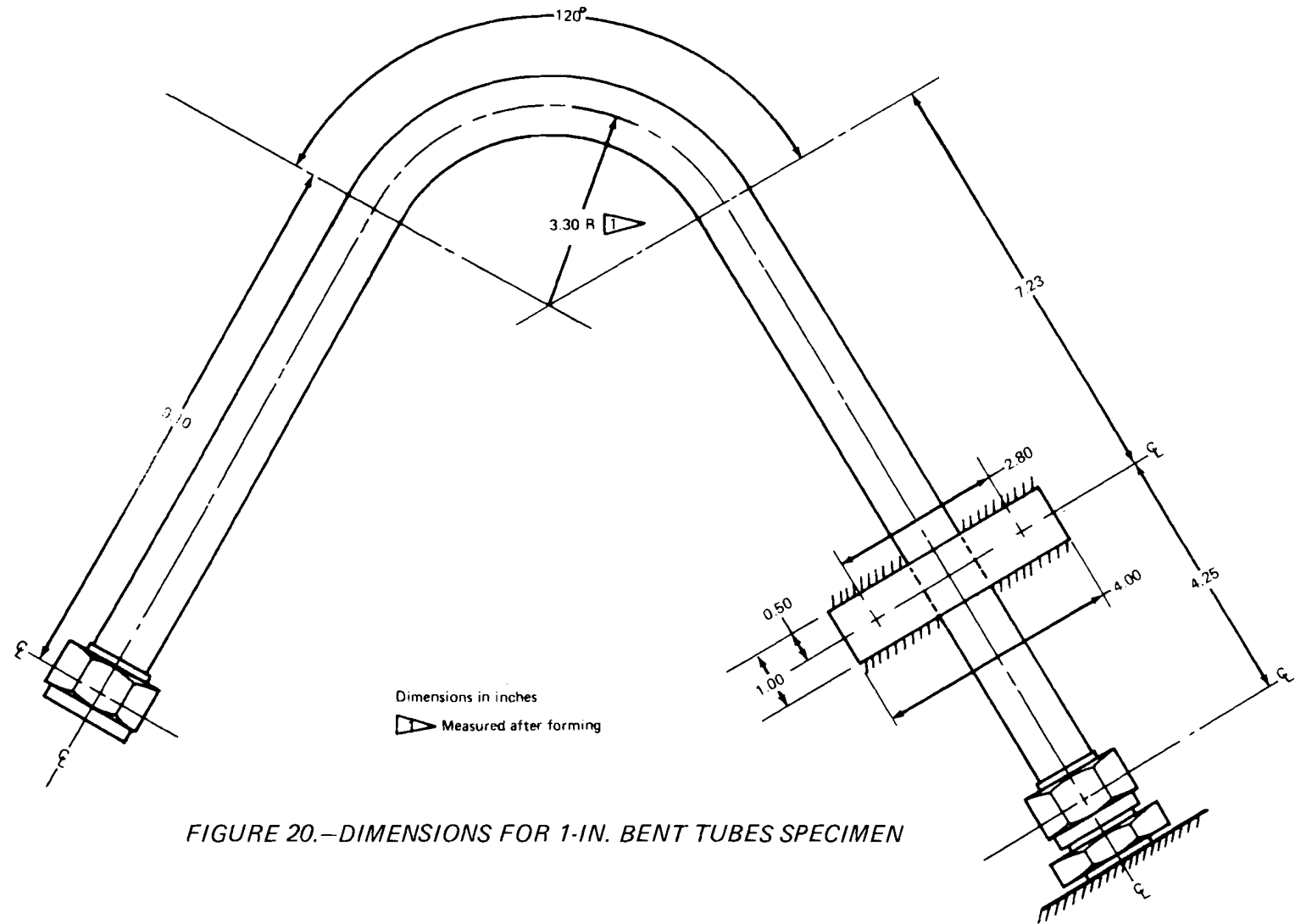


FIGURE 20.—DIMENSIONS FOR 1-IN. BENT TUBES SPECIMEN

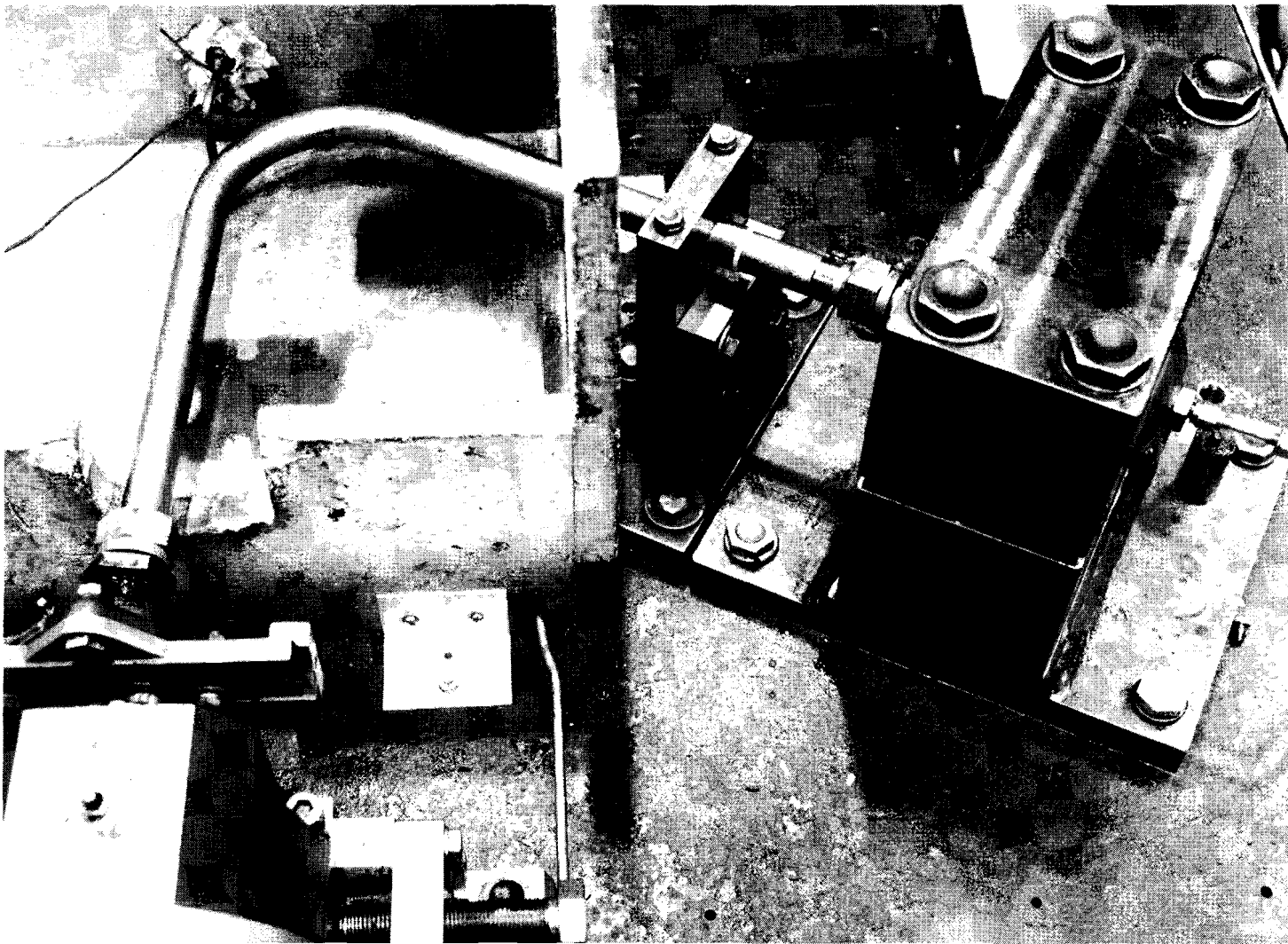


FIGURE 21.—1-IN. BENT TUBE FLEXURE TEST SETUP

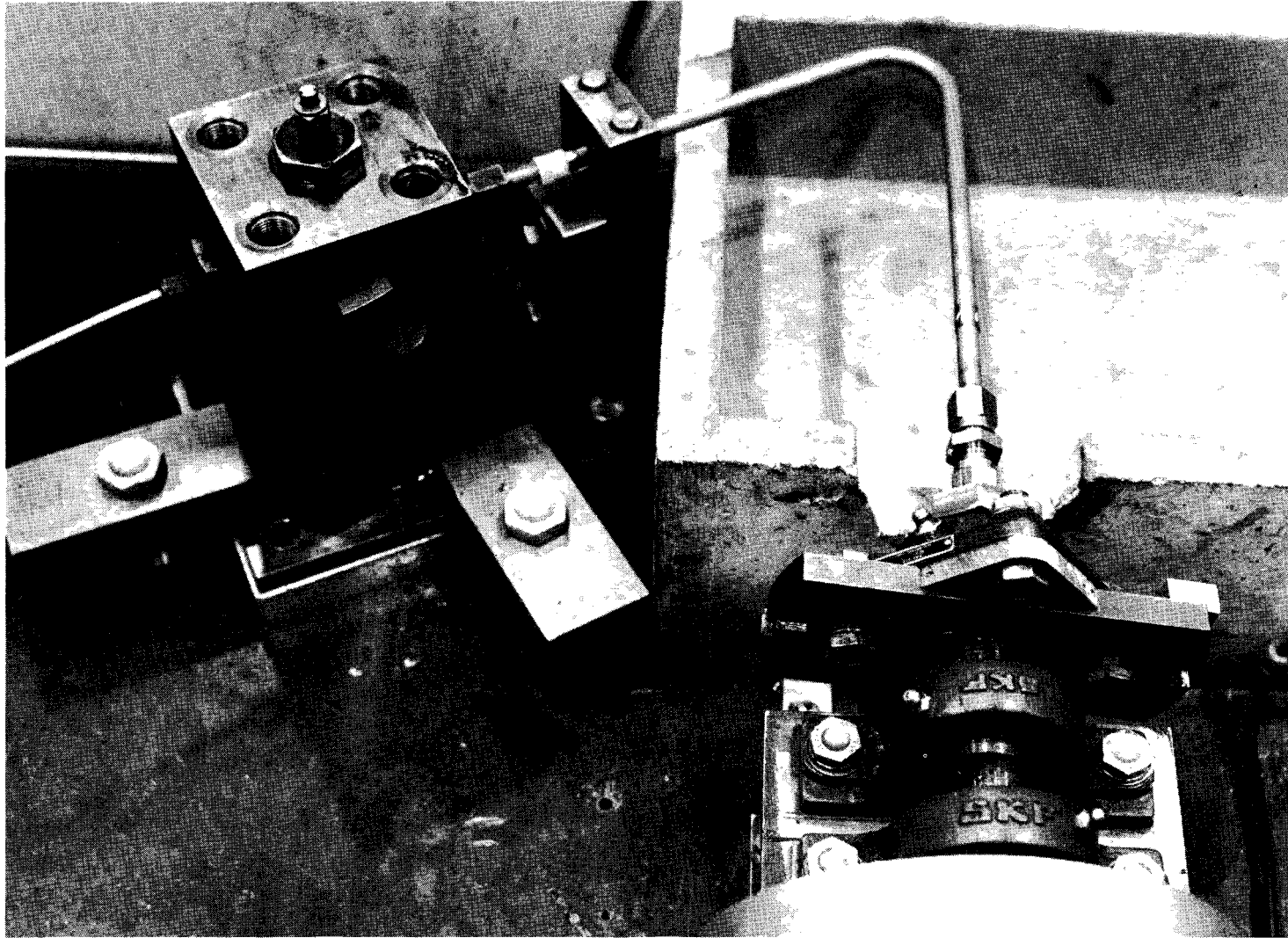
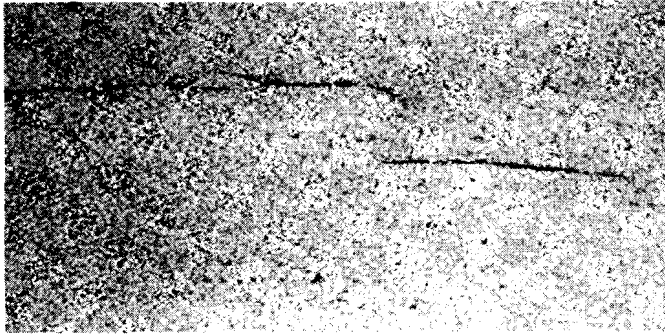
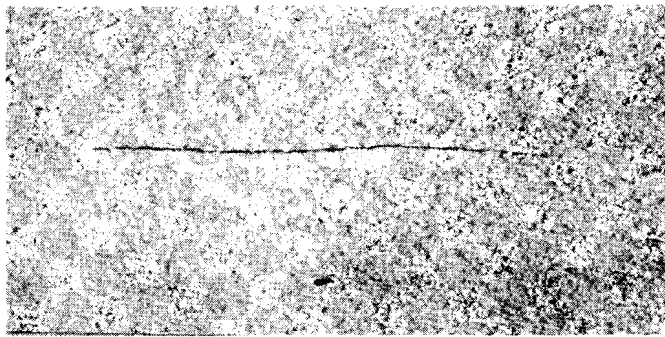


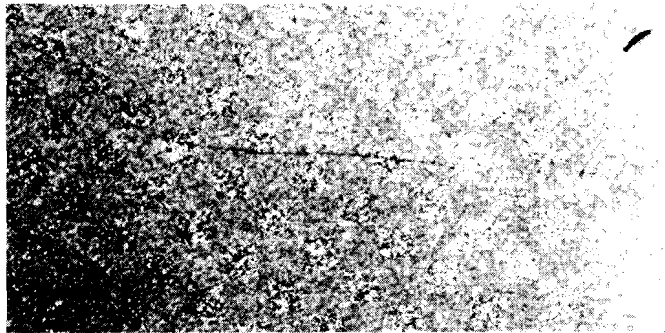
FIGURE 22.—3/8-IN. BENT TUBE FLEXURE TEST SETUP



(a) Tube 4, As-Received Finish, (20X)



(b) Tube 6, Grit-Blasted and Chemically Milled Finish (20X)



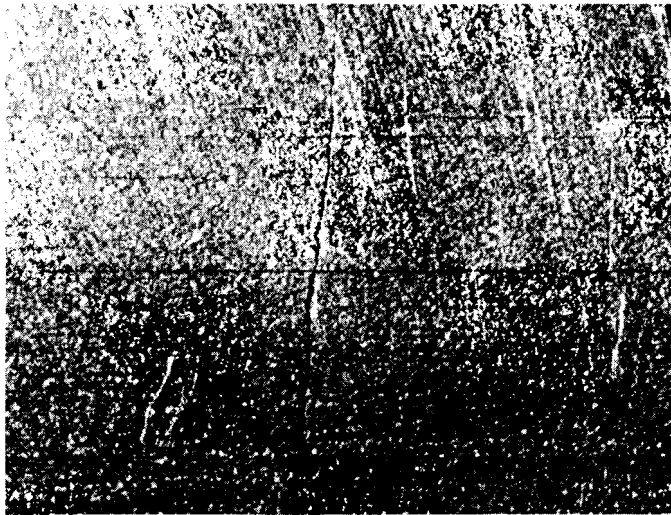
(c) Tube 7, Texture-controlled Tubing, Grit-Blasted and Chemically Milled Finish (20X)

See table 2 for tube description

FIGURE 23.—TYPICAL LONGITUDINAL CRACKS WHICH ORIGINATED ON ID OF 3/8- x .020-in. TUBING WITH THREE DIFFERENT FINISHES

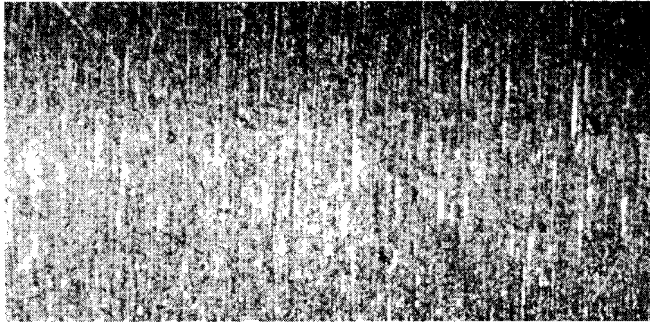


(a) Crack Originated in a Pit (13X)

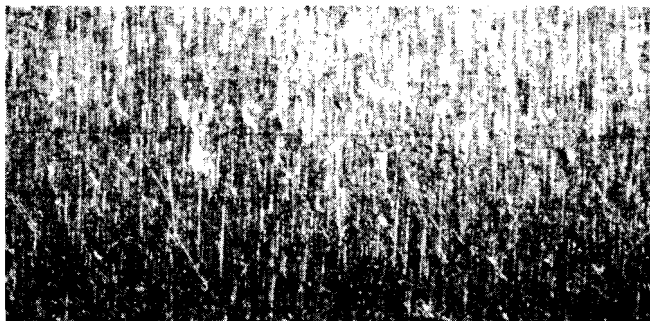


(b) Crack Originated in a Scratch (20X)

*FIGURE 24.—TYPICAL TRANSVERSE CRACKS WHICH ORIGINATED ON
OD OF 1 X .080-IN. TUBING*



Tube 1
3/8 in. x 0.20 in.
216Q-0-4
20X

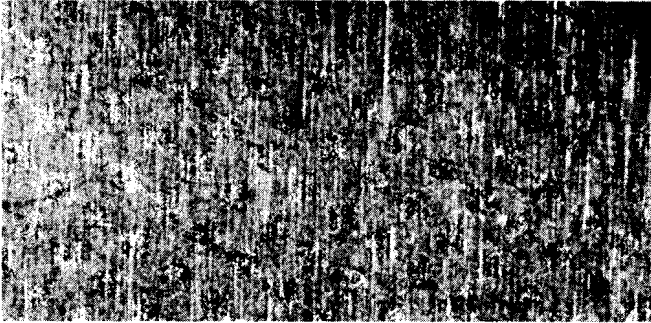


Tube 2
3/8 in. x 0.030 in.
216Q-0-5
20X



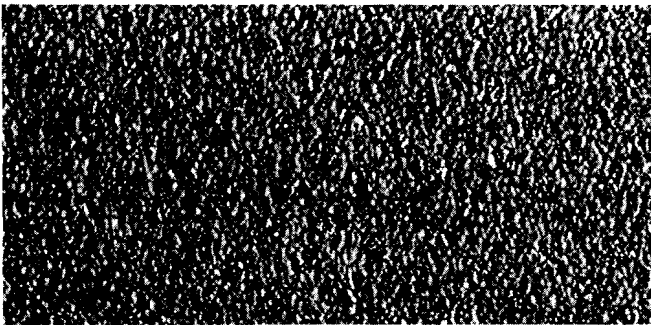
Tube 3
5/8 in. x 0.021 in.
216Q-0-6
20X

FIGURE 25.—OD SURFACE FINISH SHOWING SANDING MARKS (20X)



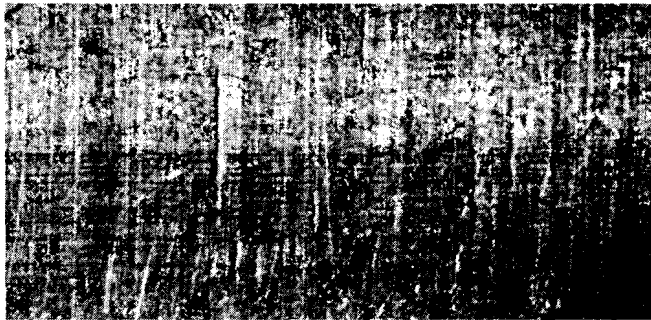
Tube 4

5/8 in. x 0.050 in.
216Q-0-7
20X



Tube 5

1 in. x 0.033 in.
216Q-0-8
20X

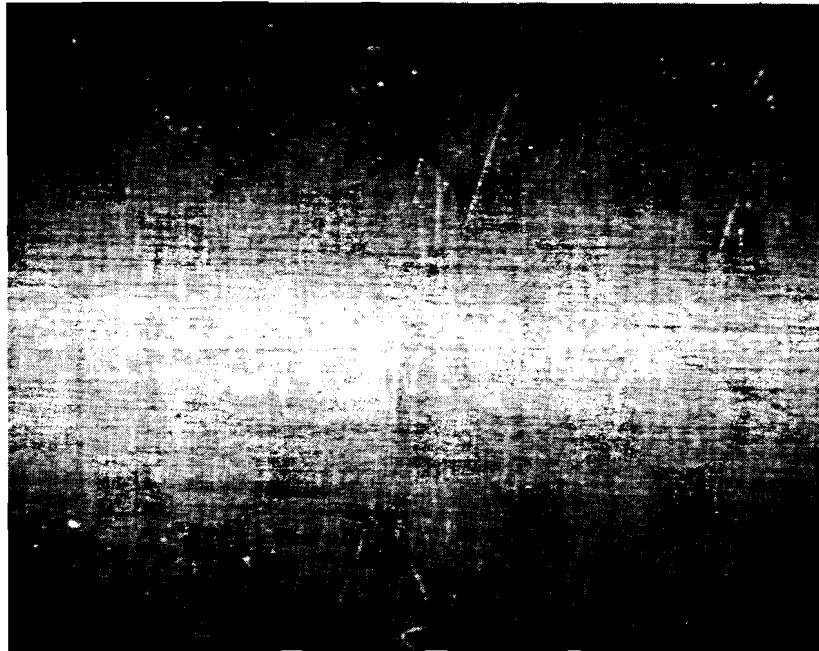


Tube 6

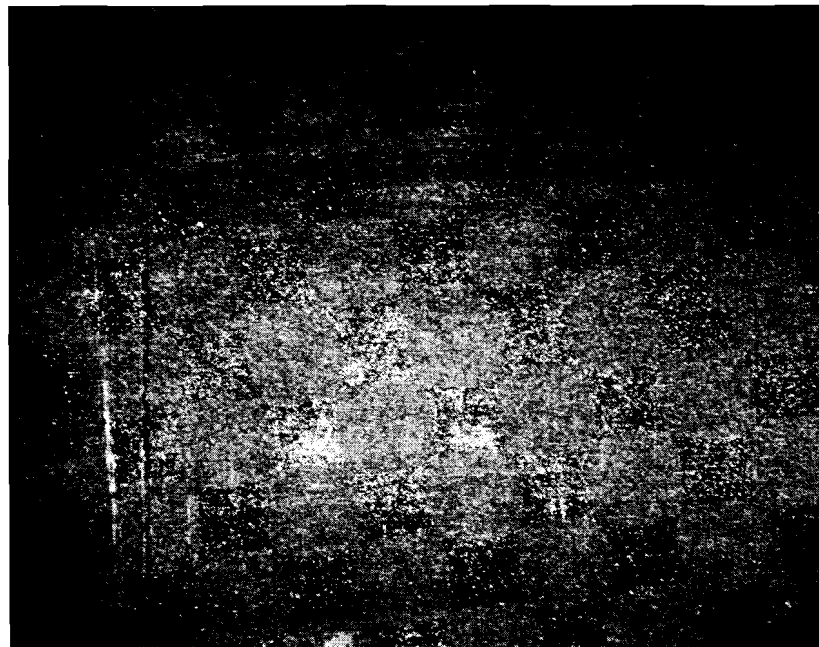
1 in. x 0.080 in.
216Q-0-9
20X

See tables 7 and 8 for tube description

FIGURE 25.—Concluded

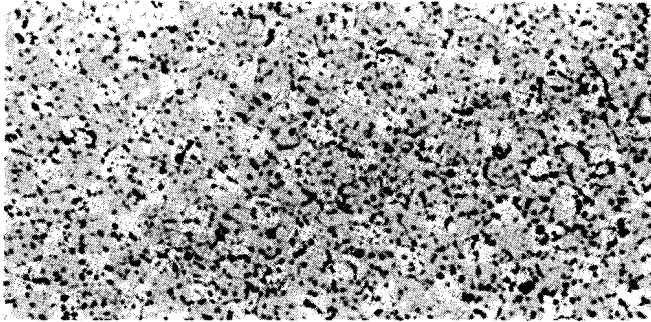


As Received Per Specification
From Bishop Tube Co.



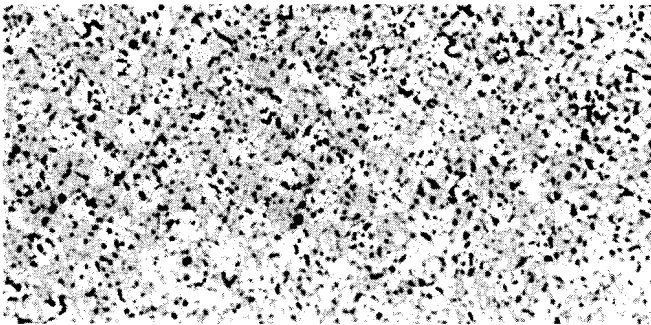
After Additional Chemical
Milling by Bishop Tube Co.

FIGURE 26.—COMPARISON OF OD FINISHES ON BISHOP 1.0 X .080 TUBING (20X)



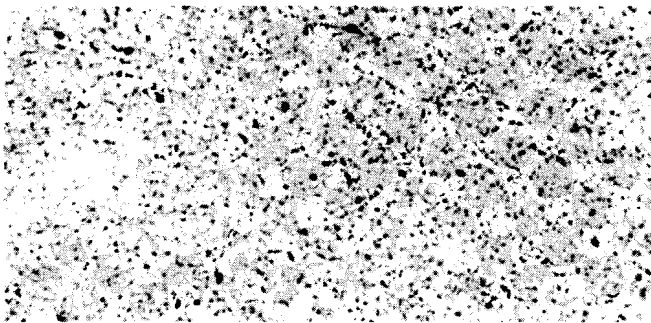
Tube 1

3/8 in. x 0.20 in.
216Q-1-1
500X



Tube 2

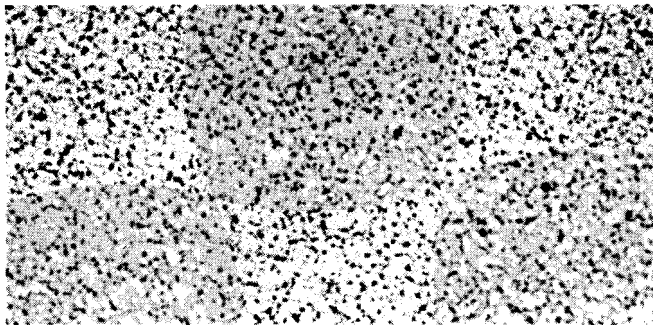
3/8 in. x 0.030 in.
216Q-2-1
500X



Tube 3

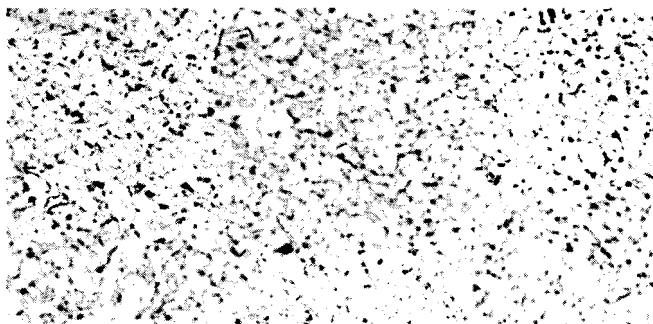
5/8 in. x 0.021 in.
216Q-1-2
500X

FIGURE 27.—PHOTOMICROGRAPHS OF 3/8, 5/8, AND 1-IN. SIZE XBMS 7-234A TUBING



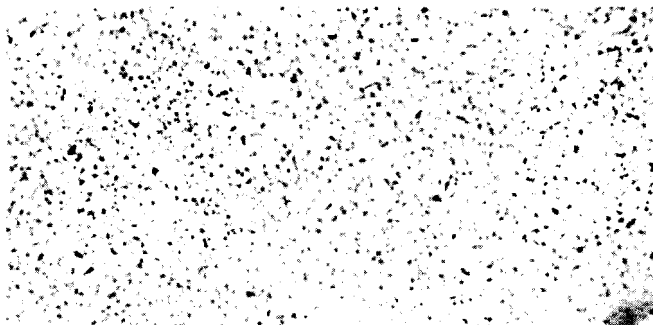
Tube 4

5/8 in. x 0.050 in.
216Q-2-2
500X



Tube 5

1 in. x 0.033 in.
216Q-1-3
500 X

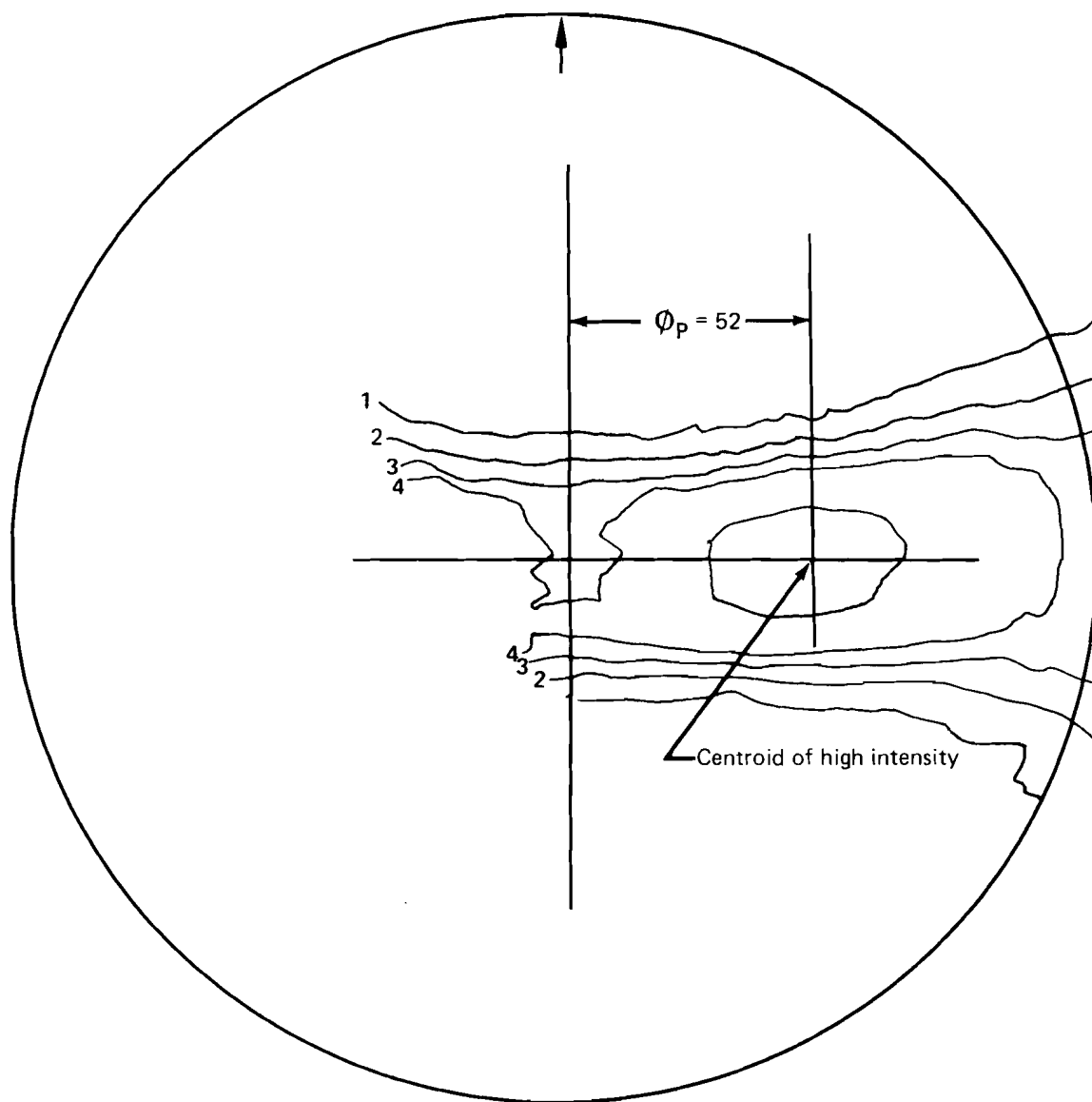


Tube 6

1 in. x 0.080 in.
216Q-2-3
500X

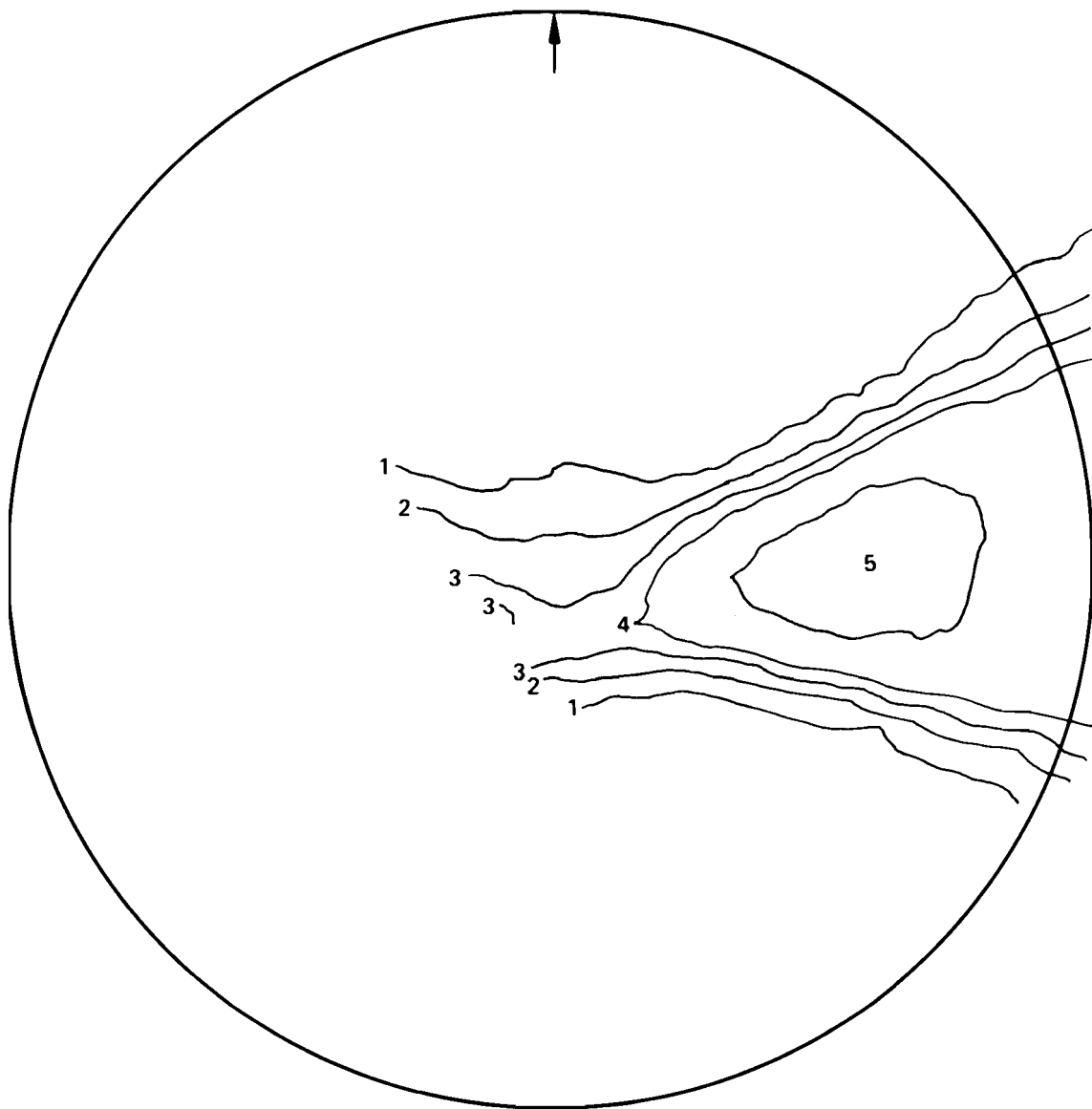
See tables 7 and 8 for tube description

FIGURE 27.—Concluded



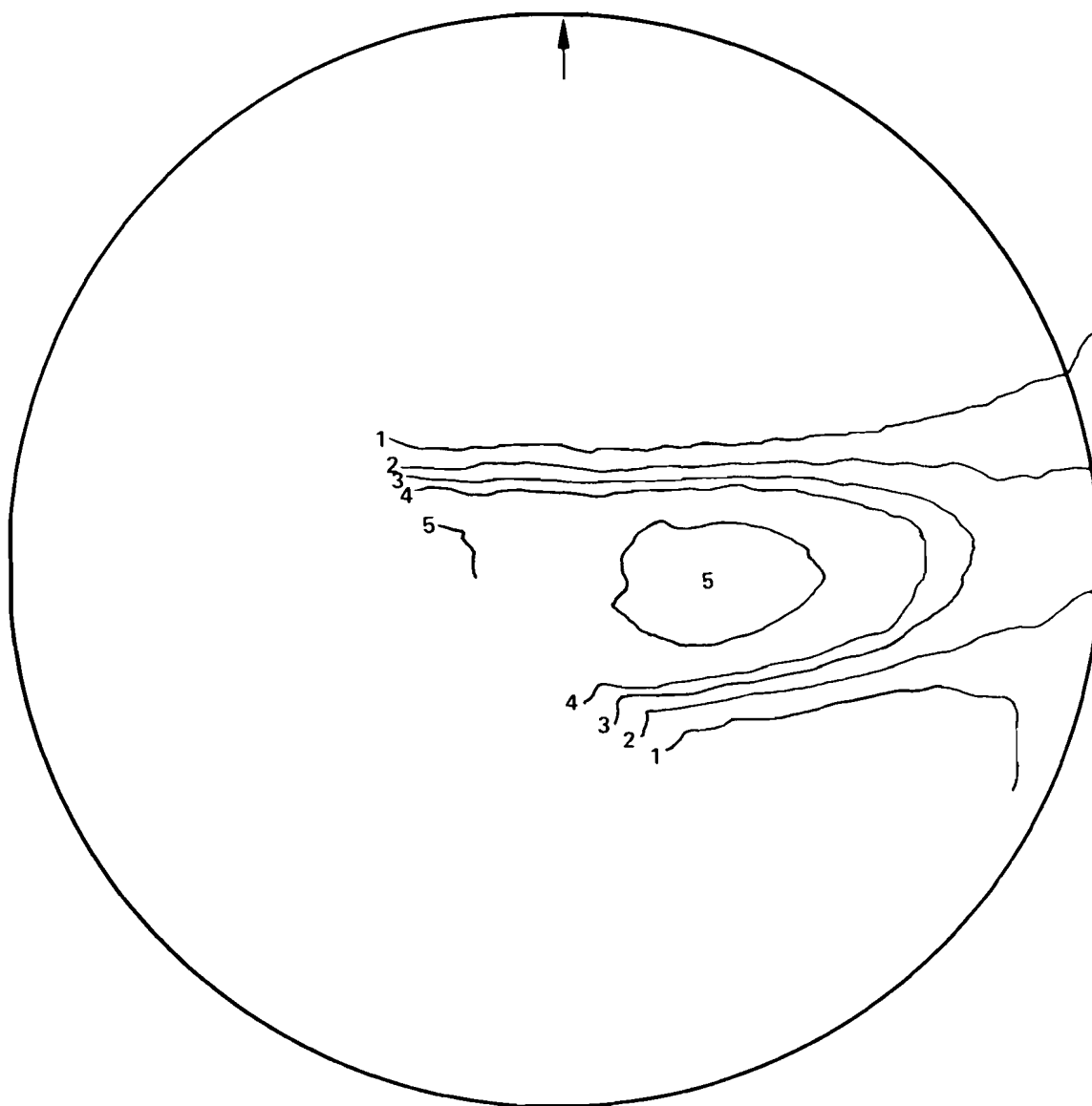
Contour lines	1	2	3	4	5
Times random X-ray intensity	.5	1.0	1.5	2.0	4.0

FIGURE 28.—BASAL PLANE POLE FIGURE FOR 3/8 X .020 IN. SUPERIOR TUBE
(TUBE 1 PER TABLE 7)



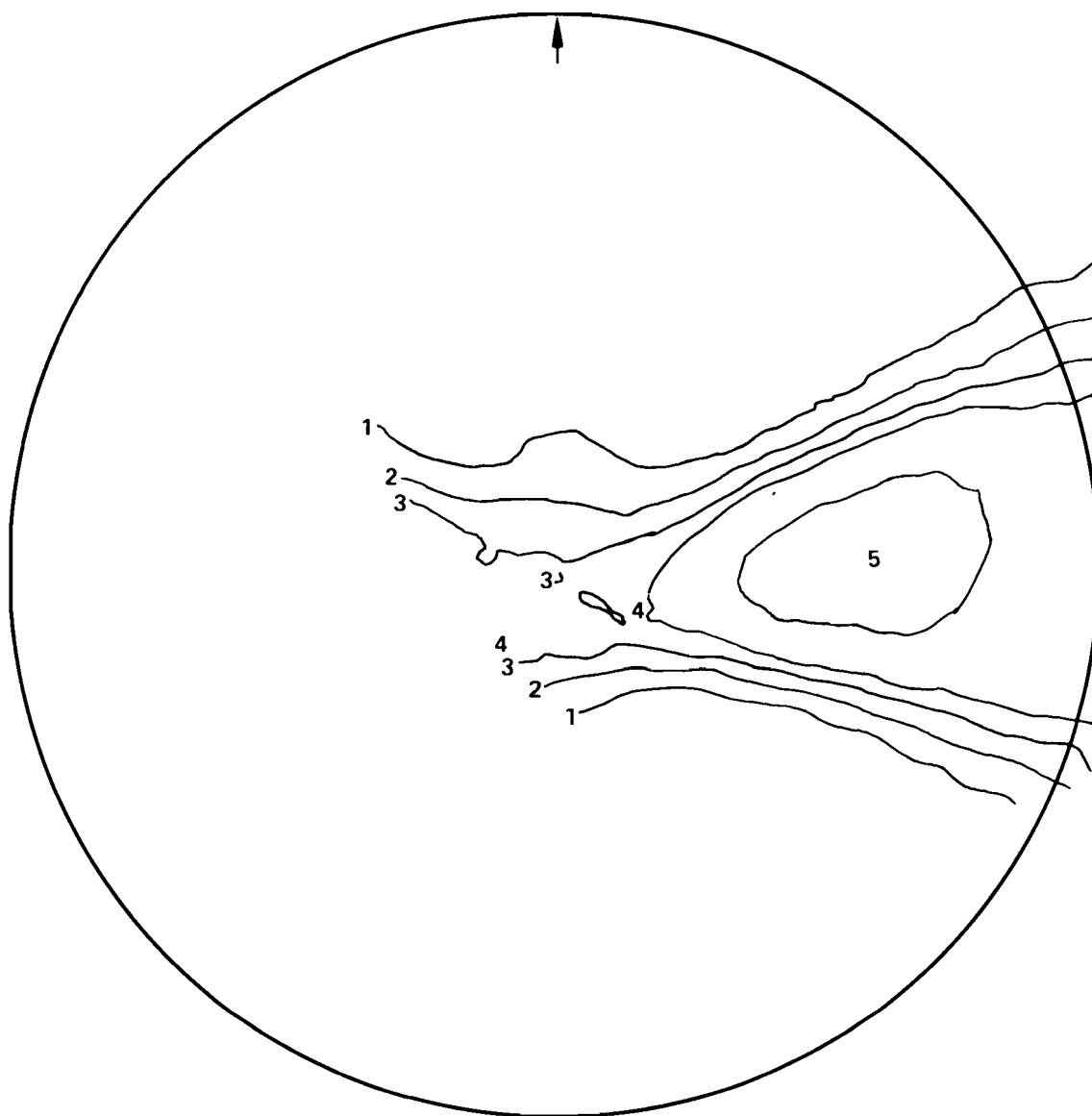
Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 29.—BASAL PLANE POLE FIGURE FOR 3/8 X .030 IN. SUPERIOR TUBE
(TUBE 2 PER TABLE 7)



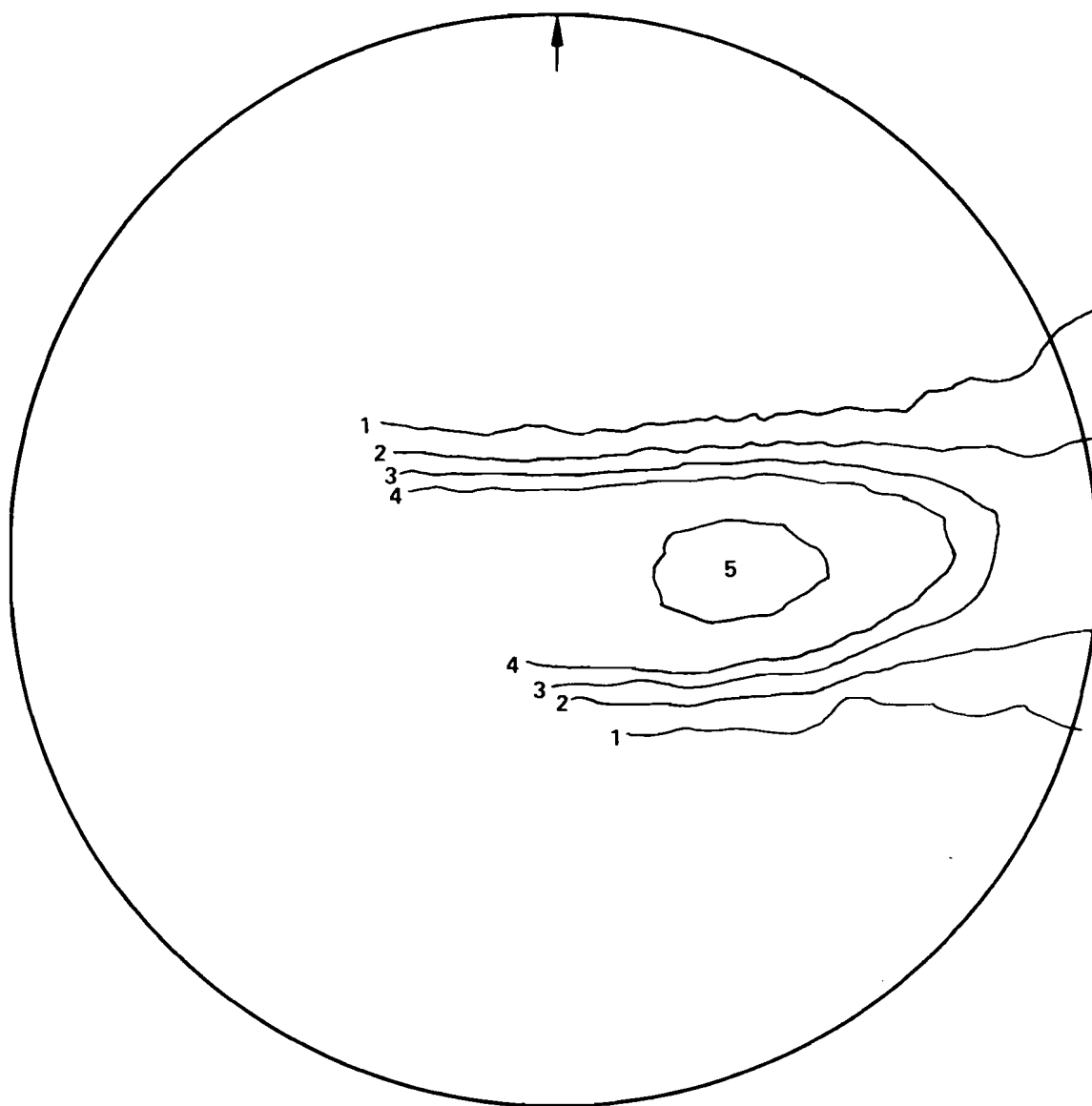
Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 30.—BASAL PLANE POLE FIGURE FOR 5/8 X .020 IN. SUPERIOR TUBE
(TUBE 3 PER TABLE 7)



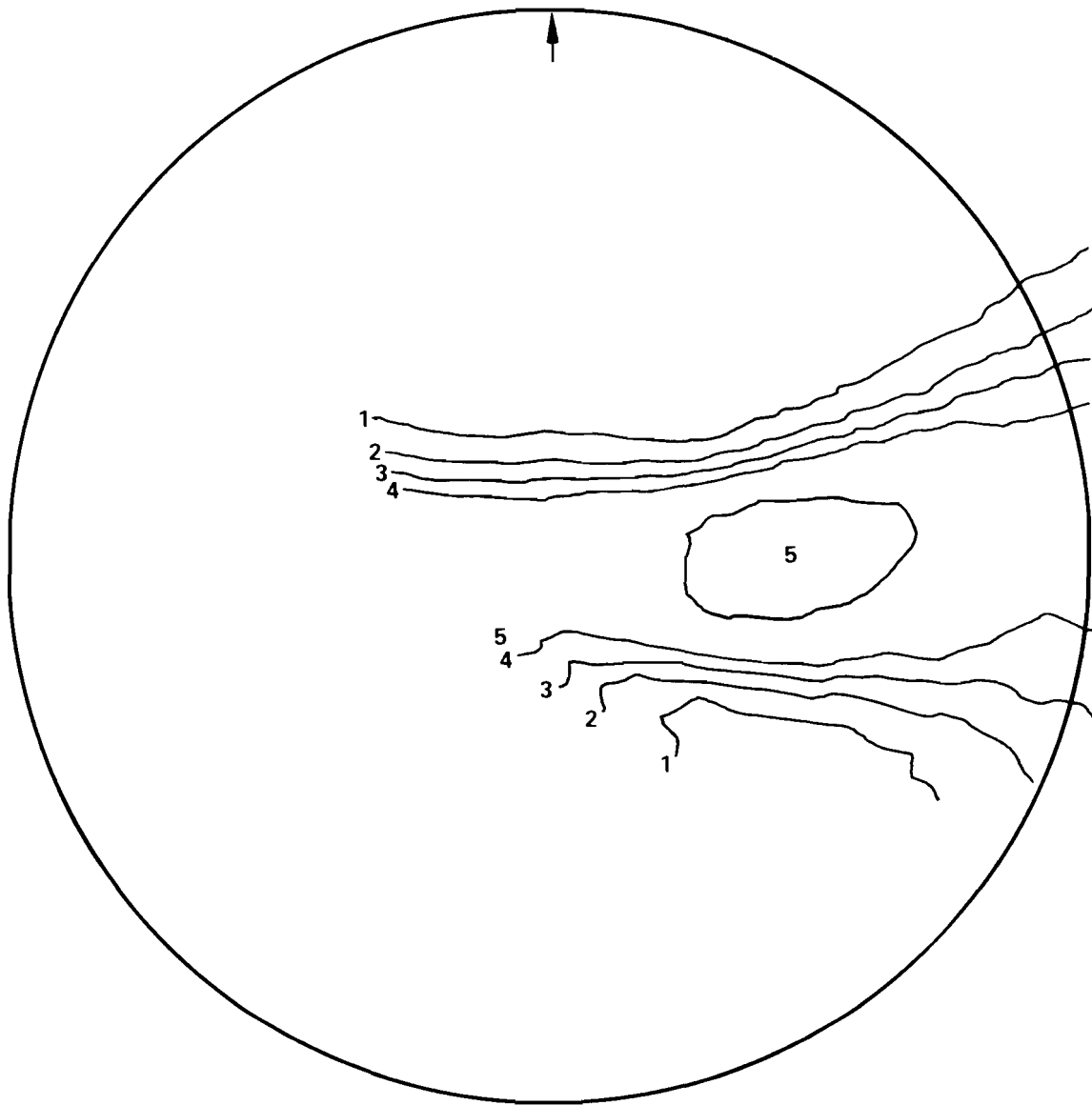
Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 31.—BASAL PLANE POLE FIGURE FOR 5/8 X .050 IN. SUPERIOR TUBE
(TUBE 4 PER TABLE 7)



Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 32.—BASAL PLANE POLE FIGURE FOR 1 X .033 IN. BISHOP TUBE
(TUBE 5 PER TABLE 7)



Contour lines	1	2	3	4	5
Times random	.5	1.0	1.5	2.0	4.0
X-ray intensity					

FIGURE 33.—BASAL PLANE POLE FIGURE FOR 1 X .080 IN. BISHOP TUBE
(TUBE 6 PER TABLE 7)

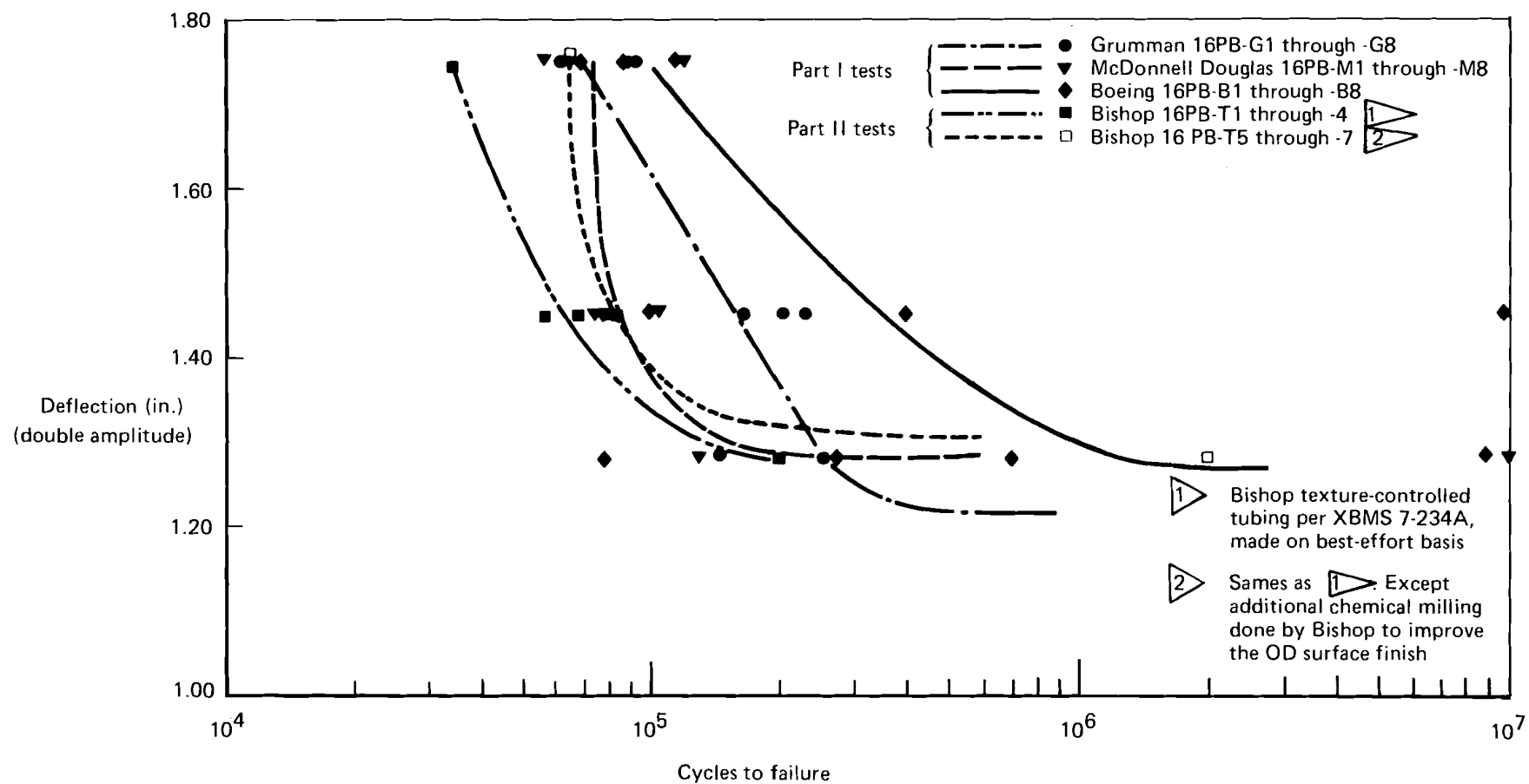


FIGURE 34.—FLEXURE FATIGUE COMPARISON FOR 1 X .080 IN. TUBING, DEFLECTION VS CYCLES TO FAILURE

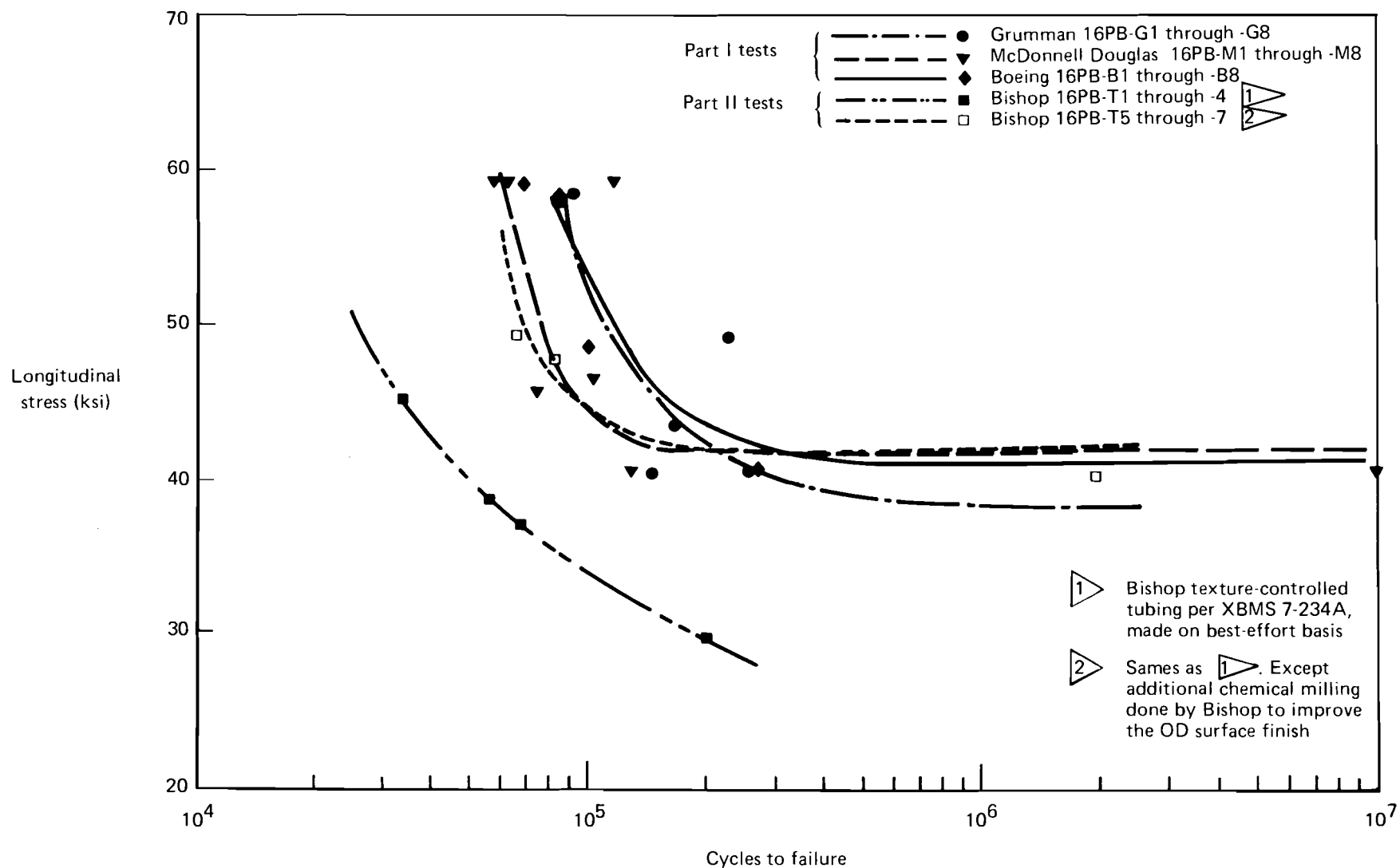


FIGURE 35.—FLEXURE FATIGUE COMPARISON FOR 1 X .080 IN. TUBING, LONGITUDINAL STRESS VS CYCLES TO FAILURE

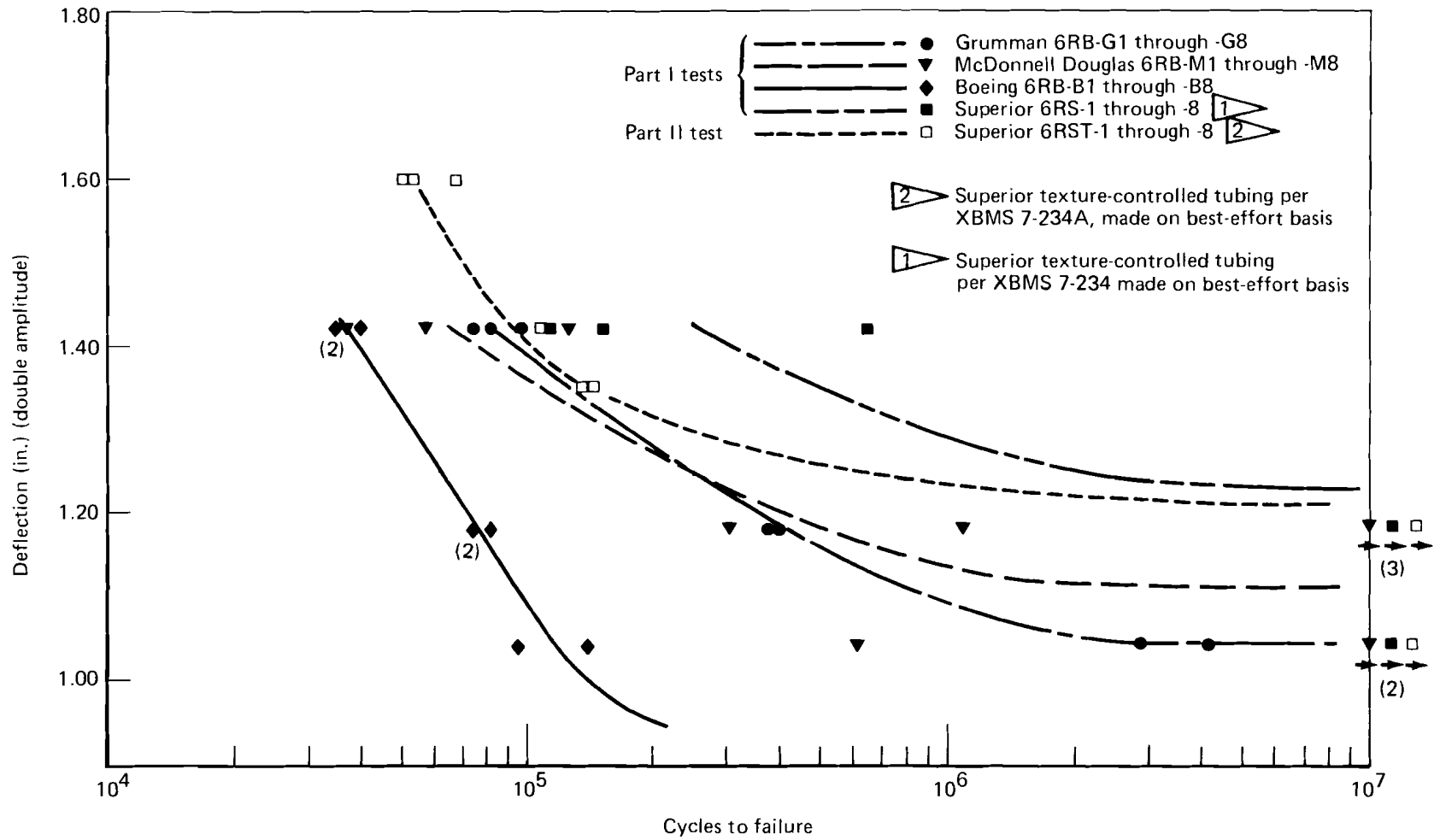


FIGURE 36.—FLEXURE FATIGUE COMPARISON FOR 3/8 X .020 IN. TUBING
DEFLECTION VS CYCLES TO FAILURE

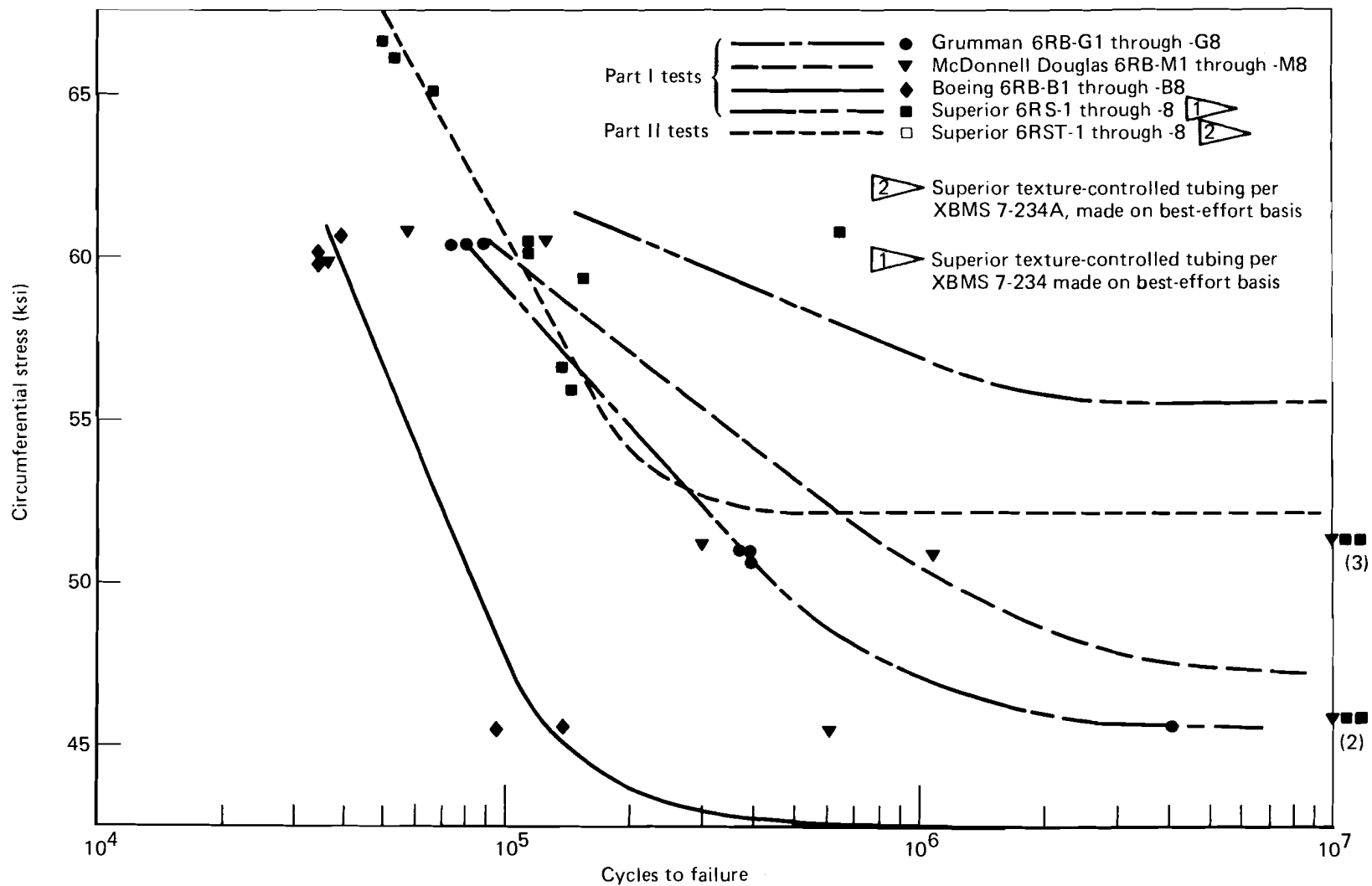


FIGURE 37.—FLEXURE FATIGUE COMPARISON FOR 3/8 X .020 IN. TUBING
CIRCUMFERENTIAL STRESS VS CYCLES TO FAILURE

APPENDIX A
PROPOSED TUBE SPECIFICATION XBMS 7-234A

1. SCOPE

- a. This specification covers Ti-3Al-2.5V seamless tubing in the cold worked and stress relieved condition. The tubing is intended for use in Type I and Type II hydraulic systems per MIL-H-5440 and at temperatures not exceeding 600F.
- b. This specification required qualified products.

2. REFERENCES

Except where a specific issue is indicated, the issue of the following references in effect on the date of invitation for bid shall form a part of this specification to the extent indicated herein.

- a. AMS 2249 - Chemical Check Analysis Limits, Titanium and Titanium Alloys
- b. ARP 603 - Impulse Testing of Hydraulic Hose Assemblies, Tubing, Coils, Fittings and Similar Fluid Systems Components
- c. ARP 1258 - Qualification of Hydraulic Tube Joints to Specified Flexure Fatigue Requirements
- d. ASA B46-1 - Surface Texture (Surface Roughness, Waviness and Lay)
- e. ASTM B338-65 - Specification for Seamless and Welded Titanium Tube for Condensers and Heat Exchangers.
- f. ASTM E-8 - Tension Testing of Metallic Materials
- g. ASTM E-120 - Methods of Chemical Analysis for Titanium and Titanium Alloys
- h. ASTM E-146 - Chemical Analysis of Zirconium and Zirconium Base Alloys
- i. BAC 5423 - Penetrant Methods of Inspection

DRAFT 3/15/72

Code Ident.No.81205

BY <u>W.E. Quist & W.F. Spurr</u>	TITANIUM 3Al-2.5V SEAMLESS TUBING FOR HYDRAULIC SYSTEMS, COLD WORKED & STRESS RELIEVED	PROPOSED
CHECKED _____		BMS 7-234A
ENGINEERING _____	BOEING MATERIAL SPECIFICATION	PAGE 1
QUAL. CONTROL _____		
MATERIEL _____		

2. (Continued)

- j. BAC 5439-2 - Ultrasonic Inspection of Tubing
- k. MIL-H-5440 - Hydraulic Systems, Aircraft, Types I and II, Design, Installation, and Requirements for
- l. MS 33611 - Tube Bend Radii

3. MATERIAL REQUIREMENTS

3.1 GENERAL

3.1.1 Tube Hollows

- a. Material used to manufacture tube hollows shall be produced by multiple melting consumable electrode practice. At least one stage shall be melted in vacuum. One stage may be melted in inert gas under slight pressure.
- b. Preparation procedures and inspection criteria for tube hollows shall be reviewed and approved by The Boeing Company or procuring agency.
- c. The metallurgical condition of tube hollows shall conform to a fine grained uniform microstructure.
- d. The I.D. and O.D. of the tube hollows shall be free from cracks, seams, laps, laminations, tears, and similar defects as determined by visual, and ultrasonic inspection methods per sections 6.1.a, and 6.3. Tube hollows shall be fluorescent penetrant inspected on the O.D. per section 6.2, and shall meet inspection requirements of BAC 5423 Category C. Ultrasonic inspection shall conform to the requirements of BAC 5439-2, Class C-10.

3.1.2 Finished Tubes

- a. All finished tubes shall be produced from tube hollows that meet the tube hollow requirements of this specification.
- b. Tubing shall be of uniform quality and condition and shall be free from cracks, seams, laps, laminations, tears, pits, and grinding or sanding marks as well as other defects which do not conform to the limits given in Section 3.10.
- c. The metallurgical condition of each tube shall be fine grained equiaxed microstructure with no evidence of Widmanstatten structure as determined by the method in Section 6.1.b.

3.1.2 (Continued)

- d. The final reduction operation shall be performed by plug drawing - preferably (not less than 5% wall reduction) or rod drawing 1 (not less than 10% wall reduction) to the finished size. Free sinking or tube rolling to the final size shall be prohibited.
- e. All finished tubes shall be penetrant inspected on the O.D. in accordance with Section 6.2 and ultrasonically inspected in accordance with Section 6.3. Tube wall thickness of 0.046 and under shall meet Class A-2 standards. Tube wall thickness of greater than 0.046 shall meet Class B-3 standards.

3.2 CHEMICAL COMPOSITION

Chemical composition shall conform to the requirements of Table I when analyzed per Section 6.4. Hydrogen, oxygen and nitrogen shall be certified for each lot 2. Check analysis shall be per AMS 2249.

TABLE I - CHEMICAL COMPOSITION

<u>ELEMENT</u>	<u>WEIGHT PERCENT</u>
Aluminum	2.5 - 3.5
Vanadium	2.0 - 3.0
Iron	0.30 (max.)
Carbon	0.05 (max.)
Hydrogen	0.015 (max.)
Oxygen	0.12 (max.)
Nitrogen	0.02 (max.)
Other Elements, Total	0.40 (max.) 3
Titanium	Remainder

3 Need not be reported. Any individual element shall not exceed 0.10%.

3.3 HEAT TREATMENT

All tubing shall be cold worked and stress relieved at a minimum temperature of 700F for not less than 30 minutes.

- 1 Free sinking of 2% maximum is permissible after rod drawing.
- 2 A lot is defined as tubing of the same diameter and wall thickness made from one heat of material, processed in a similar manner and stress relieved together.

3.4 MECHANICAL PROPERTIES

The room temperature mechanical properties of tube hollows and finished tubing shall conform to the requirements of Table II when tested in accordance with Section 6.5. The properties of finished tubing shall be determined on one specimen per 1000 feet of tubing in each lot with a minimum of three specimens per lot. Testing shall be done using the full cross-section of the tubing.

TABLE II MECHANICAL PROPERTIES

Material Condition	Ult. Tensile Strength (ksi)	Yield Strength at 2% Offset (ksi)	Elong. in 2 in. (%)	Strain Ratio: R	
				$R = \ln \frac{OD_f}{OD_0}$	$\ln \frac{W_f}{W_0}$
Annealed Tube Hollow	90 (min) 110 (max)	75 (min) 95 (max)	15.0		
Cold Worked & Stress Relieved Tubes	125 (min)	105 (min)	10.0	5/8 & under - .6 min. over 5/8 - 1.0 min.	

3.5 FLARE TEST

One specimen for each ten (10) tubes in each lot with a minimum of five (5) specimens taken from different tubes shall be tested per Section 6.6. The tubing shall be capable of being flared to a minimum of 1.2 times the original diameter without cracking or tearing of the material.

3.6 HYDROSTATIC PRESSURE RESISTANCE

Three (3) specimens from each lot shall be tested per Section 6.7. The tubes shall exhibit no leaking, cracking, or permanent set exceeding 0.002 inch per inch of diameter.

3.7 FLATTENING TEST

One specimen for each ten (10) tubes in each lot with a minimum of five (5) specimens taken from different tubes shall be tested per Section 6.8. The tubing shall show no evidence of cracking or tearing when examined at 5X magnification.

3.8 BENDING TEST

One specimen per 1000 feet of tubing in each lot with a minimum of three (3) specimens per lot shall be tested per Section 6.9. The tubing shall show no evidence of cracking, open sanding striations or tearing when examined at 5X magnification.

3.9 RESIDUAL STRESS

Three (3) specimens from each lot of tubing shall be tested per Section 6.10. The tubing shall not have more than 15 ksi residual hoop stress.

3.10 SURFACE CONDITION OF FINISHED TUBES

- a. One specimen from each of ten (10) tubes from each lot shall be tested per Section 6.1.b. If there are fewer than 10 tubes in the lot, each tube shall be examined. Outside and inside surfaces of tubing shall be free from a brittle layer (alpha-case).
- b. Surface roughness of tubing shall not exceed 32 RHR on the inside and outside surfaces. Grinding, buffing, and polishing of the surface is not acceptable following the final reduction operation. The as-drawn O.D. surface shall have a minimum of 0.002 inches removed by chemical milling. The appearance of the O.D. surface (at 20X) shall not display residual sanding or grinding marks nor pitting (from the chemical milling operation) in excess of the examples shown in Figure 1. The I.D. of the tube shall show a uniform matte finish and shall be achieved by grit blasting a minimum of 0.0005" from the surface followed by a chemical milling operation to remove an additional 0.0005" minimum. No additional abrasive treatments shall be applied.
- c. Tubing containing any type of defect greater than 0.002 inches in depth shall be rejected.

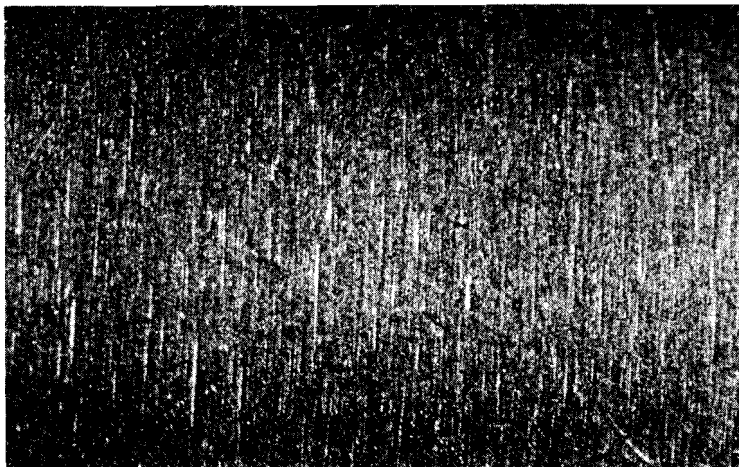
3.11 TOLERANCES

3.11.1 Wall Thickness Tolerances

The wall thickness tolerance of the tube hollows shall not exceed $\pm 10.0\%$. The wall thickness tolerances of finished tube shall not exceed $\pm 7.5\%$ or $\pm 0.002"$ whichever is greater.

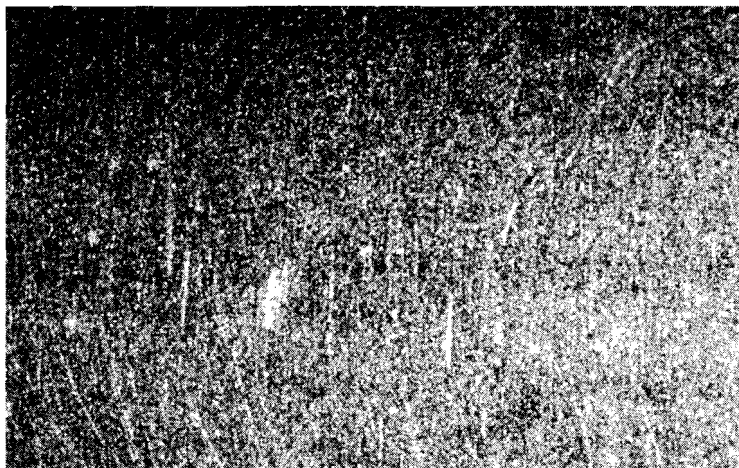
3.11.2 Outside Diameter Tolerance

Outside diameter tolerances for tubing shall be as specified in Table III. These tolerances include ovality.



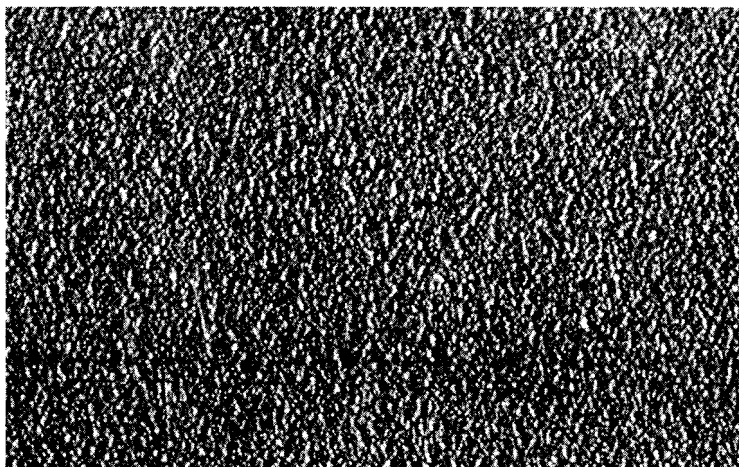
- (a) Unacceptable degree of residual grinding and sanding marks on chemically milled tube.

20X



- (b) Limit of acceptability for residual grinding and sanding marks on chemically milled tube.

20X



- (c) Limit of acceptability for pitting from the chemical milling operation.

20X

FIGURE 1.—THESE PHOTOGRAPHS ILLUSTRATE ACCEPTABLE AND UNACCEPTABLE OD SURFACE FINISHES FOR Ti-3Al-2.5V TUBING.

3.11.2 (Continued)

TABLE III
O.D. TOLERANCES

<u>Nominal Outside Diameter (Inches)</u>	<u>Diameter Tolerances (Inches)</u>
up to .093	+ .002, - .000
.094 to .187	+ .003, - .000
.188 to .499	+ .004, - .000
.500 to .999	+ .005, - .000
1.000 to 1.499	+ .007, - .000
1.500 to 2.000	+ .010, - .000

3.11.3 Straightness Tolerances

Tubing shall not deviate from straightness by more than 0.025 inch per foot length nor more than 0.125 inch in any five foot length.

4. QUALIFICATION

- a. All requests for qualification shall be directed to a Materiel Department of The Boeing Company, which will request data and samples when desired for qualification purposes. In general, data indicating compliance with all requirements of this specification for a minimum of 3 different tubing sizes from two different heats will be required.
- b. After review of supplier data or Boeing tests, the supplier will be advised as to whether product approval has been granted. Qualified products will be listed in the BMS Qualified Products List.
- c. No changes in raw material or methods of manufacture shall be made without notification and prior written approval. Requalification of the revised material may be required and a revised supplier designation may be requested. Qualified products will be listed in the BMS Qualified Products List.

4. (Continued)

- d. Hydraulic performance tests may be conducted to decide whether desired changes in surface condition, tube processing or other requirements conform with the intended use as stated under (1) Scope. As a minimum, the conventional impulse and flexure tests as required for tubing assemblies per ARP 603 and APR 1258 shall normally be conducted.

5. QUALITY CONTROL OF TUBE HOLLOWES & FINISHED TUBES

5.1 SUPPLIER QUALITY CONTROL

- a. Unless otherwise stated on the purchase order, the supplier shall furnish three (3) copies of a test report containing test data showing conformance to the requirements of this specification.
- b. The test report shall also include the purchase order number, Boeing Material Specification number (including revision letter), heat number, lot number, size and quantity of tubes from each lot and a statement that all requirements of this specification have been met.
- c. The supplier shall maintain processing records for not less than five (5) years for all material including starting stock certification, number and amount of each tube reduction, Quality Control inspection and any other information which may influence the quality of the end product.

Non-proprietary processing information shall be made available to The Boeing Company on request.

5.2 PURCHASER QUALITY CONTROL

- a. Purchaser Quality Control shall perform tests to insure conformance to the requirements of Sections 3.1.2.e, 3.4, 3.10.b, 3.10.c and 3.11.
- b. Purchaser Quality Control Department shall review supplier test reports and may conduct additional tests as deemed necessary to assure that tubes meet the requirements of this specification.
- c. Complete records shall be maintained by Purchaser Quality Control Department and will be made available to The Boeing Company on request.

6. TEST METHODS

6.1 SURFACE CONDITION

- a. Each tube hollow and finished tube shall be visually inspected for compliance with surface condition requirements per Section 3.1.1.d and 3.1.2.b.
- b. Specimens of the finished tube shall be examined in full cross section metallographically at a magnification of 500-750X for microstructure and evidence of a brittle surface layer (alpha case). The specimens shall be etched in an aqueous solution containing 1 volume percent hydrofluoric acid and shall conform to the requirements of 5.10.a.
- c. The finish of the inside and outside surfaces of each tube shall conform to the requirements of Section 3.10.b as defined by ASA E46-1.

6.2 PENETRANT INSPECTION

Tube hollows shall be inspected per BAC 5423 category C and finished tubes shall be inspected per BAC 5423, category B to meet the requirements of Sections 3.1.1.d and 3.1.2.e.

6.3 ULTRASONIC INSPECTION

- a. All tube hollows and finished tubing shall be inspected for inside and outside defects per the procedures of BAC 5439-2 and Sections 3.1.1.d and 3.1.2.e for all types and orientations of defects including longitudinal, transverse and herringbone. The tubing shall be inspected by scanning in both directions for longitudinal and transverse defects if two transducers are used. If four transducers are used and the transducers are positioned from opposite directions, the tubes need only be scanned in one direction. For herringbone type defect inspection in finished tubes the transducer(s) shall be positioned with herringbone reference standard per Figure 1.
- b. For finished tubes, the standard notches shall be Class A-2 per BAC 5439-2 for wall thicknesses less than 0.046 and Class B-3 for wall thicknesses 0.046 and greater. For tube hollows, the standard notches shall be Class C-10.

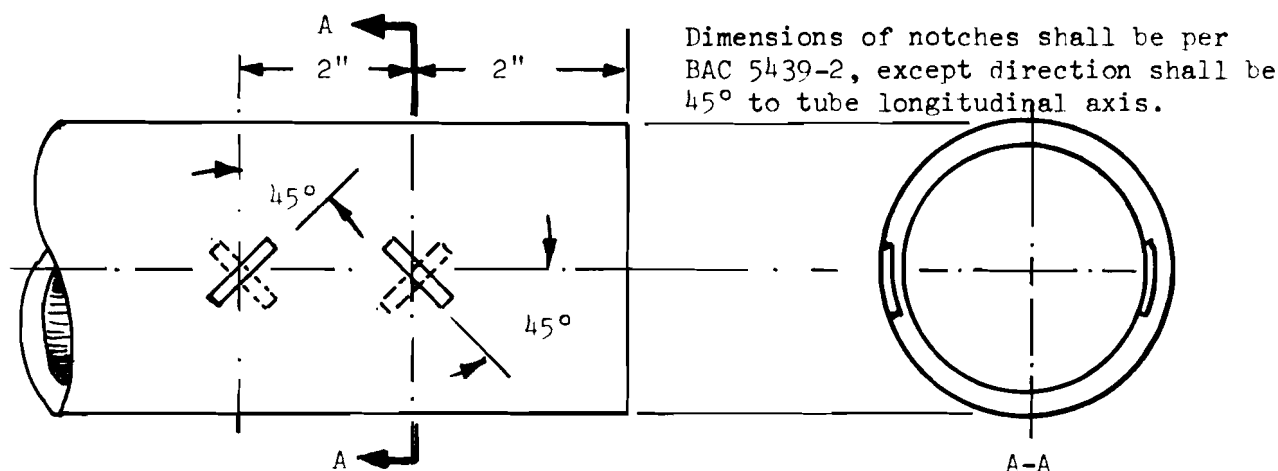


FIGURE 1 HERRINGBONE REFERENCE NOTCHES

6.4 CHEMICAL ANALYSIS

- a. Each heat shall be analyzed for conformance to the requirement of Section 3.2. The tubing supplier may use raw material certification except for oxygen, hydrogen, and nitrogen analysis which must be determined after final processing of the tube.
- b. Chemical composition for all elements except hydrogen shall be determined using ASTM E-120. Analysis for hydrogen shall be performed using the hot extraction method described in ASTM E-146. Limits for check analysis shall be according to AMS 2249. Any other analysis having equivalent or better accuracy and precision than the above methods may be used provided they are approved by The Boeing Company, Quality Control Department. Analysis for oxygen content shall be performed by a technique having a standard deviation on accuracy of 50 ppm when compared to an acceptable standard.

6.5 TENSION TESTS

The specimens shall be tension tested in accordance with ASTM E-8 and shall meet the requirement of Section 3.4. The strain rate shall be .003 - .007 inch/inch/minute through 0.2% offset plastic strain, and then increased to .075 - .125 inch/inch/minute to failure.

If a dispute occurs between the purchaser and supplier over the yield strength values, a referee test shall be performed on a machine having a strain rate pacer, using a strain rate of .005 inch/inch/minute through the yield strength.

6.5 (Continued)

The strain Ratio (R) shall be determined from the tube tension test specimens as follows:

$$R = \frac{\text{OD}_f}{\text{OD}_o} \div \frac{W_f}{W_o}$$

Where OD = average outside diameter
W = average wall thickness
f = final dimension after testing
o = original dimension before testing

The dimensions of the tube shall be measured to an accuracy of ± 0.0002 ". On tested specimens these measurements shall be taken in the necked down region approximately half way between the fracture surface and the point where uniform elongation ends.

6.6 FLARE TEST

The specimens shall be flared per ASTM B338-65 to meet the minimum flaring requirements specified in Section 3.5.

6.7 PRESSURE TESTS

- a. Hydrostatic pressure tests shall meet the requirements specified in Section 3.6. Specimens for testing shall be at least 10 inches long and shall be hydrostatic pressure tested to a pressure determined by the formula:

$$P = f_{ty} \frac{D^2 - d^2}{D^2 + d^2}$$

in which P = hydrostatic test pressure (p.s.i.)

d = maximum permissible inside diameter (D less twice the minimum permissible wall thickness, in inches).

D = maximum permissible outside diameter (Nominal O.D. plus diametrical tolerance, in inches).

f_{ty} = minimum yield strength per Table II.

- b. Each specimen shall be subjected to two (2) pressure applications with the calculated pressure to be maintained for at least two (2) minutes during each cycle.

6.8

FLATTENING TESTS

Specimens of the full section of the tube not less than two inches in length shall be cut from the tubes. The tube specimens shall be flattened between parallel plates under a gradual load applied perpendicularly to the longitudinal axis until the distance between the plates is not greater than that specified in Table IV. After examination of the outside surfaces, the samples shall be split longitudinally and the inside surfaces examined. The inside and outside surfaces shall be free from cracks, tears, breaks or opened die or polishing marks when examined at 5X magnification.

Outside Diameter to Wall Thickness Ratio, OD/t	Distance Between Plates Where t = Wall Thickness
10 or less	7t
11 to 16	12t
17 to 30	15t
31 to 50	17t

TABLE IV - FLATTENING FACTORS

6.9

BENDING TESTS

Bending tests will be conducted to meet the requirements of Section 3.8.

The specimens shall be bent through 180 degrees at room temperature about a suitable bending block having a tube centerline radius three times the outside diameter of the tube. An appropriate mandrel or tube filler shall be provided to restrict flattening to a value that meets the requirements of MS 33611.

6.10

RESIDUAL STRESS

Residual stress measurements shall meet the requirements specified in Section 3.9. Specimens for testing shall be at least 3 times the tube diameter in length.

The specimen diameter shall be measured before (D_0) and after (D_1) making a longitudinal saw cut normal to

6.10 (Continued)

the measured diameter. The cut shall be made using a sharp hack saw blade. The residual stress shall then be determined using the following formula:

$$S_r = \frac{E}{T - u^2} t \left(\frac{1}{D_o} - \frac{1}{D_1} \right)$$

where: $E = 14.1 \times 10^6$ psi

$u = 0.31$

t = wall thickness

D_o = O.D. before splitting

D_1 = O.D. after splitting

7. REJECTION AND RETEST

- a. Failure of a specimen to meet the test requirements shall be cause for rejection of the lot which it represents.
- b. At the discretion of the inspector a retest may be permitted. One specimen from each of five (5) different tubes shall be tested to replace each failed specimen of the original sample.
- c. If any of the retest specimens fails to meet the applicable test requirements, the entire lot which is represented shall be rejected with no further testing permitted.

8. MATERIAL IDENTIFICATION

8.1 MARKING MATERIAL

The marking fluid shall not be soluble in water or oil, but shall be removable in a suitable hot alkaline cleaning solution without rubbing. The marking shall be sufficiently stable to withstand normal handling, and shall have no deleterious effect on the tubing or its performance. Esterbrook (Cado) Flo-Master ink or an equivalent halogen-free marking ink is recommended.

8.2 TUBING

Tubing shall be marked with the following information, which shall be grouped and shall be repeated at intervals not to exceed two (2) feet.

8.2 (Continued)

- a. Boeing Material Specification number, including the applicable revision letter.
- b. Nominal tube diameter and wall thickness (in inches)
- c. Heat Number
- d. Lot Number
- e. Supplier's name, trademark, or other designation

9. PACKAGING AND MARKING

- a. The article container shall be legibly marked with the following:
 - (1) Supplier's name
 - (2) Description of contents. (Dimensions in inches)
 - (3) Quantity of tubes
 - (4) Purchase order number
 - (5) Boeing Material Specification number, including the applicable revision letter
 - (6) Heat Number
 - (7) Lot Number
- b. Packaging shall be suitable for storage and shall be adequate to assure safe delivery.
- c. Each tube shall be individually packaged in such a manner that it will not make contact with any other tube.

APPENDIX B

STRESS FORMULA, ANALYSIS, AND NOMENCLATURE*

Characteristic curves were determined for fatigue evaluation showing deflection vs cycles and stress vs cycles. A typical S-N diagram for titanium is shown on figure B-1, which demonstrates the dependency of stress ($\sigma_{\max}$), and life (N), on stress ratio (R). To construct valid S-N curves for the test sections, the pressures were adjusted to predetermined values such that at any single amplitude deflection (δ_{SA}) stress ratios would be maintained constant.

Figure B-2 shows the M_O and M_I relationship. The stress formula, analysis, geometry (figures B-3 and B-4) and diagrams showing typical cyclic stress (figure B-5) are included.

B.1 NOMENCLATURE

The following nomenclature is used in the analysis:

- r = mean cross-section radius of curved pipe, in.
- t = pipe wall thickness, in.
- R = bend radius of curved pipe, in.
- I = moment of inertia of pipe cross section = $\pi r^3 t / \text{in.}^4$
- E = modulus of elasticity, psi
- ν = Poisson's ratio
- M = applied moment, in.-lb (M_I in-plane; M_O out-of-plane)
- P = internal pressure, psi (subscript ρ denotes value of a factor with internal pressure)
- ϕ = circumferential location angle
- λ = $tR/r^2 \sqrt{1 - \nu^2} = h \sqrt{1 - \nu^2}$, flexibility characteristic
- ψ = PR^2/Ert , parameter related to pressure
- kp = flexibility factor

*E. C. Rodabaugh and H. H. George, "Effect of Internal Pressure on Flexibility and Stress-Intensification Factors of Curved Pipe on Welding Elbows," *Transactions of ASME*.

- σ_m = stress due to applied moment, psi (σ_{ml} longitudinal; σ_{mc} , circumferential)
- δ = tube loaded end deflection, in. (δ_{SA} single amplitude imposed deflection; δ_{mm} angular mismatch deflection, δ_{LG} linear gap deflection).
- σ_p = Circumferential stress in straight pipe due to internal pressure = Pr/t (psi)
- G = Shear modulus (psi)
- T = Torsion due to force, V (in.-lb)
- m = Moment due to virtual force, (in.-lb)
- y = Effective moment arm, in.
- X, Y = General coordinate axes
- l = Total developed centerline length of test specimen, in.
- J = Polar amount of inertia = $2\pi r^3 t$
- H = In-plane force (lb) at loaded end of tube
- V = Out of plane force (lb) at loaded end of tube
- t_V = Torsion due to virtual force (in.-lb)

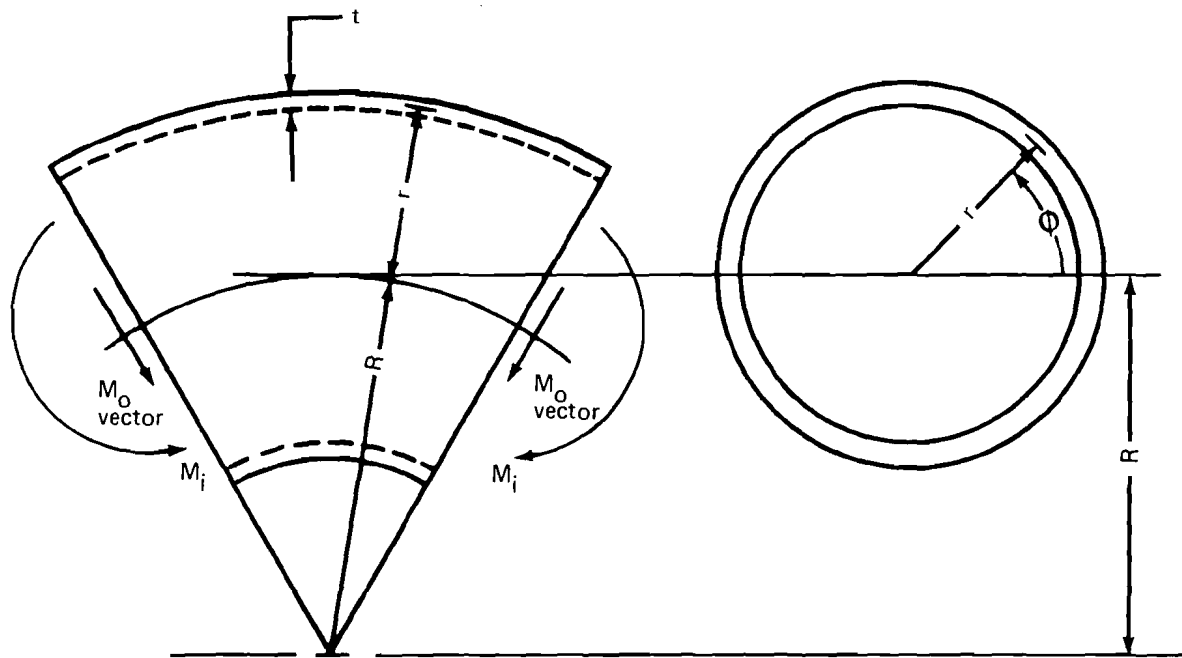


Illustration showing nomenclature

B.2 ANALYSIS:

The following tube parameters are used.

- o Straight tubing:

$$I = \pi r^3 t$$

$$J = 2\pi r^3 t$$

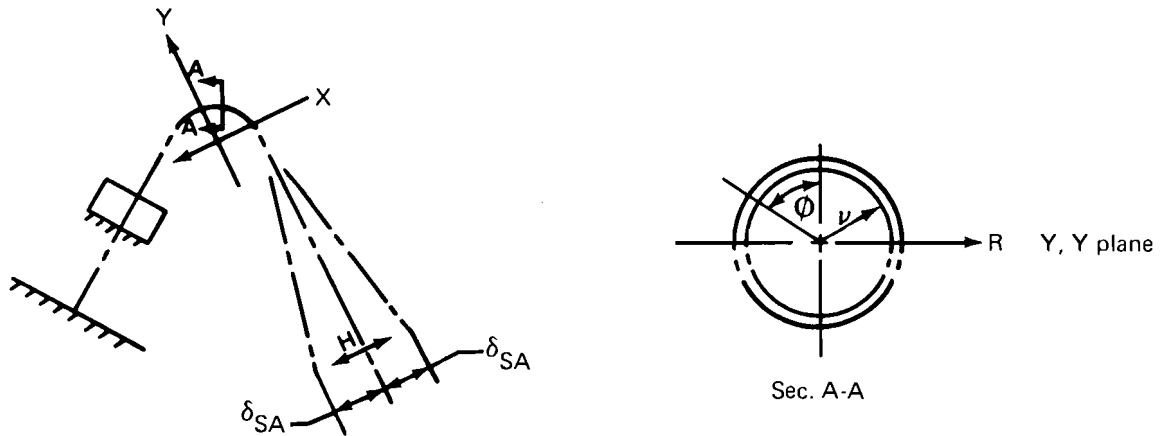
- o Curved tubing:

$$I' = kp (\pi r^3 t)$$

where

$$kp = \frac{5 + 6\lambda^2 + 24\psi}{5 + 6\lambda^2 + 24\psi} \text{ and } d_1 = \frac{-3}{5 + 6\lambda^2 + 24\psi}$$

Using those tube parameters and tube geometry as shown:



For in-plane bending

$$H = \int_0^l \frac{\pm \delta_{SA}}{EI} M_M dl \quad (1)$$

and

$$M_i = \pm Hy \quad (1-A)$$

For out-of-plane bending:

$$V = \frac{\pm \delta_{SA}}{\int_0^L \frac{M_M dl}{EI} + \int_0^L \frac{T t_V dl}{JG}} \quad (2)$$

and

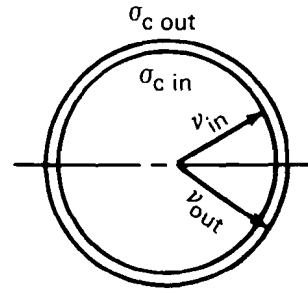
$$M_O = +Vy \quad (2-A)$$

For pressure stresses:

$$\sigma_{Pc(in)} = P \frac{r_{in}^2}{r_{out}^2 - r_{in}^2} \left(1 + \frac{r_{out}^2}{r_{in}^2} \right) \quad (3)$$

$$\sigma_{Pc(out)} = \frac{2P r_{in}^2}{r_{out}^2 - r_{in}^2} \quad (3-A)$$

$$\sigma_{P_l} = \frac{Pr}{2t} \quad (3-B)$$



For flexural stresses:

In-plane bending; longitudinal stress:

$$\sigma_{M_{LL}} = \frac{kp M_i r}{I(1 - \nu^2)} \left[1 + \frac{3d_1}{2} \sin \phi - \frac{d_1}{2} \sin 3\phi \right] = 3r d_1 \cos 2 \quad (4)$$

In-plane bending; circumferential stress:

$$\sigma_{M_{LC}} = \frac{kp M_i r}{I(1 - \nu^2)} \left[\pm 3\lambda d_1 \cos 3\phi + \nu \left(\frac{1 - 3d_1}{2} \right) \sin \phi - \frac{\nu}{2} d_1 \sin 3\phi \right] \quad (5)$$

Out-of-plane bending; longitudinal stress:

$$\sigma_{M_{OL}} = \frac{kp M_{Or}}{I(1 - \nu^2)} \left[\left(1 + \frac{3d_1}{2} \right) \cos \phi - \frac{d_1}{2} \cos 3\phi \pm 3\nu \lambda d_1 \sin 2\phi \right] \quad (6)$$

Out-of-plane bending; circumferential stress:

$$\sigma_{M_{OC}} = \frac{kp M_{Or}}{I(1 - \nu^2)} \left[\pm 3\lambda d_1 \sin 2\phi + \nu \left(1 + \frac{3d_1}{2} \right) \cos \phi - \frac{\nu}{2} d_1 \cos 3\phi \right] \quad (7)$$

In the above equations for stress due to flexure, where $\pm$ is shown the plus sign applies to inside wall surface and the minus sign applies to outside wall surface.

Then total stress on any element is given by:

$$\epsilon \sigma_C = \sigma_{PC} + \sigma_{M_O} C \text{ or } \sigma_{M_i} C \text{ (circumferential stress)} \quad (8)$$

$$\epsilon \sigma_L = \sigma_{PL} + \sigma_{M_O} L \text{ or } \sigma_{M_O} L \text{ (longitudinal stress)} \quad (8-A)$$

It is shown above that for a given tube geometry, tube wall stresses, due to flexure, are a function only of pressure and tube end deflection. For the tube end deflections shown above moments, and resulting flexural stresses, are periodic, of constant amplitude, and the phase angle between M_i and M_O is 90° (fig. B-2).

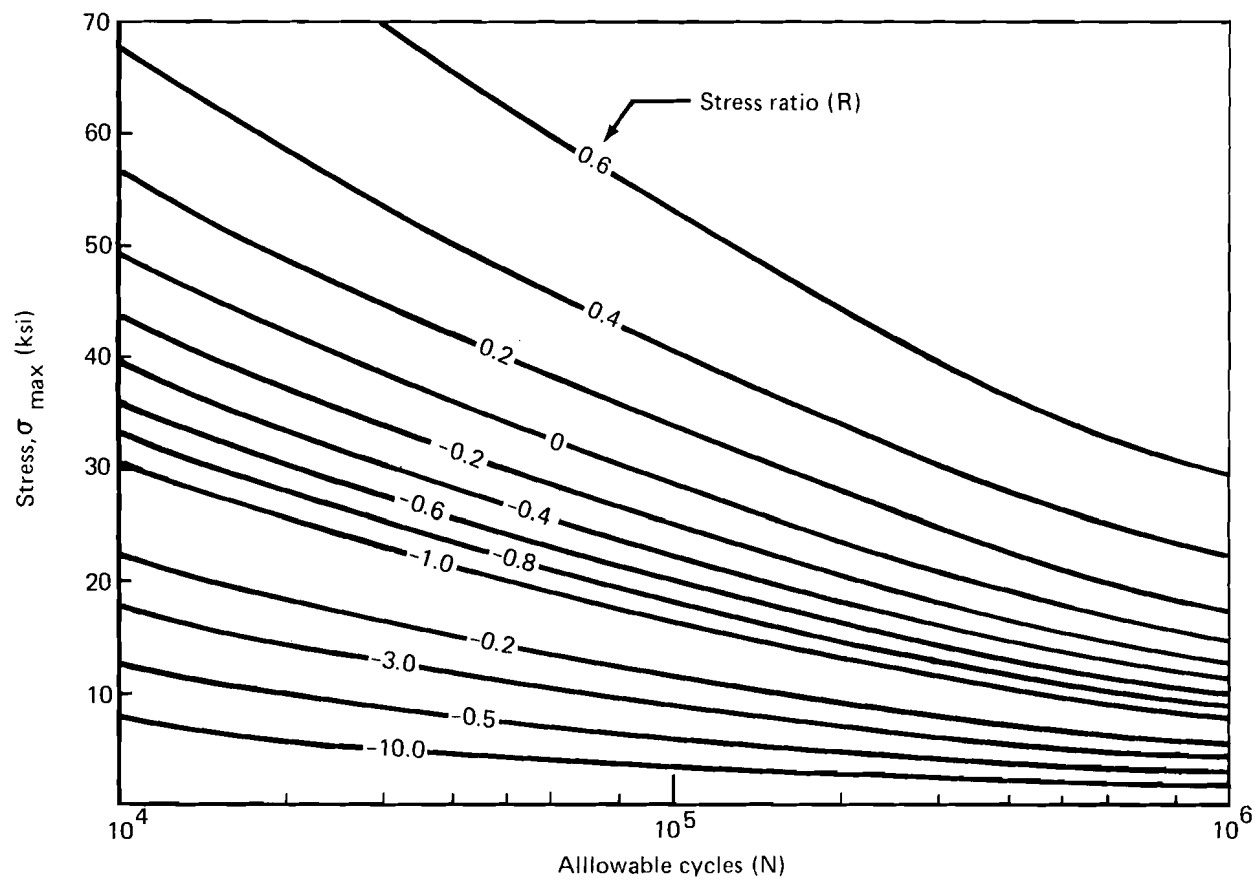


FIGURE B-1.—TYPICAL S-N DIAGRAM AND STRESS RATIOS FOR TITANIUM

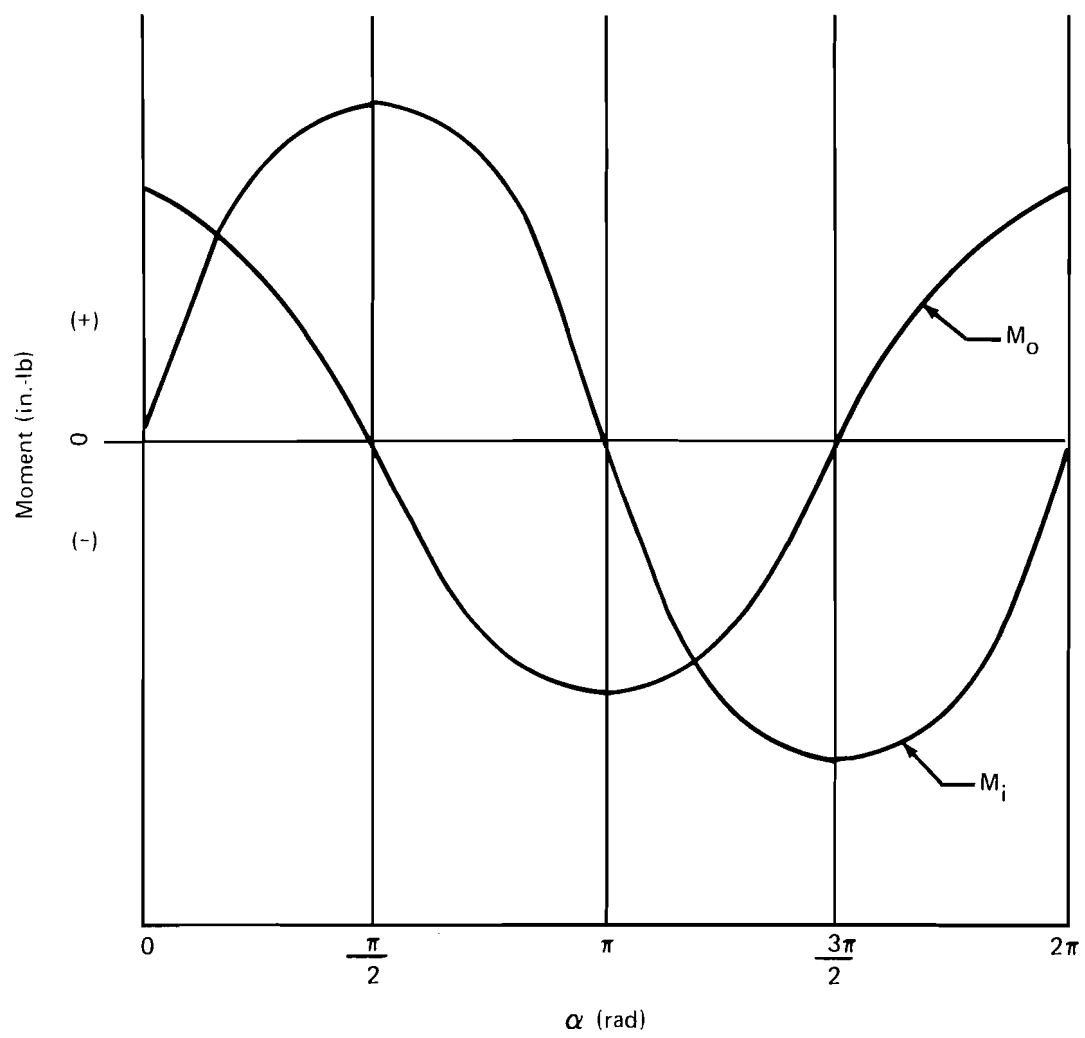
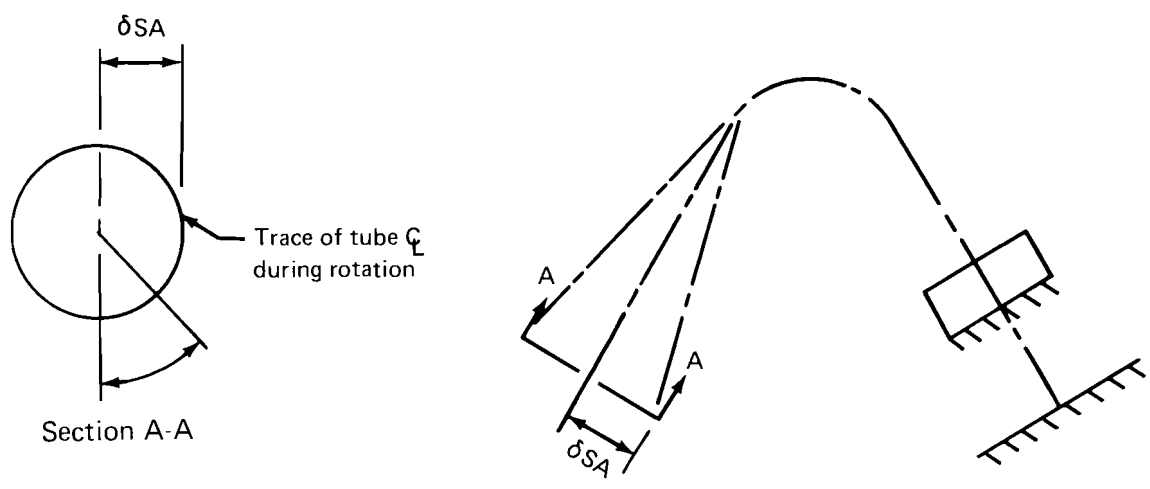


FIGURE B-2.— M_o AND M_i RELATIONSHIP

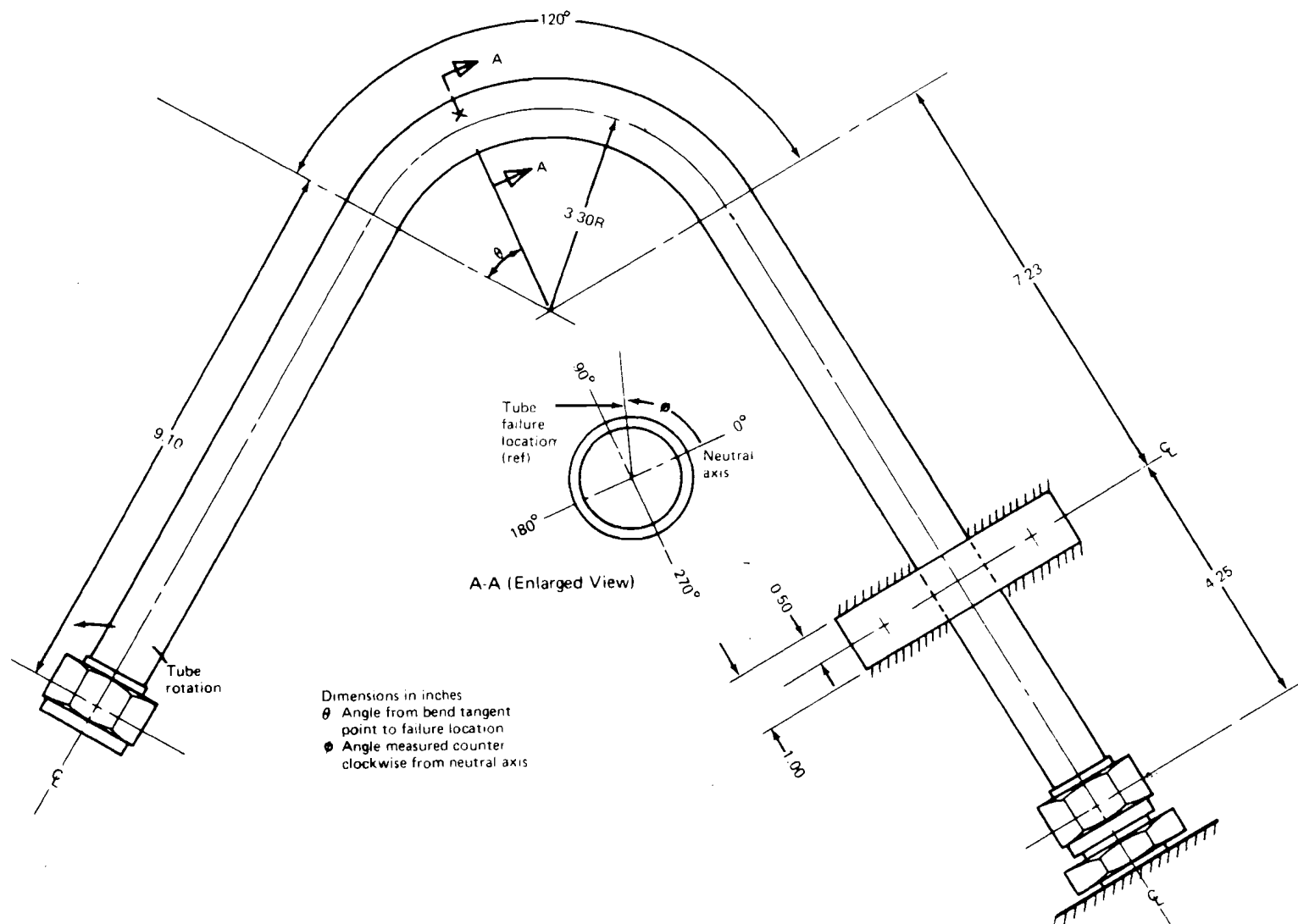


FIGURE B-3.—NOMENCLATURE AND DIMENSIONS FOR STRESS AND FAILURE ANALYSES FOR 1.0 X .080 IN. SPECIMENS

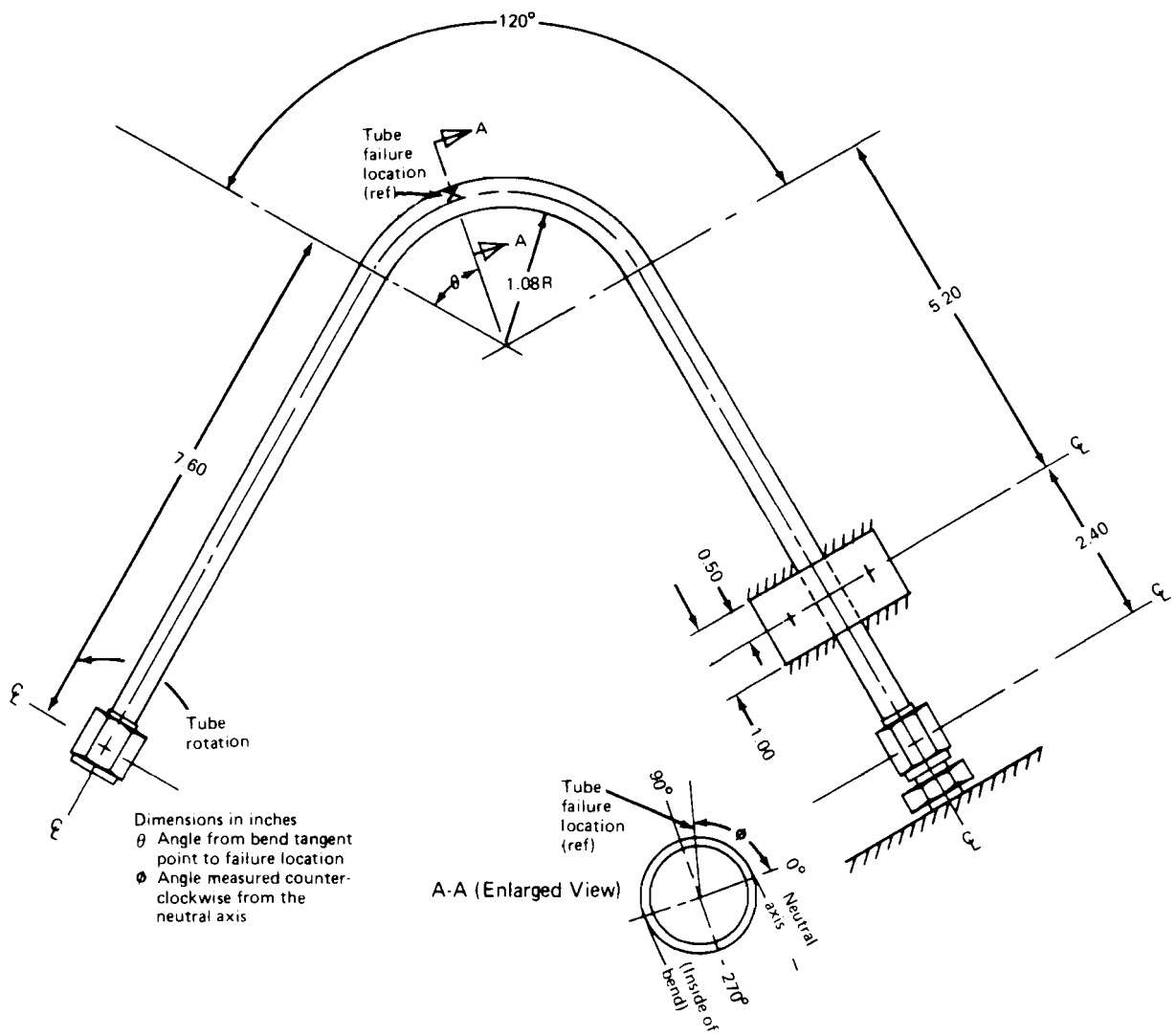


FIGURE B-4.—NOMENCLATURE AND DIMENSIONS FOR STRESS AND FAILURE ANALYSES FOR 3/8 X .020 IN. SPECIMENS

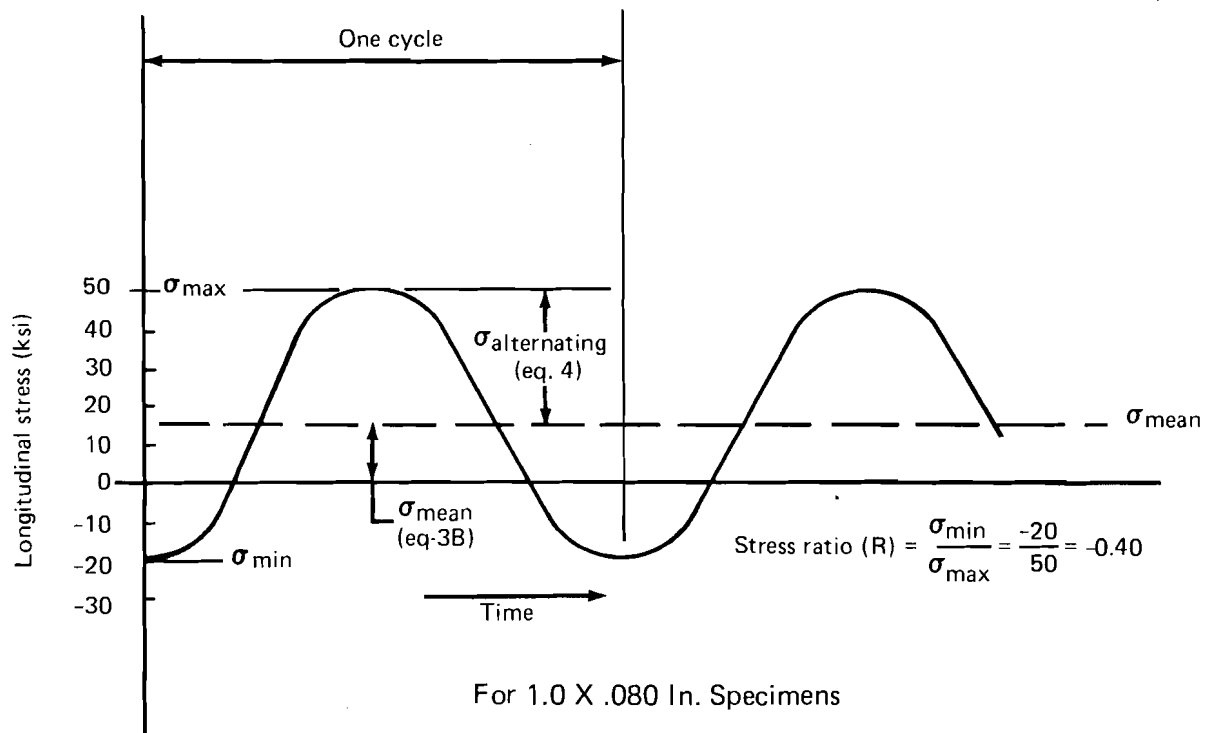
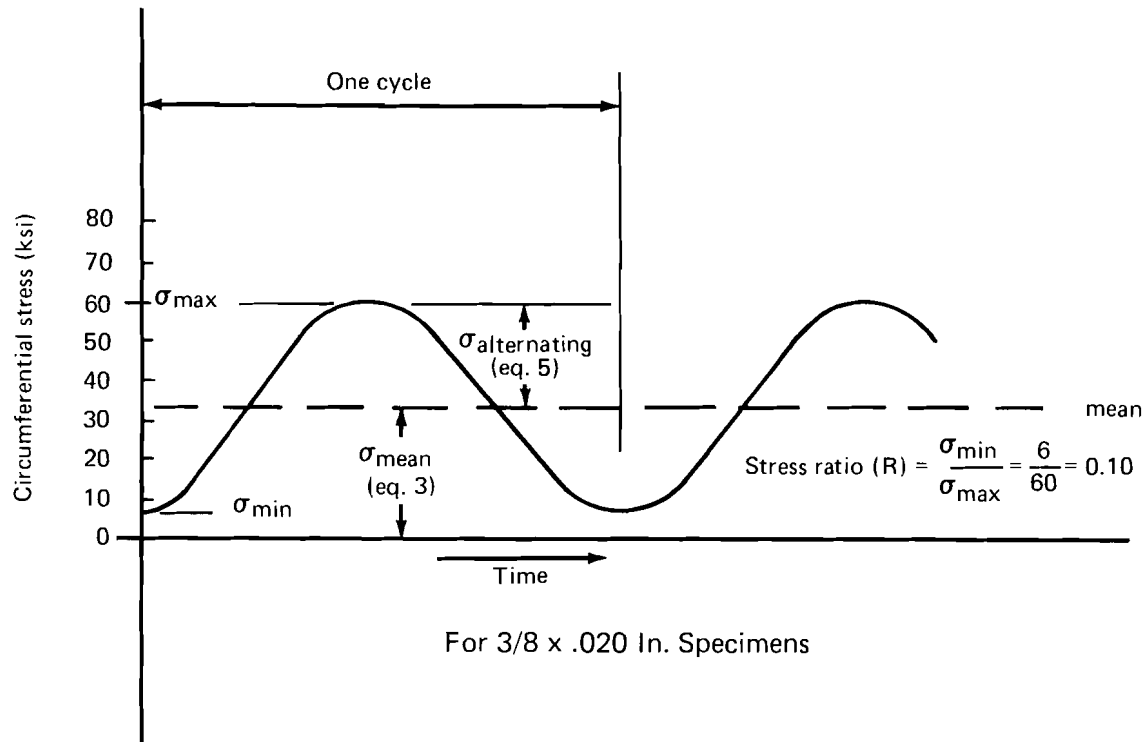


FIGURE B-5.—TYPICAL STRESS DESIGN CRITERIA

APPENDIX C

**BOEING TEST REPORT T6-5722-3 "METALLURGICAL EXAMINATIONS
OF MISCELLANEOUS Ti-3Al-2.5V TUBES AND TUBE HOLLOWS IN SUPPORT OF
DOT CONTRACT DOT-FA-SS-71-12 PHASE I, TASK 6, SUBTASK 1"
DATED 7-25-72**

THE **BOEING** COMPANY

COMMERCIAL AIRPLANE DIVISION

RENTON, WASHINGTON

DOCUMENT NO. T6-5722-3

TITLE: Metallurgical Examinations of Miscellaneous Ti-3Al-2.5V
Tubes and Tube Hollows in Support of DOT Contract DOT-FA-SS-71-12;
Phase 1, Task 6, Subtask 1.

MODEL Contract

ISSUE NO. _____ TO: _____ (DATE) _____

W. E. Quist
PREPARED BY W. E. Quist 7/25/72
SUPERVISED BY L. B. Alstra 8-3-72
APPROVED BY R. A. Davis 8-9-72
APPROVED BY _____

(DATE) _____

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REFERENCES

1. Structures Staff-Materials Metallurgical Laboratory
Job Numbers 465P and 480P.
2. Structures Staff-Materials Metallurgical Laboratory
Job Number 13Q and 51Q.
3. Structures Staff-Materials Metallurgical Laboratory
Job Number 52Q.
4. Structures Staff-Materials Metallurgical Laboratory
Job Number 71Q.



SUMMARY

Test reports T6-5722-1, -2, and -3 summarizes all metallurgical investigations performed on Ti-3Al-2.5V tubing evaluated in support of DOT Contract DOT-FA-SS-Phase 1, Task 6, Sub-task 1. Report -1 covers tubing studied during the initial screening evaluation of the contract. The primary emphasis was on 3/8" Dia. x 0.020" wall and 1.0" Dia. x .080" wall tubing which had been given various I.D. surface treatments. In addition, a 3/8" Dia. x 0.020" wall tube was included which was produced to possess an optimum crystallographic texture. Report -2 covers all tubing procured for the final evaluation phase of the contract. The tubing, principally 3/8" Dia. x .020" wall and 1.0" Dia. x .080" wall, was manufactured on a best effort basis to the proposed material specification XBMS 7-234A. This specification incorporated improved raw materials, processing (including texture) and quality assurance provisions. The improved tubing was primarily utilized for the evaluation of various types of joints. Report -3 covers four miscellaneous investigations that were performed to generate fundamental technology on the metallurgical aspects of tube processing and properties. These included evaluations performed on finished and partially finished tubes and tube hollows from various tube manufacturers as well as an in-house heat treatment study.

Four separate and independent investigations are presented in this -3 report. Each study is presented as a separate entity, including its own summary. They are as follows:

- PART I - CRYSTALLOGRAPHIC TEXTURE AND STRUCTURE DETERMINATION ON Ti-3Al-2.5V TUBING STOCK RECEIVED FROM SUPERIOR TUBE COMPANY.
- PART II - CRYSTALLOGRAPHIC TEXTURE DETERMINATIONS ON Ti-3Al-2.5V TUBING AND TUBE HOLLOWES RECEIVED FROM THE ZIRCONIUM TECHNOLOGY (ZIRTECH) AND WAH CHANG COMPANIES, ALBANY, OREGON.
- PART III - R-VALUE DETERMINATIONS ON FIVE Ti-3Al-2.5V COLD WORKED AND STRESS RELIEVED TUBES RECEIVED FROM THE BISHOP TUBE COMPANY.
- PART IV - THE EFFECT OF AGING AT 450°F ON THE STRENGTH OF Ti-3Al-2.5V COLD WORKED AND STRESS RELIEVED TUBING.

This test report is principally intended to document data generated during the course of the investigation and addresses itself only briefly to the more general application of the data or philosophy of testing.

AD 19460



PART I - CRYSTALLOGRAPHIC TEXTURE AND STRUCTURE DETERMINATIONS ON
Ti-3Al-2.5V TUBING STOCK RECEIVED FROM THE SUPERIOR TUBE CO.

SUMMARY

Crystallographic texture determinations have been performed by X-ray diffraction techniques on two tube hollows and three finished or partially finished Ti-3Al-2.5V tubes. The tube hollows were extruded by RMI and ITT Harper in the α - β and β phase ranges respectively, but nevertheless exhibited very similar textures. The finished and partially finished tubes conformed to the relationships previously noted; namely that relatively large diameter thin walled tubes possess a better texture (basal planes in a more radial orientation) than do the smaller diameter, thicker walled tubes.

INTRODUCTION:

The Superior Tube Company, Norristown, Pa., has submitted several samples of Ti-3Al-2.5V tubing for evaluation of crystallographic texture and microstructure. Two samples were from tubing that had been partially processed using somewhat unconventional processing schedules as outlined in Attachment 1. Two other samples were from tube hollows that had been received from ITT Harper in one case and RMI in the other. A final sample was taken from a finished tube made from one of the Harper tube hollows, (See Attachment 2). The purpose of this investigation was to help establish the effect of processing on crystallographic texture and microstructure so that a better understanding of these parameters can be developed.

RESULTS AND DISCUSSION

Crystallographic Texture

Tubes used during the present investigation are outlined in Table I-1.

The results of the X-ray pole figure determinations are shown in Figures I-1 through I-5. (Also see reference 1). Samples A and B exhibited typical tubing texture with sample B having a slightly improved radial orientation of basal plane poles relative to tube A. The considerably reduced wall thickness and only slightly reduced diameter of tube B, compared to A, combine to make the improved texture of tube B the expected situation.



Table I-I - Crystallographic Texture of Various Ti-3Al-2.5V TUBES

Ident. No.	Tube Size	Manufacturer	Heat No.	ϕ^* Angle	Comments
A	.555"x.0375"	Superior	-	35°	Partially finished tube; 4 of 8 bench draws comp.; 48% CW; Final tube size - .375"x0.020"(projected).
b	.743"x.054"	Superior	-	43°	Partially finished tube; 2 of 4 bench draws comp.; 47% CW; Final tube size - .625" x .040" (projected)
1-30	.875"x.095"	RMI	304450-06	45°	Tube hollow received by Superior from RMI; Annealed.
2-30	.875"x.097"	ITT Harper	295611	41°	Tube hollow received by Superior from Harper; Annealed at 1350°F.
3-30	.500"x.036"	Superior- Harper	295611	56°	Finished tube processed by Superior from the Harper Tube Hollow - 2-30. Annealed at 1350°F

*The angle between the centroid of the basal plane pole peak and the 0 degree pole measured along the 270° axis; pole figure analysis.

The tube hollow samples 1-30 (RMI) and 2-30 (Harper) displayed very similar textures even though the manufacturing procedures for these products are thought to be somewhat different. Harper tube hollows are extruded (bare) in the all Beta (β) region (possibly as high as 2200°F) and RMI tube hollows are extruded (clad in steel) in the α - β region. The RMI product was extruded as a 2-5/8" x .375" wall tube and cold reduced in three steps, including three anneals, to the .875" x .095" size that was shipped to Superior. The ITT Harper tube hollow was extruded to a 2" x .095" size and tube reduced at Superior to the .875" x .095" size.

Attachment 1 states that the R ratio of the RMI tube was approximately 0.6 whereas that of the Harper tube was 1.8, a large and significant difference. The X-ray analysis would certainly not support this difference in R values, i.e. the R-value results indicate a very different texture and the pole figures a very similar texture.



Sample 3-30, which was prepared from the Harper tube hollow 2-30, exhibited a less favorable radial texture than did the starting stock. As the wall thickness was reduced from .097" to .036", with only a moderate diameter reduction, this deterioration in texture was not expected and can not be easily explained at present. The ratio of wall reduction to diameter reduction corresponds to a T ratio* of 1.47 which is thought to enhance the development of radial texture.

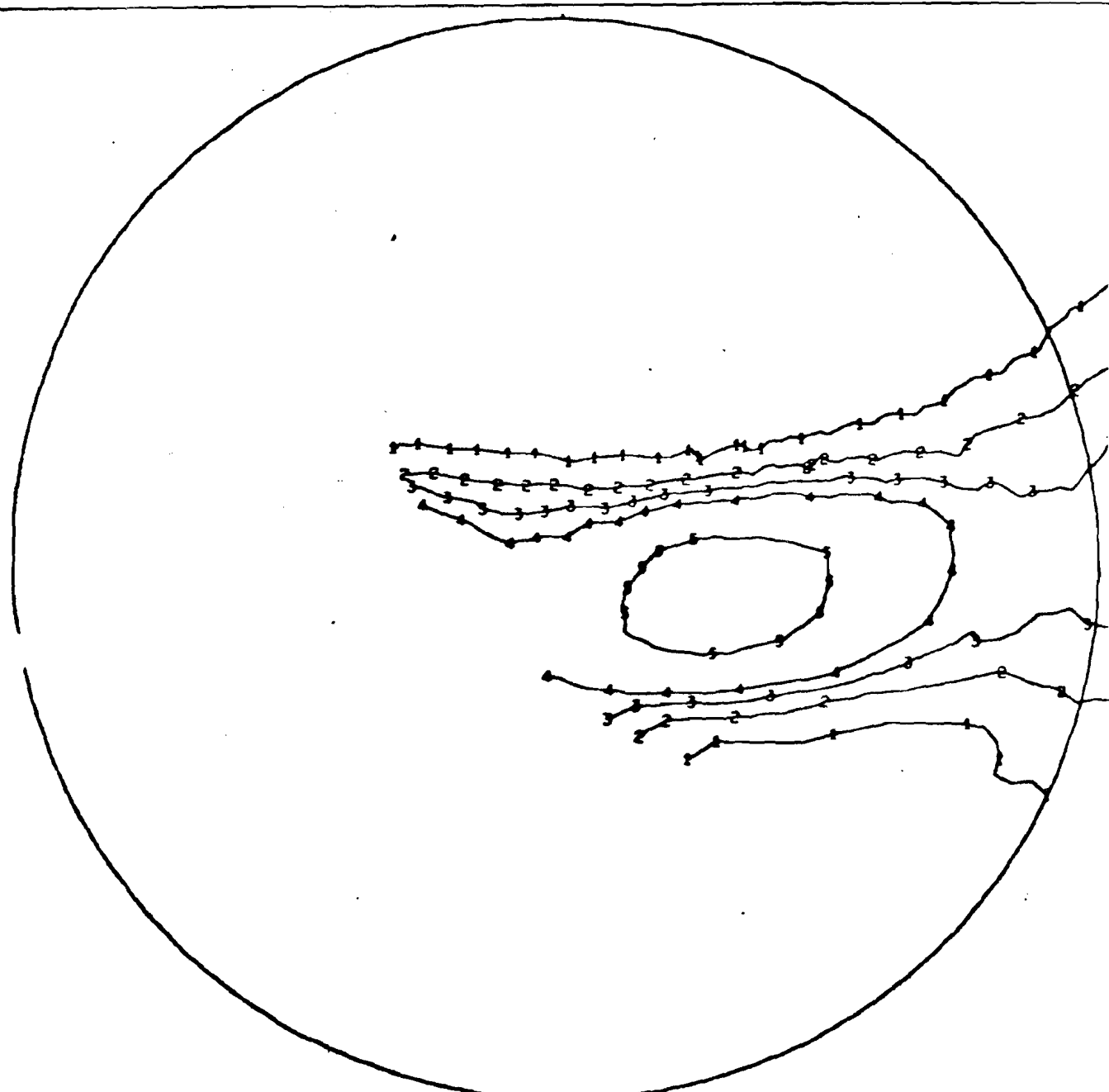
The reasons for these apparent differences are not fully understood at present although the poor surface finish present on the RMI tube is thought to be at least partially responsible.

Microstructure

A microstructural examination of the two tube hollows was performed in addition to the texture examination. The Harper hollow possessed a very poor surface finish and also contained some laps or tears. An example of this condition is shown in Figure I-6. These tears are considered to occur as a result of a very large grain size in the extruded tube hollow. The microstructure of the RMI and Harper tube hollows are shown in Figure I-7. Both hollows show a typical microstructure of equiaxed alpha phase at this stage in their processing.

$$* T = \frac{\frac{W}{W_o}}{\frac{I.D.}{I.D._o}}$$

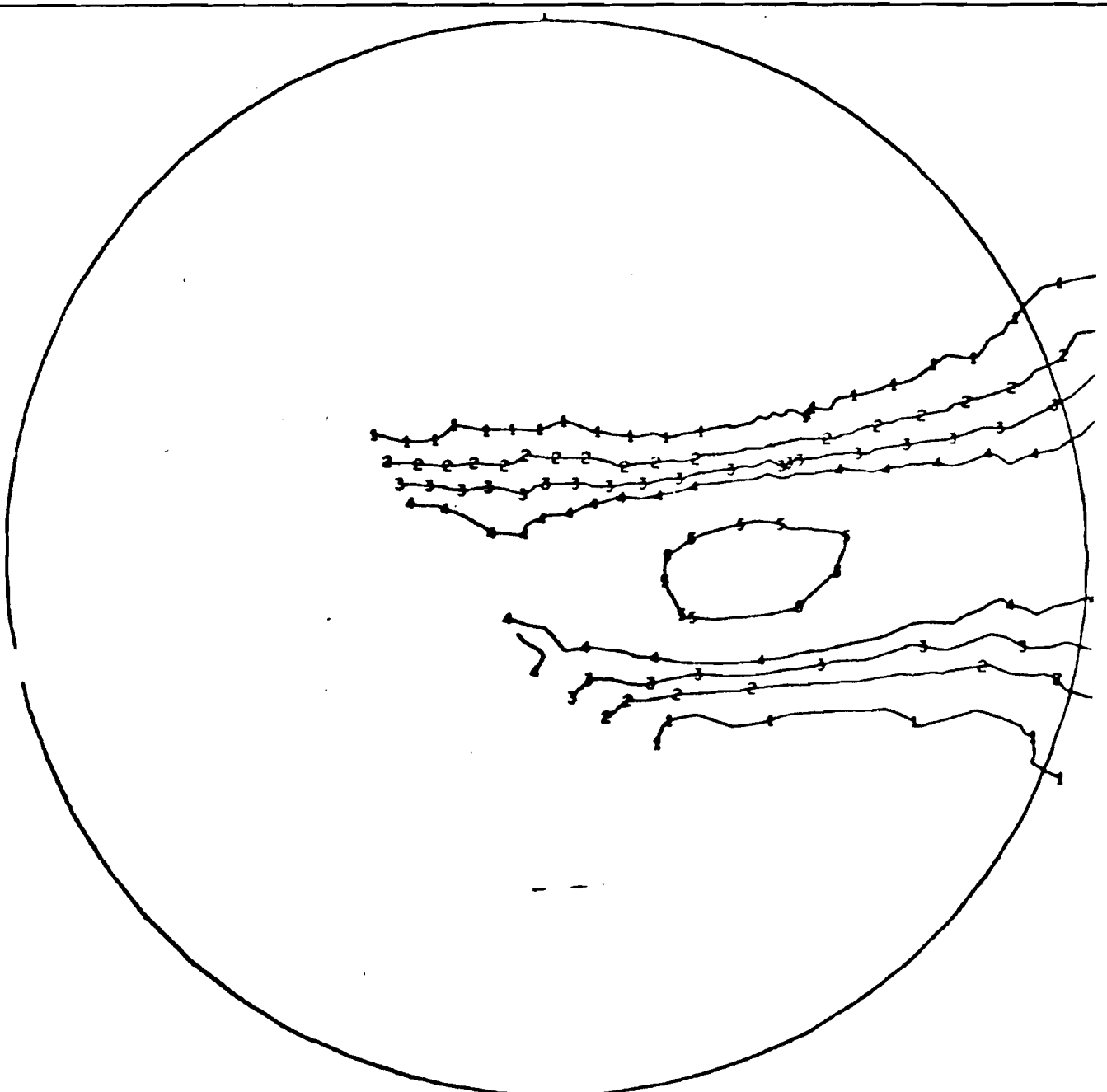




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6	0.0000	7	14.0000	8	20.0000	9	25.0000	0	30.0000

JOB NO 465P SAMPLE 0.555 O.D.X0.0375 W DATE 11/15/71
 RADIATION CU AT 35 KV 28 MA COUNTER TUBE PROP AT 1.95 KV
 BLITS 2 H 2V ENTRANCE 5 H 1V RECEIVING ENGINEER R.H.OLSEN
 SCAN RATE 1 PSI/MIN 72 ALPHA/MIN (0002) HKL
 PHA 50 BASE 30. WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 459.0 K(A) 101.914 CALC DATE 11/29/71

Figure I-1 Pole figure for tube A. This partially finished tube was 0.555" x 0.0375" in size and had undergone 4 of 8 panel bench draw operations.

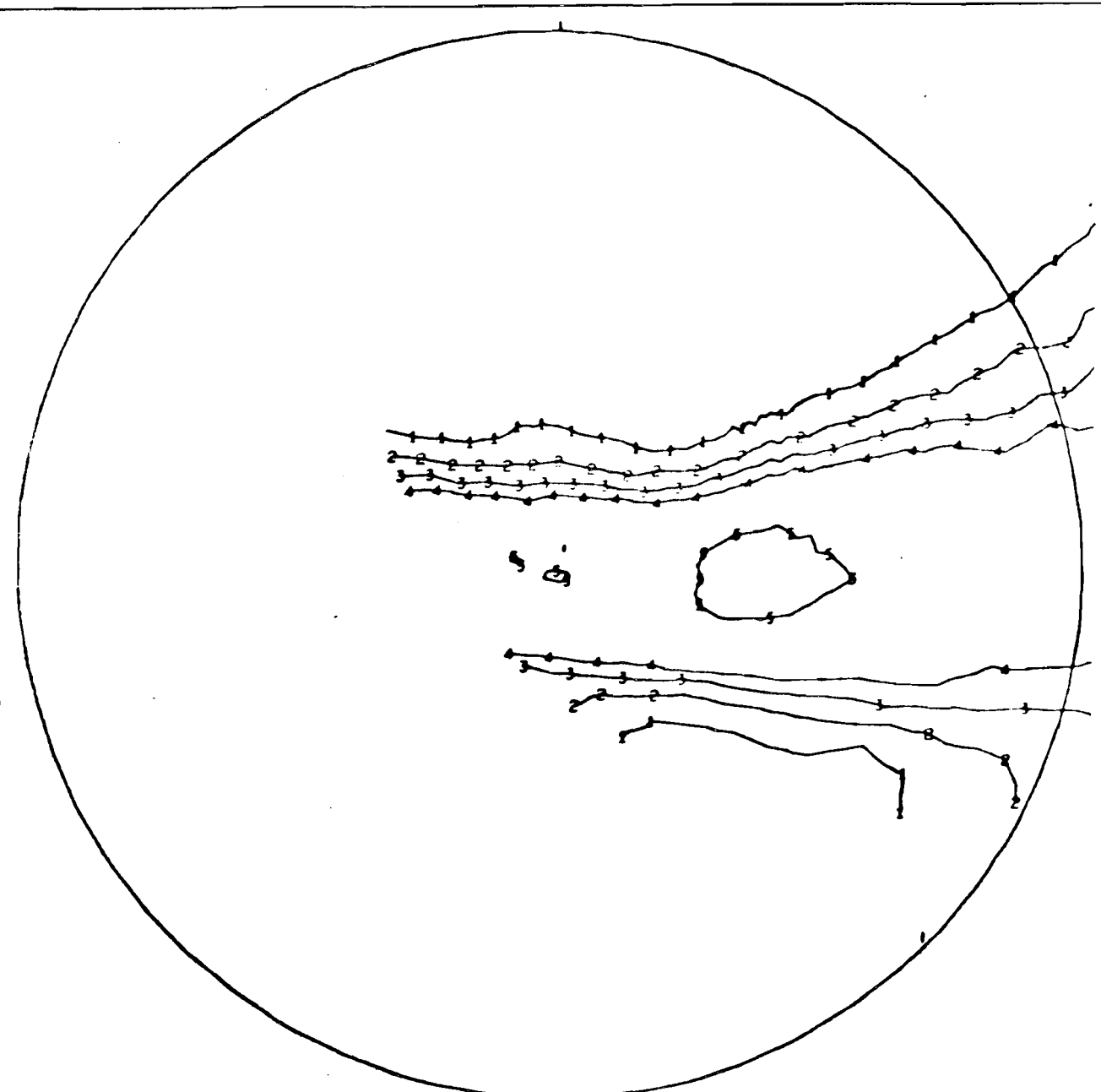


1	.5000	2	1.0000	3	1.5000	4	2.0000	5	4.0000
6	6.0000	7	14.0000	8	20.0000	9	25.0000	0	30.0000

JOB NO 465P SAMPLE 0.743 O.D. X 0.054 W DATE 11/15/71
 RADIATION CU AT 35 KV 28 MA COUNTER TUBE PROP AT 1.95 KV
 SLITS 2 H 2V ENTRANCE 5 H 1 V RECEIVING- ENGINEER R.H. OLSEN
 SCAN RATE 1 PSI/MIN 72 ALPHA/MIN (0002) HRL
 PHA 5. BASE 30. WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 459.0 K(A) 132.029 CALC DATE 11/29/71

Figure 1-2 Pole figure for tube B. This partially finished tube was 0.743" x 0.054" in size and had undergone 2 of 4 planned bench draw operations.



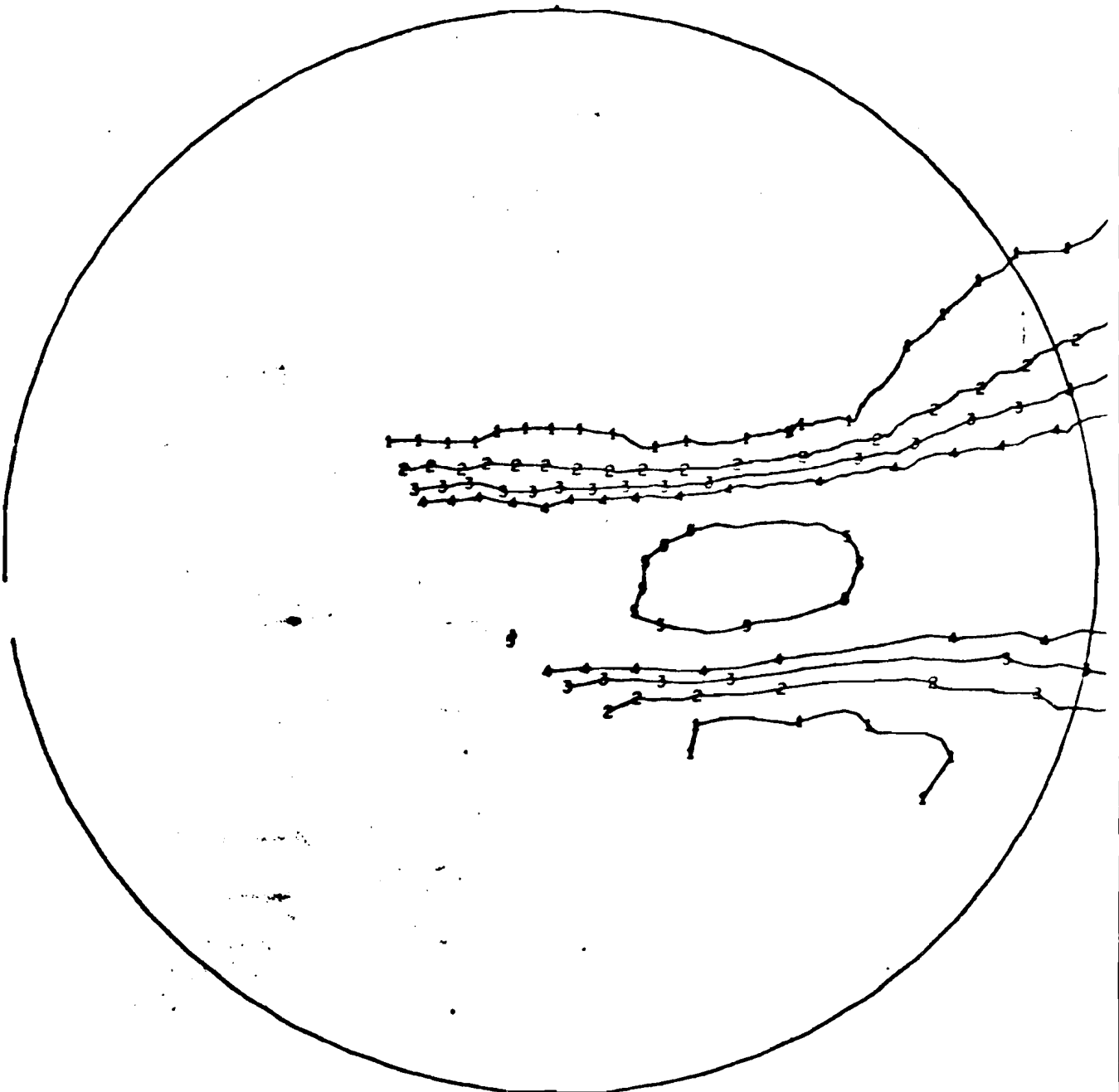


1	.5000	2	1.0000	3	1.5000	4	2.0000	5	4.0000
6	8.0000	7	14.0000	8	20.0000	9	25.0000	0	30.0000

JOB NO. 480P SAMPLE 1-30 DATE 1/1/72
 RADIATION CU AT 35 KV 28 MA COUNTER TUBE PROP AT 1.95 KV
 SLITS 2 H 2V ENTRANCE 5 H 1V RECEIVING ENGINEER R.H. OLSEN
 SCAN RATE 1 PSI/MIN 72 ALPHA/MIN (0002) HXL
 PHA 5. V BASE 30, V WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 449.0 K(A) 146.718 CALC DATE 01/12/72

Figure I-3 Pole figure for tube hollow 1-30. This sample was 0.875" x 0.095" in size and was made by RMI for the Superior Tube Co.





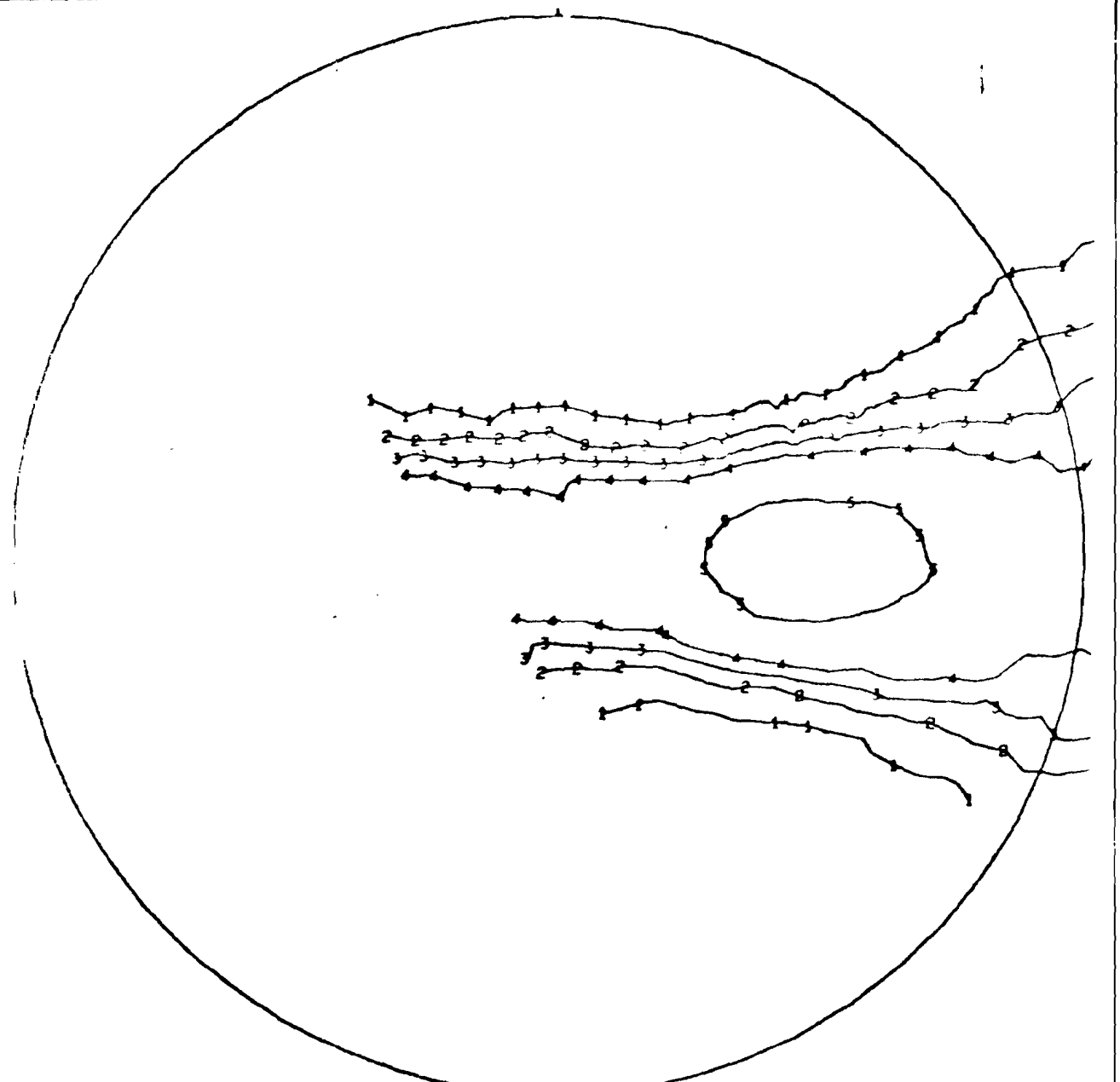
1	.5000	2	1.0000	3	1.5000	4	2.0000	5	4.0000
6	8.0000	7	14.0000	8	20.0000	9	25.0000	0	30.0000

JOB NO. 480P SAMPLE 2-30 DATE 1/7/72
 RADIATION CU AT 35 KV 28 MA COUNTER TUBE PROP AT 1.95 KV
 SLITS 2 H 2V ENTRANCE 5 H 1V RECEIVING ENGINEER R.H. OLSEN
 SCAN RATE 1 PSI/MIN 72 ALPHA/MIN (0002) HKL
 PHA 5. V BASE 30. V WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 449.0 K(A) 136.559 CALC DATE 01/12/72

Figure I-4 Pole figure for tube hollow 2-30. This sample was 0.875" x 0.097" in size and was extruded at Harper for the Superior Tube Co.



J16-047

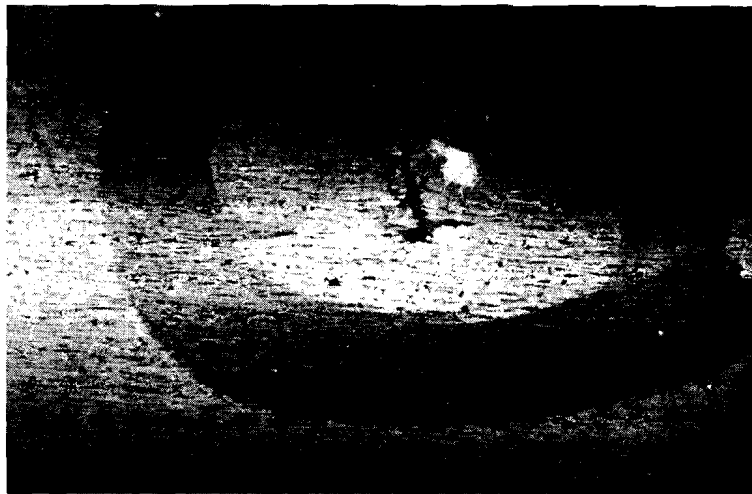


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JOB NO. 480P SAMPLE 3-30 DATE 1/6/72
 RADIATION CU AT 35 KV 28 MA COUNTER TUBE PROP AT 1.95 KV
 SLITS 2 M 2V ENTRANCE 5 M 1 V RECEIVING ENGINEER R.M. OLSEN
 SCAN RATE 1 PSI/MIN 12 ALPHA/MIN (0002) MKL
 PHA 5. V BASE 30.V WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 449.0 K(A) 154.809 CALC DATE 01/12/72

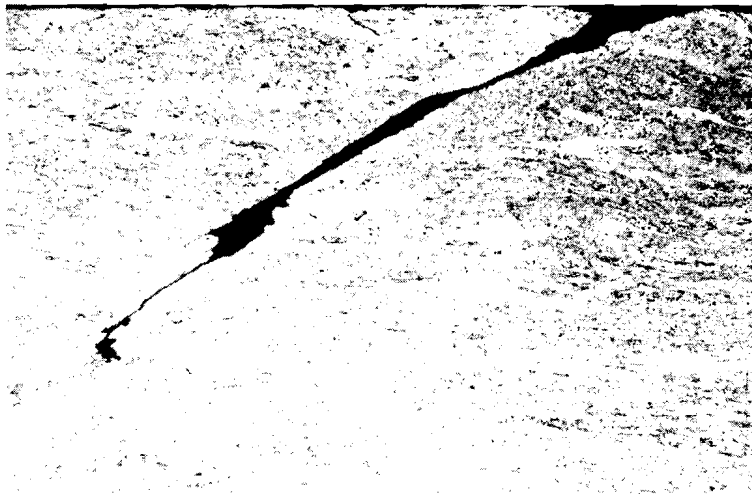
Figure I-5 Pole figure for tube 3-30. This finished tube was 0.500" x 0.036" in size and was made by the Superior Tube Co. from the Harper Tube Hollow 2-30. See Figure I-4.

D: 4100 3740 0VIG.2/7



20X

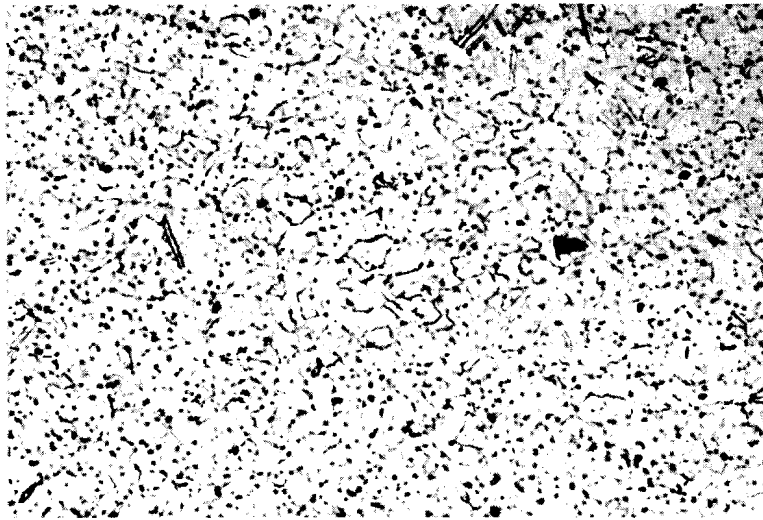
(a)



50X

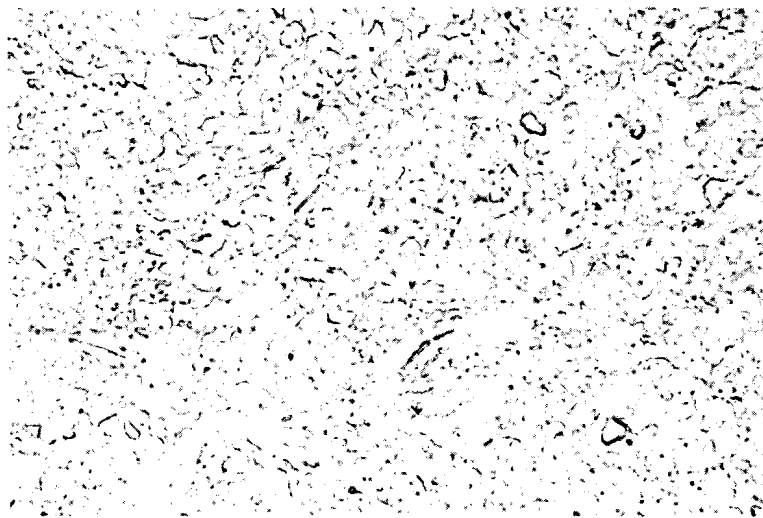
(b)

FIGURE I-6.—A LAP OR TEAR THAT WAS PRESENT IN THE HARPER TUBE HOLLOW; SPECIMEN 2-30. THIS CONDITION IS CONSIDERED TO RESULT FROM A LARGE GRAIN SIZE IN THE AS-EXTRUDED TUBE HOLLOW.



RMI tube hollow 500X

(a)



ITT Harper tube hollow 500X

(b)

FIGURE I-7.—MICROSTRUCTURE OF RMI AND HARPER TUBE HOLLOW. THESE PHOTOS SHOW TYPICAL EQUIAXED TRANSFORMED β STRUCTURES FOR Ti-3Al-2.5V TITANIUM.

October 13, 1971

Mr. Don Goehler
15612 Southeast Tenth Avenue
Bellvue, Washington 98008

Dear Don:

Here are two samples taken from your test lots about half way thru the drawing schedule sequence:

I. .555 x .0375" Wall piece:

This was cut from the lot destined to finish at .375 x .020 Wall. This piece represents the lot after completing four of a total of eight bench draws. Sample condition is as-drawn (approximately 46% cold work) and pickled. If you want to anneal, we use 1250°F for 1 hour at least. Stress relieving would be done at 850°F.

II. .743" x .054" Wall:

(Destined for .625 x .040" W)

This size piece represents the lot after completion of two of a total of four bench draws. Sample condition is as drawn (approximately 47% cold work) and pickled. Annealing is as in I.

If you have further questions, please call. I'm very sorry for the delay on your lots and will rush them thru as fast as possible.

Best regards,

SUPERIOR TUBE COMPANY

T. W. Rees

T. W. Rees,
Development Metallurgist

TWR:gm

Enc.

SUPERIOR TUBE COMPANY • NORRISTOWN, PA. • 19404

PHONE 215-489-7221
215-273-2070TELETYPE 510-060-6410/G411
TELEX 003-4274

November 12, 1971

Mr. Don Cochler
15612 Southeast Tenth Ave.
Bellevue, Washington 98003

Dear Don:

As part of your texture program, I thought it might be of interest to send some of our starting raw material and a description of its history. As a result, here are samples of two different suppliers, IMI Harper and IMI, both at the .875 x .095 size. (Your test lots were made from IMI material).

Background:

IMI: Superior buys stock from IMI at a size of .875 x .095 W. We understand that IMI produces this size by extruding a hollow at 2-5/8" OD x 3/8" W followed by three cold tube reductions (rolling) and anneals. Our anisotropy test on this material, as calculated after tensile elongation using this formula: $\text{Strain Ratio} = R = \ln(\Delta OD) / \ln(\Delta W)$, showed a value of only 0.6. We consider a value of 1.0 respectable but would prefer 1.5 to 2.0.

HARPER: Because the IMI stock showed a low R value, Superior decided to buy an as-extruded hollow and tube reduce in-house. A heavy wall thickness was ordered to permit primarily wall reduction (a characteristic we feel is important in gaining high R values) during processing. The stock was extruded to 2" x 3/8 W and tube reduced twice to reach the .875 x .095" size. The R value of this stock was approximately 1.8.

We cannot explain why the IMI R-value is so much lower since starting sizes for both lots are not that different. We do know that IMI extrudes a clad billet (temperature not known) and Harper pushes bare, probably in the all beta region. Perhaps this is a factor.

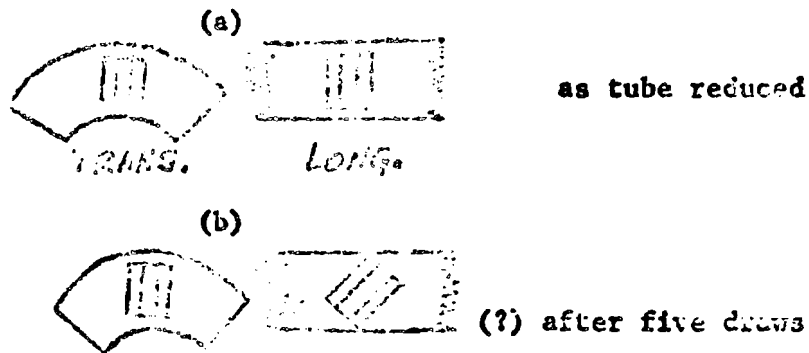
We wanted to use this Harper stock for your test program, hopefully to give a very strong texture, but as you know the stock arrived too late. The next best thing I can offer is a sample tube at .900 x .096" Wall drawn down in five bench operations for Grain as a trial evaluation of Harper. We note that between .875 and .900, the R-value dropped to 1.3. This was unexpected since texture and ductility still are high. We think that possibly the grain orientation is rotating from (a) to

SUPERIOR TUBE COMPANY • NORRISTOWN, PA. 19404

Subject: Mr. Don Goshler

11/12/71

(b) shown below due to the shearing distortion associated with rod drawing.



If this is the case, it would appear that a tube reduced tube might have an inherent advantage in developing strong favorable textures, although the drawn tube would still be quite ductile in the transverse direction.

If any questions arise about the processing history for either your test lots or the accompanying samples, please contact us.

Best regards,

SUPERIOR TUBE COMPANY

T. W. Rees

T. W. Rees,
Development Metallurgist

TWR:gm

PART II - CRYSTALLOGRAPHIC TEXTURE DETERMINATIONS ON Ti-3Al-2.5V TUBING
AND TUBE HOLLOW RECEIVED FROM THE ZIRCONIUM TECHNOLOGY
(ZIRTECH) AND WAH CHANG COMPANIES, ALBANY, OREGON

SUMMARY

Crystallographic texture determinations using computerized X-ray pole figure techniques have been performed on two Ti-3Al-2.5V samples from a single Wah Chang tube-hollow (head and tail end), and on four pieces of Ti-3Al-2.5V tubing that had been processed by somewhat different procedures. The nose end of the tube hollow demonstrated a good radial texture whereas the tail end exhibited a greatly deteriorated crystallographic texture. The partially finished tubes demonstrated improved texture as the ratio of the wall thinning reduction to outside diameter reduction increased. No effect of other processing variables was noted.

INTRODUCTION

Crystallographic texture studies were made by X-ray diffraction on four pieces of Ti-3Al-2.5V cold work and stress relieved (CWSR) tubing that was received from Zirtech. These samples represented four different processing schedules that were derived by using two sizes of starting stock (2.5" x 0.350" and 2.5" x 0.180") and processing them to two finished sizes; 0.5 dia. x 0.029" wall and 0.375" dia. x 0.022" wall. One of the processing schedules involved four reduction passes and the remaining schedule, five passes. See Attachment A for details of the processing. All tubes were made on Pilger tube reducing mills.

Texture studies were also performed on two pieces of a Ti-3Al-2.5V tube hollow that was made by Wah Chang Co. for Zirtech. One sample was from the nose end (N) and the other was from the tail end (T) of a ~14' long extrusion. This tube hollow was as extruded (~1300°F) and was 2.5" dia. x 0.450" wall in cross section.

RESULTS AND DISCUSSION

The results of the crystallographic texture study are shown in Figures II-1 through II-6 and Table II-1. See also Reference 2.



Table II-1 - The Crystallographic Texture of Ti-3Al-2.5V Tubes and Tube Hollows

Specimen Number	Supplier	Size (O.D." x Wall Thick")	Condition	Ø Angle*
1. (T4-054-131C)	Zirtech	0.5" x 0.029"	?	52°
2. (TR-018-030)	Zirtech	0.5" x 0.029"	?	38°
3. (TR-002-CONR-1)	Zirtech	0.375" x 0.022"	?	44°
4. (TR-059-233A)	Zirtech	0.375" x 0.022"	?	49°
5. (N - Code 3)	Wah Chang	2.5" x 0.450"	As-extruded	0° **
6. (T - Code 3)	Wah Chang	2.5" x 0.450"	As-extruded	50° ***

* The angle between the centroid of the basal plane pole peak and the 0 degree pole along the 270° axis, pole figure analysis.

** Peaks were on the 0 and 180° axis, but were strongly basal.

*** Very elongated peak (ridge) along the 270° axis.

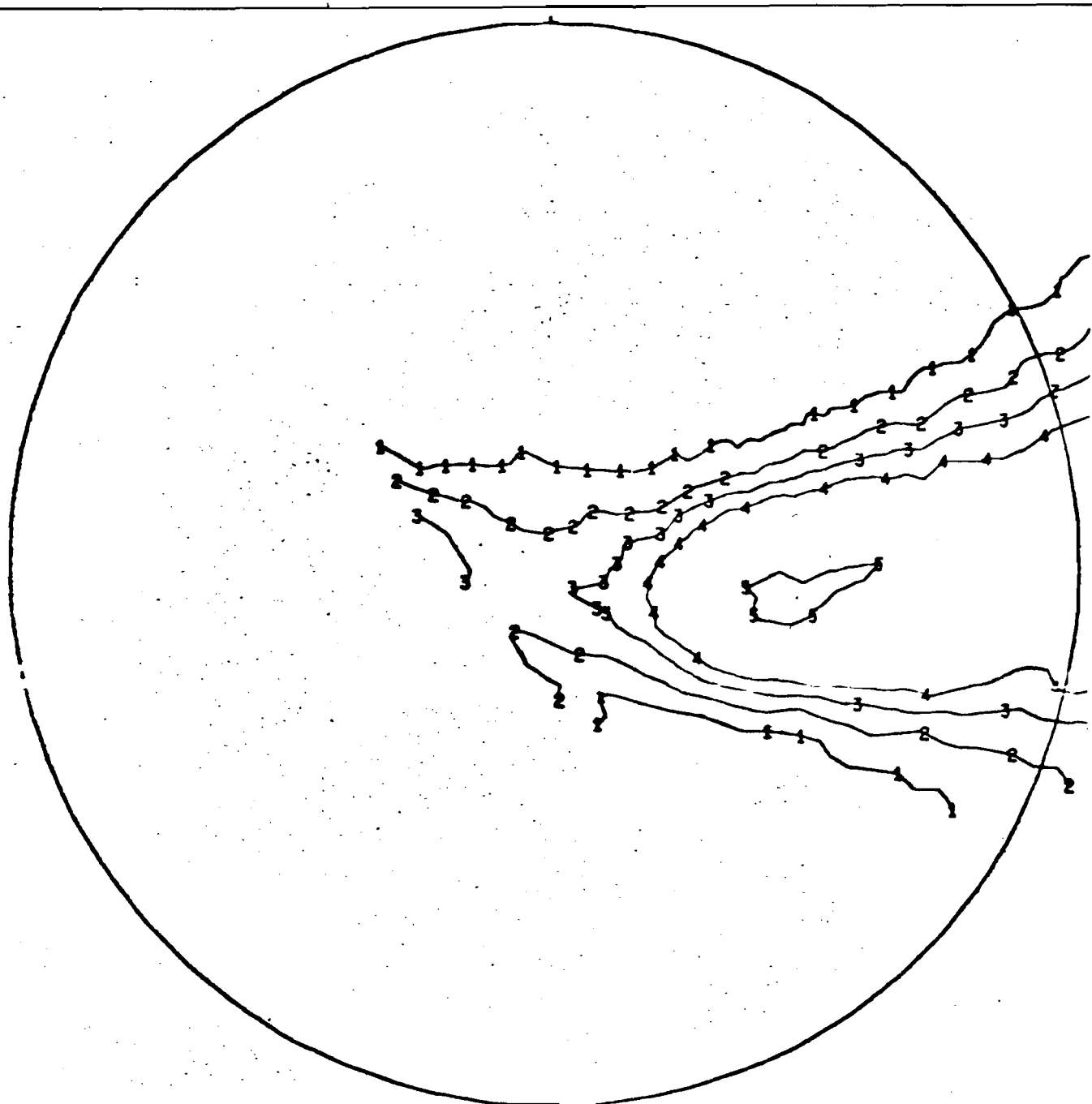
A general pattern that has been noted in previous Boeing studies, as well as in the literature, is that a favorable orientation of basal plane poles develops during processing when diameter reduction is minimum and wall reduction is maxima. This pattern was found to be followed exactly in the finished tubes obtained from Zirtech as will be noted by comparing tubes 1 and 2, and 3 and 4. The tubes fabricated from the thicker wall starting stock (2 and 3) had the most favorable texture in both cases examined.

Comparison of finished tubes that had been processed from the same starting stock indicated that the smaller diameter-thinner wall tubes had about the same texture as the larger-heavier walled tube. The incremental differences in the diameter and wall thickness between the two tube sizes apparently compensated for each other with respect to crystallographic texture considerations. Compare Figures II-1 and II-4, and II-2 and II-3. The number of reductions used to produce the finished tube did not appear to have a major effect on the texture developed in the tubes.



The tube hollow specimens produced by Wah Chang exhibited somewhat different textures. The nose end of the extrusion, which would be expected to undergo a minimum amount of deformation demonstrated an unusually "good" texture with a strong radial orientations of basal planes. See Figure II-5. The tail end of the extrusion (Figure II-6) exhibited an elongated ridge of basal plane poles along the 270° axis (stereogram) with its centroid at approximately $\phi = 50^\circ$. This texture was considered to be inferior to the nose end sample (Figure II-5) but was not so bad as to prevent a tube manufactured from this section from having a satisfactory texture. The texture differences between the nose and tail end of the extruded hollow were thought to be different enough to cause substantial differences in the texture of similarly processed finished tubes however.



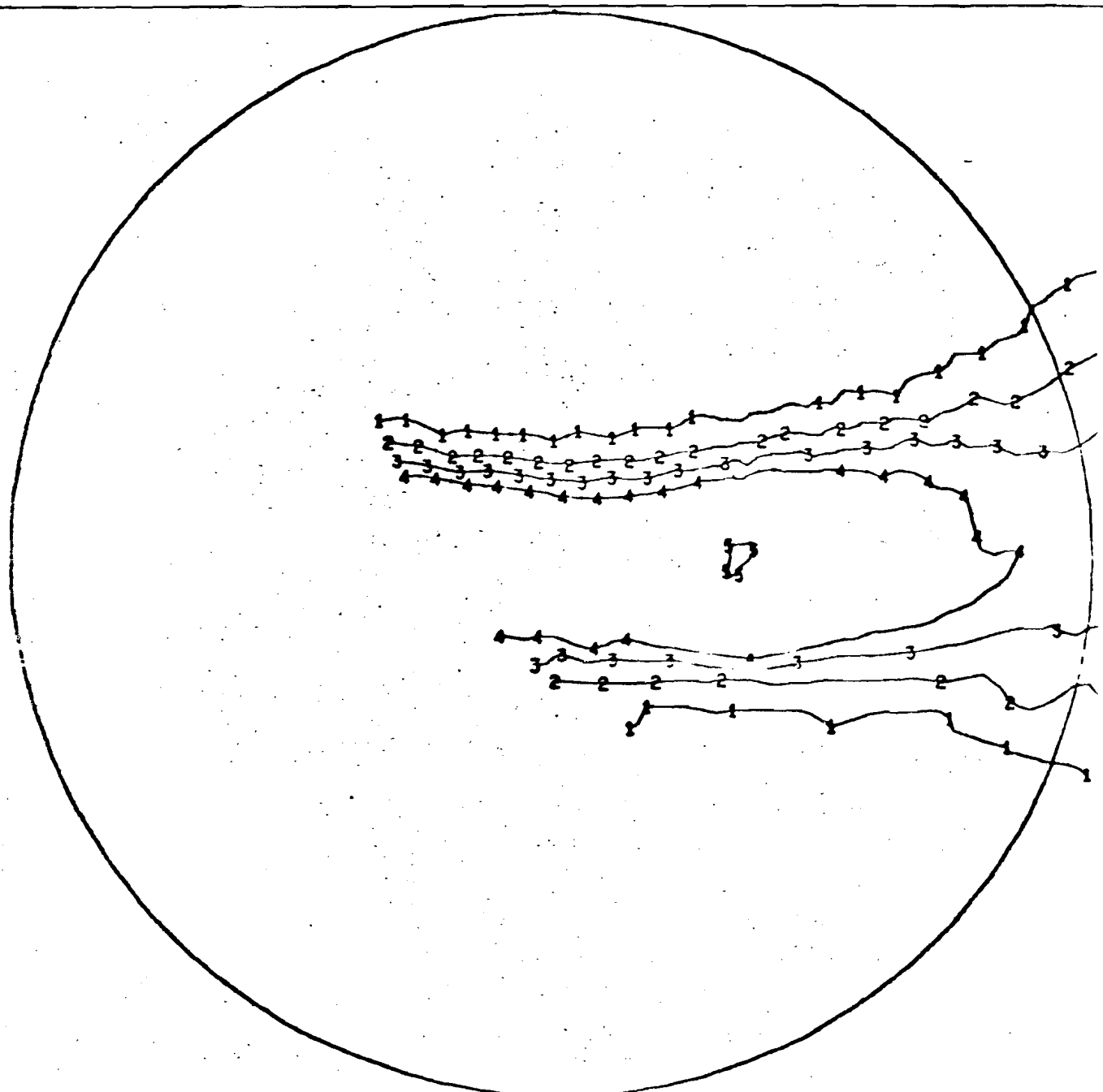


1	.5000	2	1.0000	3	1.5000	4	2.0000	5	4.0000
6	8.0000	7	14.0000	8	20.0000	9	25.0000	0	30.0000

JOB NO. 130 SAMPLE T4-054-131C DATE 1/24/72
 RADIATION CU AT 35 KV 28 MA COUNTER TUBE PROP AT 1.95 KV
 SLITS 2 H 2V ENTRANCE 5 H 1 V RECEIVING ENGINEER R.H. OLSEN
 SCAN RATE 1 PSI/MIN 72 ALPHA/MIN (0002) HKL
 PHA 5. V BASE 3D. V WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 421.0 K(A) 129.687 CALC DATE 02/14/72

Figure II-1 Pole figure for specimen 1; (T4-054-131C). This tube was 0.500" x 0.029" in size and was fabricated in five tube reducing operations from a 2.5" x 0.180" tube hollow.

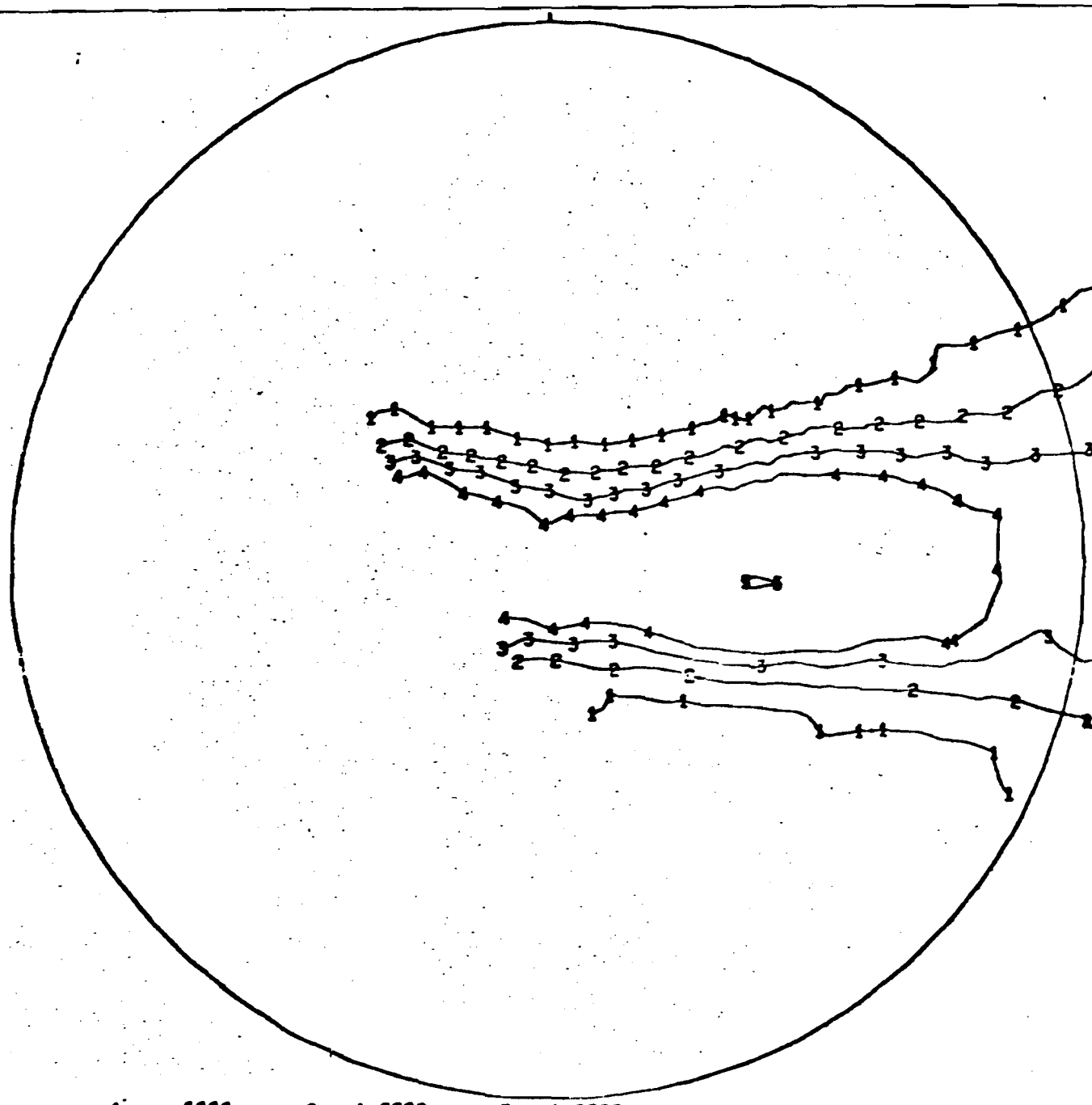




1	.5000	2	1.0000	3	1.5000	4	2.0000	5	4.0000
6	8.0000	7	14.0000	8	20.0000	9	25.0000	0	30.0000

JOB NO. 130 SAMPLE T4-018-030 DATE 1/21/72
 RADIATION CU AT 35 KV 28 MA COUNTER TUBE PROP AT 1.95 KV
 SLITS 2 H 2V ENTRANCE 5 H 1 V RECEIVING ENGINEER R.H. OLSEN
 SCAN RATE 1 PSI/MIN 72 ALPHA/MIN (0002) HKL
 PHA 5. V BASE 30. V WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 421.0 K(A) 109.860 CALC DATE 02/14/72

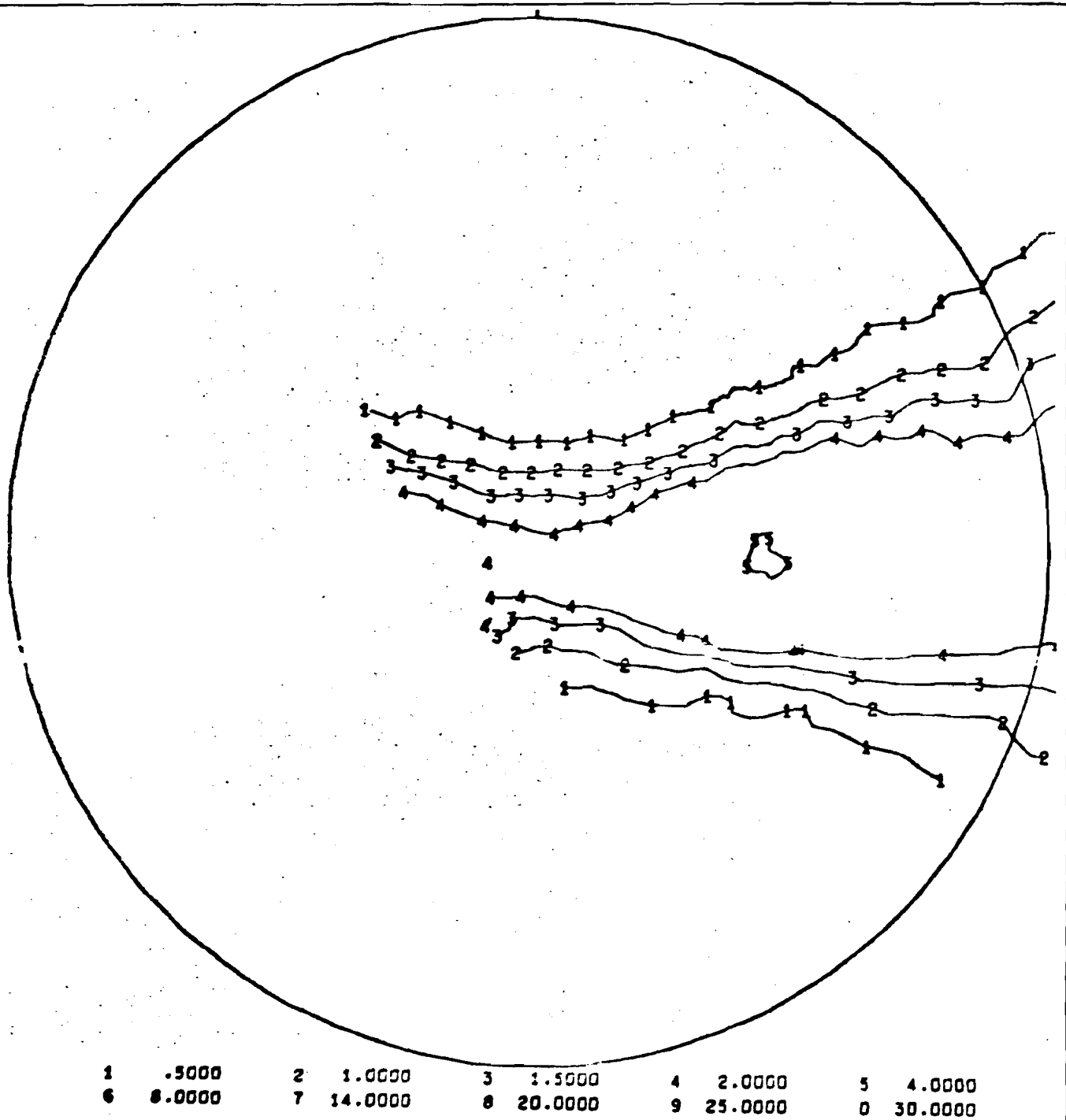
Figure II-2 Pole figure for specimen 2; (T4-018-030). This tube was 0.5"x 0.029" in size and was fabricated in four tube reducing operations from a 2.5" x 0.180" tube hollow.



1	.5000	2	1.0000	3	1.5000	4	2.0000	5	4.0000
6	8.0000	7	14.0000	8	20.0000	9	25.0000	0	30.0000

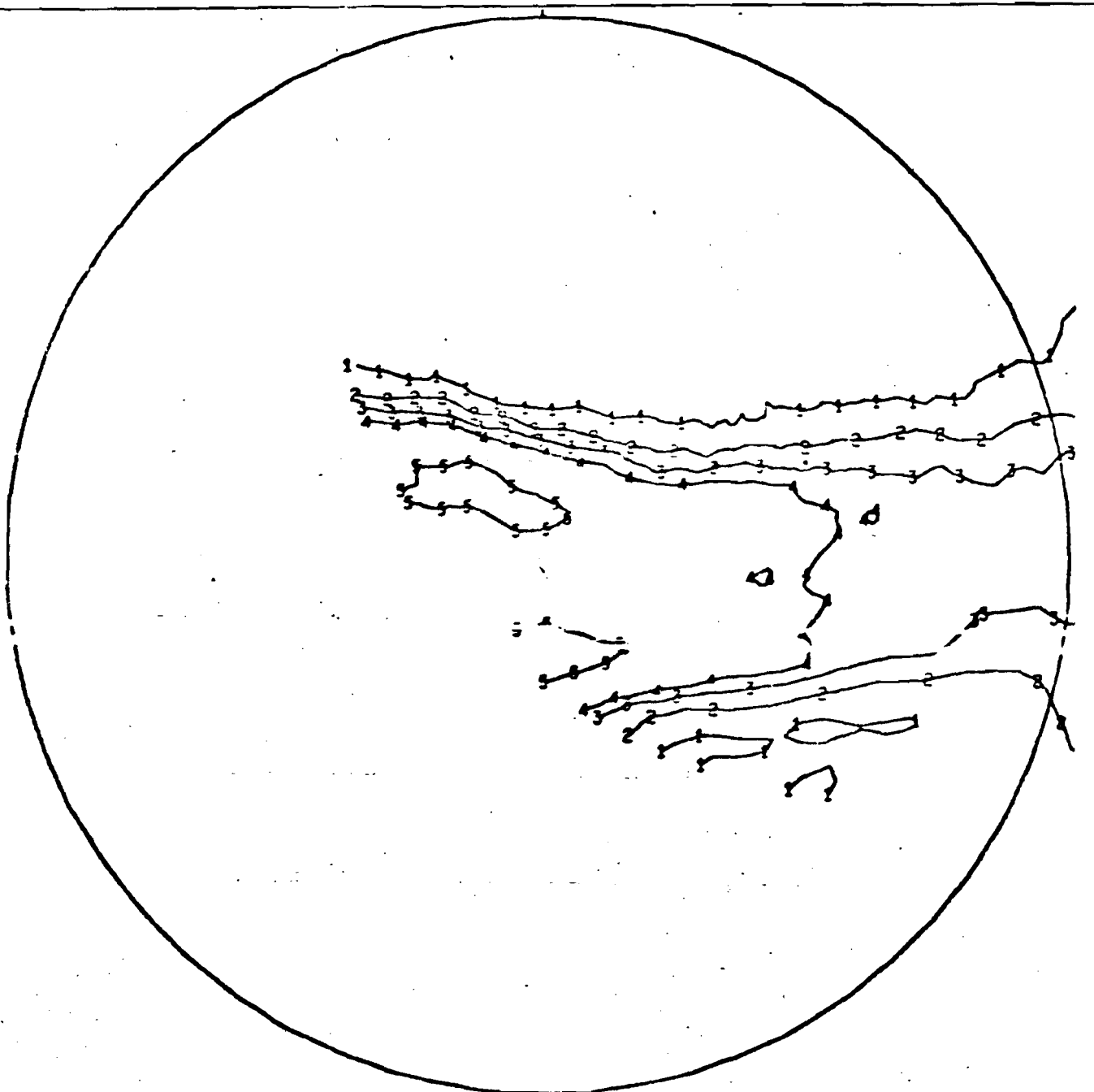
JOB NO. 130 SAMPLE T4-002-CONR-1 DATE 1/21/72
 RADIATION CU AT 35 KV 28 MA COUNTER TUBE PROP AT 1.95 KV
 SLITS 2 H 2V ENTRANCE 5 H 1 V RECEIVING ENGINEER R.H. OLSEN
 SCAN RATE 1 PSI/MIN 72 ALPHA/MIN (0002) HKL
 PHA 5. V BASE 30. V WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 421.0 K(A) 110.801 CALC DATE 02/14/72

Figure II-3 Pole figure for specimen 3; (T4-002-CONR-1). This tube was 0.375" x 0.022" in size and was fabricated in five tube reducing operations from a 2.5" x 0.180" tube hollow.



JOB NO. 138 SAMPLE T4-059-233A DATE 1/21/72
 RADIATION CU AT 35 KV 28 MA COUNTER TUBE PROP AT 1.95 KV
 SLITS 2 H 2V ENTRANCE 5 H 1V RECEIVING ENGINEER R.H. OLSEN
 SCAN RATE 1 PSI/MIN 72 ALPHA/MIN (0002) HKL
 PHA 5. V BASE 3D. V WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 421.0 K(A) 136.081 CALC DATE 02/14/72

Figure II-4 Pole figure for specimen 4; (T4-059-233A). This tube was 0.375" x 0.022" in size and was fabricated in five tube reducing operations from a 2.5" x 0.180" tube hollow.

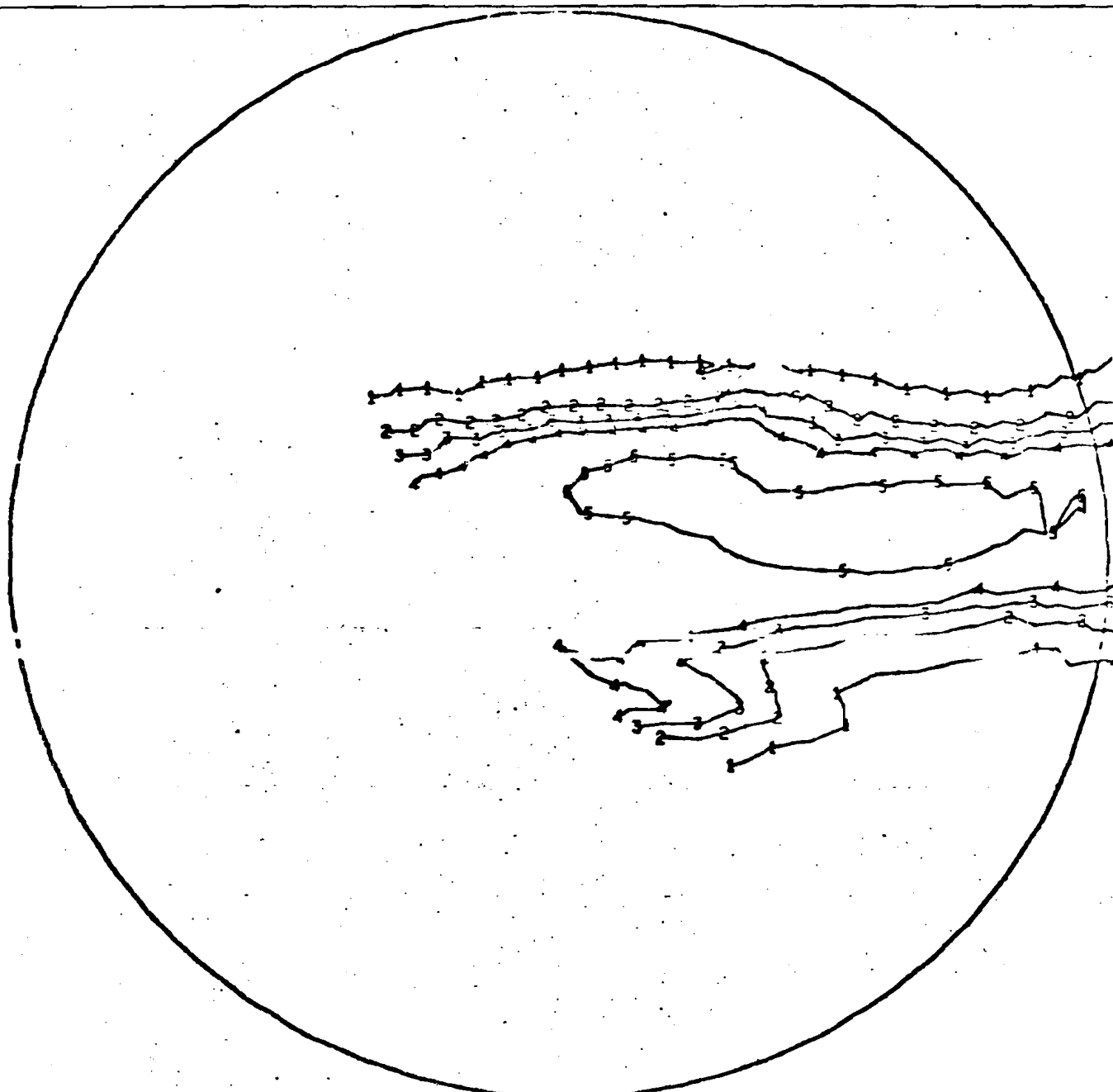


1	.5000	2	1.0000	3	1.5000	4	2.0000	5	4.0000
6	8.0000	7	14.0000	8	20.0000	9	25.0000	0	30.0000

JOB NO. 510 SAMPLE N-CODE 3 DATE 2/23/12
 RADIATION CU AT 35 KV 20 MA COUNTER TUBE PROP AT 1.95 KV
 SLITS 2 H 2V ENTRANCE 5 H 1 V RECEIVING ENGINEER R.H. OLSEN
 SCAN RATE 1 PSI/MIN 1/2 ALPHA/MIN (0002) HKL
 PHA 5. V BASE 30. V WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 333.0 K(A) 81.5/1 CALC DATE 03/02/12

Figure II-5 Pole figure for specimen 5; (N-Code 3). This specimen was from the nose end of a 14 foot long extruded tube hollow and was 2.5" x 0.450" in size.





1	.5000	2	1.0000	3	1.5000	4	2.0000	5	4.0000
6	6.0000	7	14.0000	8	20.0000	9	25.0000	0	30.0000

JOB NO. 518 SAMPLE TUBE HOLLOW T CODE 3 DATE 4/12/72
 RADIATION CU AT 35 KV 28 MA COUNTER TUBE PRCP AT 1.85 KV
 SLITS 2 M 2V ENTRANCE 5 M 1 V RECEIVING ENGINEER H. OLSEN
 SCAN RATE 1 PSI/MIN 72ALPHA/MIN (0002) HRL
 FPA 18. V BASE 18. V WINDOW CALIBRATION SAMPLE SILVER
 RANDOM INTENSITY 394.0 K(A) 172.105 CALC DATE 04/24/72

Figure II-6 Pole figure for specimen 6 (T-Code 3). This specimen was from the tail end of the 14 foot long extrusion from which specimen 6 (T-Code 3) was taken. This specimen was 2.5" x 0.450" in size.

ZIRCONIUM TECHNOLOGY CORPORATION
 P.O. BOX 947, ALBANY, OREGON 97321 • (503) 926-7743

December 16, 1971

The Boeing Company
 Commercial Airplane Division
 P.O. Box 3707
 Seattle, Washington 98214

ATTN: Mr. M.J. Hartman,

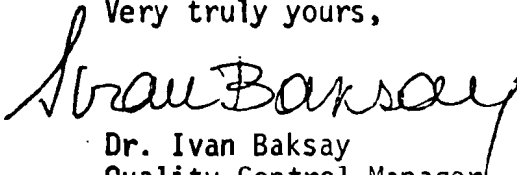
Dear Mr. Hartman:

We are sending to you, under separate cover, two different size tube samples for your planned texture investigations. The pass schedules applied were as follows:

1. 1/2" O.D. x 0.029" w
 - a. Lot No. T4-054-131C
 Pass Schedule:
 2.5" x 0.180" → 1.88" x 0.135"
 1.88" x 0.135" → 1.38" x 0.087"
 1.38" x 0.087" → 1.00" x 0.057"
 1.00" x 0.057" → 0.750" x 0.041"
 0.750" x 0.041" → 0.500" x 0.029"
 - b. Lot No. T4-018-030
 Pass Schedule:
 2.5" x 0.350" → 1.625" x 0.200"
 1.625" x 0.200" → 1.00" x 0.095"
 1.00" x 0.095" → 0.755" x 0.068"
 0.755" x 0.068" → 0.500" x 0.029"
2. 0.375" O.D. x 0.022" W
 - a. Lot No. T4-002-00NR-1
 Pass Schedule:
 2.5" x 0.350" → 1.750" x 0.205"
 1.750" x 0.205" → 1.250" x 0.143"
 1.250" x 0.143" → 0.840" x 0.083"
 0.840" x 0.083" → 0.571" x 0.0365"
 0.571" x 0.0365" → 0.375" x 0.022"
 - b. Lot No. T4-059-233A
 Pass Schedule:

2.5" x 0.180" → 1.750" x 0.137"
1.750" x 0.137" → 1.250" x 0.095"
1.250" x 0.095" → 0.840" x 0.054"
0.840" x 0.054" → 0.567" x 0.032"
0.567" x 0.032" → 0.375" x 0.022"

Very truly yours,


Dr. Ivan Baksay
Quality Control Manager

IB/mds

cc: C.E. Forney
W.W. Stephens

PART III - R-VALUE DETERMINATIONS ON FIVE Ti-3Al-2.5V COLD WORKED AND STRESS RELIEVED TUBES RECEIVED FROM THE BISHOP TUBE CO.

SUMMARY

Five Ti-3Al-2.5V cold worked and stress relieved tube tensile specimens from the Bishop Tube Co. have been evaluated for crystallographic texture using R values determinations. All values were moderate to low, having a range of 0.494 to 1.052. The relatively large diameter, thin walled tubes generally displayed the most preferred texture, a predominately radial orientation of basal plane poles.

INTRODUCTION

Five Ti-3Al-2.5V cold worked and stress relieved (CWSR) tube tensile specimens from the Bishop Tube Co. were submitted to The Boeing Company for evaluation of crystallographic texture. The evaluation technique used was an R value determination as outlined in XBMS 7-234A. This type of evaluation is obtained by making tube diameter and wall thickness measurements before testing and after testing at approximately 1/4 to 1/2" from the fracture surface. The following formula has been used;

$$R = \ln \frac{O.D._f}{O.D._o} \div \ln \frac{W_f}{W_o}$$

RESULTS AND DISCUSSION

The diameter and wall thickness measurements made for the five tubes are shown in Table III-1 together with the calculated R values. (See Reference 3).

The R value calculations indicate that Tube No. 1 (large diameter-moderate wall thickness - 1.0" x .048") possessed a more preferred crystallographic texture than the 3/4" and 3/8" tubes that were tested. The results are in agreement with previous observations that large diameter, relatively thin wall tube has a more radial texture (preferred) than do smaller diameter, relatively thicker walled tube. The data indicates that Tube No. 6 had the highest R ratio of all the tubes tested, but the measurement accuracy on this 1/4" x 0.017" tube is considered to be poor because of the small Δ values involved.

All R values are somewhat lower than expected considering the size ranges of the subject tubes. This could be a result of (1) relatively thin walled starting stock, (2) imperfect measurement techniques, or (3) overoptimistic expectations on R value numbers. Data accumulated to date indicates that all these items may be responsible in part. Item 1, in particular, must be more thoroughly investigated.



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REV SYMTABLE III - 1 - R-VALUE CALCULATIONS FOR TI-3Al-2.5V CWSR TITANIUM
TUBES MANUFACTURED BY THE BISHOP TUBE CO.

Tube Number	Tube Size (Inches)	Wall Thickness		Outside Diameter		R Value
		Before Test W_o - in.	After Test W_f - in	Before Test $O.D._o$ - in	After Test $O.D._f$ - in	
1	1.0" x .048"	0.0485	0.0454	1.0015	0.9352	1.038
2	3/4" x .040"	0.0396	0.0365	0.7515	0.7102	0.695
3	3/4" x .040"	0.0400	0.0366	0.7489	0.7168	0.494
4	3/8" x .020	0.0196	0.0181	0.3777	0.3598	0.606
5	1/4" x .017	0.0167	0.0158	0.2512	0.2370	1.052

BISHOP

NO. T6-5722-3

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J18-047

PART IV - THE EFFECT OF AGING AT 450°F ON THE STRENGTH OF Ti-3Al-2.5V COLD WORKED AND STRESS RELIEVED TUBING

SUMMARY

The strength properties of 1" dia. x 0.033" wall Ti-3Al-2.5V cold worked and stress relieved titanium tubes have been examined with respect to the effect of aging at 450°F. A tube was exposed for 112 hours and its properties compared to a standard unaged sample. No changes in strength or ductility were noted.

INTRODUCTION

Some fatigue data has suggested that Ti-3Al-2.5V cold worked and stress relieved (CWSR) tubing is unstable at 450°F. The purpose of this investigation was to determine if 112 hours of aging at 450°F would cause an appreciable change in the ultimate and yield strength properties of 1.00" dia. x .033" wall Ti-3Al-2.5V CWSR tubing. A change in these mechanical properties would indicate general instability of this heat treatment condition at 450°F and would suggest that more stringent limitations be imposed on proposed high temperature applications of this material.

RESULTS AND DISCUSSION

The tubing used in this investigation was as follows:

Tube: Ti-3Al-2.5V per XBMS, 7-234A
Condition: Cold Worked & Stress Relieved
Producer: R.M.I.
Size: 1.00" x 0.033"
Heat No.: H.T. 304042-22
Thermal Treatment: 450°F - 112 hours

The mechanical test results are shown in Table IV-1.

TABLE IV-1 - Mechanical Properties of Aged and As-Received Ti-3Al-2.5V CWSR Tubes.

Condition	UTS (ksi)	YTS (ksi)	Elongation %
As Received	139.0	116.9	16.0
After Heat Cycle	138.5	116.8	15.0

DT 4122 7/16/66 G. G. B/71

The results of these tests indicate that no degradation of mechanical properties takes place in Ti-3Al-2.5V CWSR tubing during short time exposure at 450°F. (See Reference 4). Extended times at these temperatures may cause some reduction in strength but the present data would indicate that any effort of this type would be minimal. This investigation does not eliminate the possibility that fatigue behavior at 450°F, or after exposure at 450°F, may be ill affected in some manner but the prospect of this happening is considered minimal.

