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STRUCTURAL ANALYSIS AND FATIGUE TEST OF THE RANGER ANTI-ARMOR/ANTI-PERSONNEL WEAPON SYSTEM (RAAWS)

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13. ABSTRACT *(Maximum 200 words)*
The Ranger Anti-Armor/Anti-Personnel Weapon System (RAAWS) was investigated to determine its structural strength and fatigue life. The RAAWS is an 84-mm lightweight, shoulder-fired recoilless weapon produced by FFV Ordnance, Sweden. The tube consists of a thin steel rifled liner overwrapped with a graphite/epoxy composite jacket. This investigation includes a finite element stress analysis, firing tests, laboratory strain and material property tests, and fatigue tests to determine the interim safe fatigue life for the weapon.

14. SUBJECT TERMS
Ranger Anti-Armor/Anti-Personnel Weapon System (RAAWS), Recoilless Rifle, Composite Gun Tube, Fatigue Tests, Finite Element Stress Analysis, Firing Tests, Strain Measurements, Material Tests, Chemical Analysis, Thermogravimetric Analysis, Differential Scanning Calorimetry

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TABLE OF CONTENTS

Tables

List of Illustrations

INTRODUCTION

Background

The U.S. Army, under the Ranger Anti-Armor/Anti-Personnel Weapon System (RAAWS) Program, purchased the Carl Gustaf M3 recoilless rifle from FFV Ordnance, Sweden for use by the 75th Ranger Regiment. A review of the contractor-supplied fatigue test data determined that this data did not meet U.S. Army requirements. Therefore, it was determined that Benét Laboratories should conduct a fatigue test of two tubes in accordance with the International Test Operations Procedure (ITOP) 3-2-829 in order to establish an interim safe service life for the weapon. Normal procedure for fatigue life testing requires that the tubes be fired prior to laboratory hydraulic cycling in order to produce metallurgical damage, i.e., small cracks at the bore surface (heat checking) that initiate the fatigue process. Since the manufacturer's recommended life for this weapon is 500 rounds, it was decided that the two tubes selected for fatigue testing (Serial numbers (SN) 14002 and 14003) would each be fired with 500 rounds by FFV at the Hugelsta Proving Ground, Sweden, and then shipped to Benét Laboratories for hydraulic fatigue testing. These rounds were not used in the calculation of the interim safe service life of the weapon because they were fired below the extreme service condition pressure.

Description

The 84-mm Carl Gustaf M3 is a lightweight shoulder-fired recoilless-type weapon (see Figures 1 and 2). The barrel consists of a thin steel liner overwrapped with a composite jacket made of carbon fiber in an epoxy matrix. The steel venturi is attached to the rear of the barrel by the axis pin and the fastening strap. The steel liner's rifling is 1 mm (0.039 in.) deep, and the liner itself is 0.5 mm (0.20 in.) thick. The tube has several brackets and mounting lugs held in place to its outer surface by adhesive bonding and additional circumferential composite windings.

STRESS ANALYSIS

Procedure

A stress analysis using an ABAQUS finite element computer code was performed. The analysis calculates von Mises stress as a function of internal pressure. Figure 3 represents the geometry of a tube profile. Figure 4 is an overlay of the pressure profile of the FFV 651 round conditioned at 140°F plus 3.1 standard deviations.

Results

Figure 5 is the calculated maximum stress at the inner diameter of the steel liner. The analysis indicates a maximum von Mises stress of 113 Ksi. According to FFV, the minimum yield strength of the steel is also 113 Ksi. It is important to note that the liner was designed for minimum weight. In a conventional all-steel tube, this design would be considered marginal. The difference between an all-steel tube and the Carl Gustaf M3 structure is that the metal liner is only intended to provide rifling and act as a protective barrier from the hot propellant gases. Pressure containment is the function of the composite jacket.

Figure 6 is the calculated maximum stress at the inner diameter of the composite jacket. Unlike the liner, the composite jacket is designed with a high margin of safety. The analysis indicates a maximum von Mises stress of 85.2 Ksi. The tensile strength of the jacket material is approximately 240 Ksi. This gives a safety factor of 2.8, almost twice the required value of 1.5.

FIRING TEST

Procedure

In order to determine the down bore pressures and proper strain level for fatigue testing, a weapon provided by FFV was strain gaged and test fired to measure strains at the outer surface of the tube and venturi in the circumferential (hoop) direction. A total of 18 strain gages were mounted on the tube at the locations shown in Figure 7. Axial locations 1 through 5 are measured from surface E on drawing F1303-009160E. Location 6 is measured from the rear surface of the venturi. The weapon was then test fired by FFV at the Hugelsta Proving Ground and strain data were collected. The pressure at which this tube should be tested is the extreme service condition pressure (ESCP), which for this weapon is the pressure of the type 651 round fired at the maximum service temperature of +60°C (140°F). However, the rounds tested were the 551 type, which were heated to +60°C prior to firing, producing a maximum chamber pressure of 65.9 MPa (9555 Psi). A maximum of seven channels of data can be recorded at one time, therefore, the test was run using three groups of six channels each. The first group used gages 1,4,8,11,14, and 1(V), the second group used gages 2,5,9,12,15, and 2(V), and the third group used gages 3,6,10,13,16, and 3(V). For each group, three rounds were fired, and data for each of the gages were collected.

The strain gages used were Micro-Measurements Model CEA-06-25OUT-120 provided by Benét Laboratories. The data were collected on a Racal Store 7.5-inch tape recorder and later transferred to a Nicolet oscilloscope where it was stored on a disk. This disk was later supplied to Benét Laboratories where the data were reduced to determine the strains at the various locations as a function of internal pressure.

Results

In order to ensure that the correct pressures were achieved, the muzzle velocity of each round was measured and compared to the known velocity of 289.5 meters per second (see Table 1). Results of the strain data are given in Table 2 with average values calculated for each location on the tube. This data was then used to determine the internal pressure at each of the gage locations using the ABAQUS finite element code (Table 3). In order to calculate these pressures, the elastic modulus of the composite jacket must be known. The modulus calculated from the known chamber pressure (9555 Psi) and the strain data at the chamber outer diameter at 205 mm was determined to be 20.0 Msi using an average of both this firing test and the laboratory strain tests.

LABORATORY MATERIAL TESTS

Procedure

The steel liner was too thin to take tensile or Charpy specimens, however, some physical properties of the materials used in the fabrication of the weapon were determined. Hardness was measured and a section was analyzed to determine the chemical composition. The filament/resin ratio of the composite material was determined by both chemical and optical methods, and the glass transition temperature of the resin was also measured. Micrographs were taken of the various cross sections of the tube to study the microstructure of the materials used.

Results

Chemical analysis of the steel liner is shown in Table 4. The material was found to have a lower percentage of molybdenum and vanadium and a higher percentage of sulfur than normally found in our gun steel. The hardness of the steel liner was 28 to 33 measured on the Rockwell C scale, which indicates an approximate tensile strength of 145 Ksi. This is lower than that normally used in U.S. tubes, however, it was probably done to increase the ductility of the liner since most of the tube's strength is provided by the composite jacket. Figure 8 is a photomicrograph of a cross section of the steel liner that shows the microstructure to be tempered martensite. Such a structure promotes good tensile strength, ductility, and toughness.

Thermogravimetric analysis (TGA) of the composite jacket (Figure 9) showed that it has an average resin content of 32.22 percent by weight. Differential scanning calorimetry (DSC) of the jacket material (Figure 10) revealed no further curing exotherm, thus the material was totally cured. The glass transition temperature of this material was 146.2 ± 0.9°C measured at a scanning rate of 20.0 deg/min. Analysis of the composite jacket using a Cambridge Olympus Q-10 Image Analysis System (Table 5) showed a resin content of 41.4 percent by volume for tube SN 14002. This converts to 33.5 percent by weight, which is in very close agreement to the TGA figure of 32.2 percent. This analysis also showed extremely low void contents of 0.172 percent and 0.045 percent for the two tubes, which indicates that the winding and curing process for the composite jackets was of very high quality. This is further shown by Figure 11, a photomicrograph of a typical cross section of the hoop fibers that shows a well-compacted void-free composite. Figure 12 shows a section of the interface between the composite jacket and the steel liner. This photograph shows a tight interface free of any gaps indicating a good bond at this surface.

LABORATORY STRAIN TESTS

Procedure

After the two weapons each had 500 rounds fired on them, they were then shipped to the Experimental Mechanics Branch of Benét Laboratories where they were disassembled and the tubes cut according to Figure A1 (see Appendix) to produce a breech and muzzle test specimen for each tube. The specimens had seal pockets machined in each end (Figures A2 and A3) and were then assembled with their respective end caps and seals for testing (Figures A4 and A5). Tube SN 14003 had three strain gages applied to the outside diameter at 205-mm from the rear face of the tube (RFT). These gages were Micro-Measurements CEA-06-25OUT-120 applied in the hoop direction only. The specimen was then placed in a high capacity press to contain the end cap load and was hydraulically pressurized in steps to a maximum of 9600 Psi. Pressure and strain measurements were taken at each step. Similarly three gages were applied to the muzzle specimen of the same tube at the 715-mm location from the RFT and pressure/strain measurements were taken.

Results

The strain data are given in Table 6 for the two specimens tested. The strains at the 205-mm location were in very good agreement between the firing test (2370) and the laboratory test (2510). This confirmed that our laboratory test was closely duplicating the actual firing pressures. The strains at this location also show an excellent correlation of within 1.65 percent deviation between the laboratory test and the theoretical results. When interpolating to a pressure of 9555 Psi, the strain result based on average data is 2497, which is within 0.26 percent deviation of the theoretical result of 2504. This agreement indicates an excellent experimental procedure in the modulus calculation and test setup process. However, from Table 3, the maximum chamber pressure of 9555 Psi at the 205-mm location produces a hoop strain of 22370. Based on this strain, the ABAQUS code predicted a pressure of 9045 Psi. Hence, the laboratory setup duplicates the actual firing pressure within 5.34 percent. The strains at the 715-mm location show a very good correlation of within 4.7 percent deviation between the laboratory test and the theoretical results. At the muzzle location, however, the laboratory equipment was not able to produce a pressure low enough to duplicate the firing pressure.

FATIGUE TESTS

Procedure

After the strain tests were completed, the specimens were assembled in the press where they were hydraulically fatigue cycled to the required test pressure until failure. The breech specimens were cycled to a maximum pressure of 9600 Psi. The rear of the muzzle specimens was 600 mm from RFT. The pressure at this point, which would normally be the maximum test pressure, was found to be 2800 Psi based on the pressures calculated from the firing strain tests. However, the decision was made to increase the maximum test pressure to 3800 Psi for the following reasons. The critical factor in fatigue testing is the difference between maximum and minimum pressure. The test equipment used has a minimum pressure limit of approximately 1000 Psi. Therefore, in order to maintain a pressure difference of 2800 Psi, the maximum pressure was increased to 3800 Psi. At this higher maximum pressure, stresses remained in the safe range for this material.

Results

The pre-test inspection of the specimens using fiber optics and magnetic particle inspection showed no indications of cracks, wear, erosion, or heat checking on the bore. Results of the fatigue tests are given in Table 7. The specimen with the shortest life was the breech specimen of tube SN 14002, which failed at 7090 cycles. The tests of the two muzzle specimens were stopped at 14,280 cycles--twice the maximum breech specimen. Muzzle SN 14002 showed no indication of failure; SN 14003 had a 0.6-inch long crack along the radius of the rifling groove at the muzzle end.

The two breech specimens had failures of the steel liners. SN 14003 had a 1 1/2-inch crack along the edge of a rifling groove at the muzzle end. A section was cut from the tube and then split to reveal the fracture surface (Figure 13). SN 14002 had a similar 1-inch crack along the edge of a rifling groove near the muzzle end. A section was also cut from this tube and then split to reveal the fracture surface, as shown in Figure 14. A scanning electron microscope was then used to magnify the surface (up to 8000X) to more clearly show the fatigue striations (Figures 15 and 16).

CONCLUSIONS/RECOMMENDATIONS

Close inspection and analysis of these two weapons as described in this report indicate a high quality of materials and workmanship in the manufacturing process. The stresses calculated by the finite element analysis were in close agreement with those measured in the composite jacket during testing. These stresses were low compared to the normal tensile strength of this type of material. The bore surfaces showed no indications of erosion after firing 500 rounds. The interim fatigue life resulting from these tests is one-third of the lowest number of cycles or 2360 rounds. This is over four times the recommended life of 500 rounds. However, if a fatigue life greater than 500 rounds is to be established, we recommend that four additional weapons (total of six) be tested to establish a full safe service life.

Table 1. Muzzle Velocity/Chamber Pressure (FFV Data)

Round Number	Muzzle Velocity M/sec	Chamber Pressure MPa	Ammunition Temperature
1	290.7	61.6	+60°C
2	285.6	63.4	
3	290.1	66.9	
4	290.2	64.5	
5	284.8	63.9	
6	290.3	67.8	
7	286.1	64.2	
8	288.6	64.2	
9	292.7	68.2	
10	290.9	67.5	
11	290.8	67.7	
12	292.7	70.0	
13	289.4	67.0	
Average	**289.5**	**65.9** (9555 Psi)	

Table 2. Firing Test Strain Data
(551 Round at 60°C)

Gage Number	Round Number	Strain x 10^{-6}	Gage Number	Round Number	Strain x 10^{-6}
1	1	2200	8	1	1100
	2	2300		2	1100
	3	2300		3	1100
2	4	2300	9	4	1200
	5	2100		5	1100
	6	2400		6	1300
3	7	2500	10	7	1100
	8	2700		8	1100
	9	2500		9	1100
	Average	**2370**		**Average**	**1130**
4	1	1800	11	1	1400
	2	1800		2	1000
	3	1700		3	1100
5	4	1600	12	4	800
	5	1600		5	900
	6	1800		6	800
6	7	1700	13	7	900
	8	1700		8	900
	9	1700		9	900
	Average	**1710**		**Average**	**970**

Table 2. Continued

Gage Number	Round Number	Strain x 10⁻⁶	Gage Number	Round Number	Strain x 10⁻⁶
14	1	1000	1(V)	1	1200
	2	800		2	1600
	3	700		3	1200
15	4	600	2(V)	4	1300
	5	700		5	1200
	6	700		6	1500
16	7	700	3(V)	7	1600
	8	700		8	1400
	9	700		9	1500
	Average	**730**		**Average**	**1390**

Table 3. Calculated Pressure

Gage Location mm RFT	Hoop Strain x 10^{-6}	Test Pressure Psi	Calculated Pressure Psi
205	2370	9555	-
360	1710	-	7178
480	1130	-	3969
715	970	-	2002
800	730	-	1229

Table 4. Chemical Analysis of Steel Liner

Chemical Analysis Report
Analyte 1 Carbon = 0.331/0.339/0.330
Analyte 2 Manganese = 0.617/0.646/0.630
Analyte 3 Phosphorus = 0.007/0.008/0.007
Analyte 4 Sulfur = 0.017/0.027/0.017
Analyte 5 Silicon = 0.273/0.312/0.281
Analyte 6 Copper = 0.042/0.055/0.043
Analyte 7 Nickel = 2.931/2.924/2.955
Analyte 8 Chromium = 1.130/1.115/1.138
Analyte 9 Vanadium = 0.009/0.016/0.009
Analyte 10 Molybdenum = 0.191/0.182/0.194

Table 5. Image Analysis Results

Tube SN 14002 **Sectioned 19.5 Inches From RFT**
Summations
Total Fields = 10
Mean Volume Fraction - Phase 1 = 41.401 (Resin)
Standard Deviation - Phase 1 = 1.172
Mean Volume Fraction - Phase 2 = 58.471 (Fiber)
Standard Deviation - Phase 2 = 1.171
Mean Volume Fraction - Phase 3 = 0.127 (Voids)
Standard Deviation - Phase 3 = 0.066
Total Area Surveyed = 274604 Square Microns
Tube SN 14003 **Sectioned 19.5 Inches From RFT**
Summations
Total Fields = 10
Mean Volume Fraction - Phase 1 = 44.002 (Resin)
Standard Deviation - Phase 1 = 2.380
Mean Volume Fracture - Phase 2 = 55.953 (Fiber)
Standard Deviation - Phase 2 = 2.378
Mean Volume Fraction - Phase 3 = 0.045 (Voids)
Standard Deviation - Phase 3 = 0.033
Total Area Surveyed = 274604 Square Microns

Table 6. Laboratory Test Strain Data
(in./in.x10^{-6})

M3 Recoilless SN 14003 Breech Section Gage Location - 205 mm RFT					
Pressure (Ksi)					
Gage	5.0	7.0	9.0	9.6	0.0
1	1288	1799	2310	2489	0
2	1321	1844	2373	2558	0
3	1273	1773	2276	2455	0
1	1322	1862	2336		0037
2	1360	1923	2402		0050
3	1295	1847	2304		0040
1	1357	1852	2380	2540	0
2	1387	1891	2427	2594	0
3	1292	1768	2271	2424	0
1	1376	1899	2374		0050
2	1410	1947	2419		0065
3	1298	1810	2251		0040
Average	**1332**	**1851**	**2344**	**2510**	**0047**
Calculated	**1310**	**1834**	**2358**	**2515**	
% Deviation	**1.65**	**0.918**	**0.600**	**0.200**	

Table 6. Continued

M3 Recoilless SN 14003 Muzzle Section Gage Location - 715 mm RFT				
Pressure (Ksi)				
Gage	4.5	0.0	4.5	0.0
1	2547	0142	2550	0155
2	2568	0165	2565	0172
3	2454	0168	2439	0174
Average	**2523**	**0158**	**2518**	**0167**
Calculated	**2405**		**2405**	
% Deviation	**4.7**		**4.5**	

Table 7. Fatigue Test Results

Specimen	Test Pressure (Psi)	Fatigue Cycles
14002 Breech	9600	7090
14002 Muzzle	3800	14,280 (No failure)
14003 Breech	9600	7140
14003 Muzzle	3800	14,280

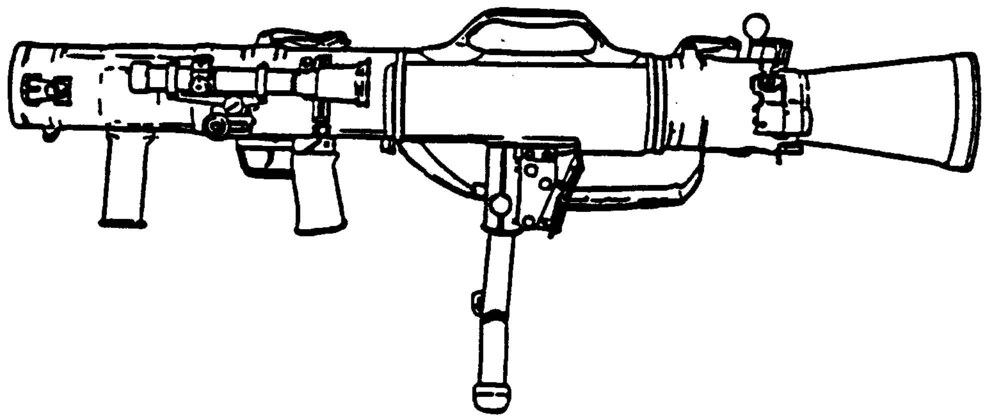


Figure 1. Carl Gustaf M3 recoilless rifle, left side.

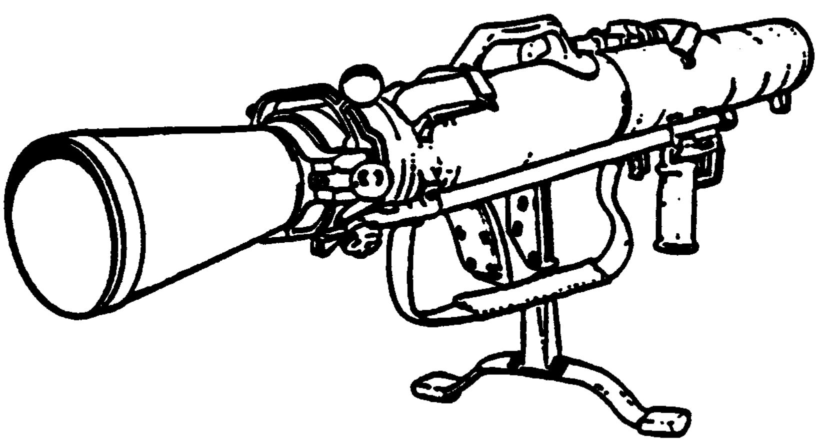


Figure 2. Carl Gustaf M3 recoilless rifle, right side.

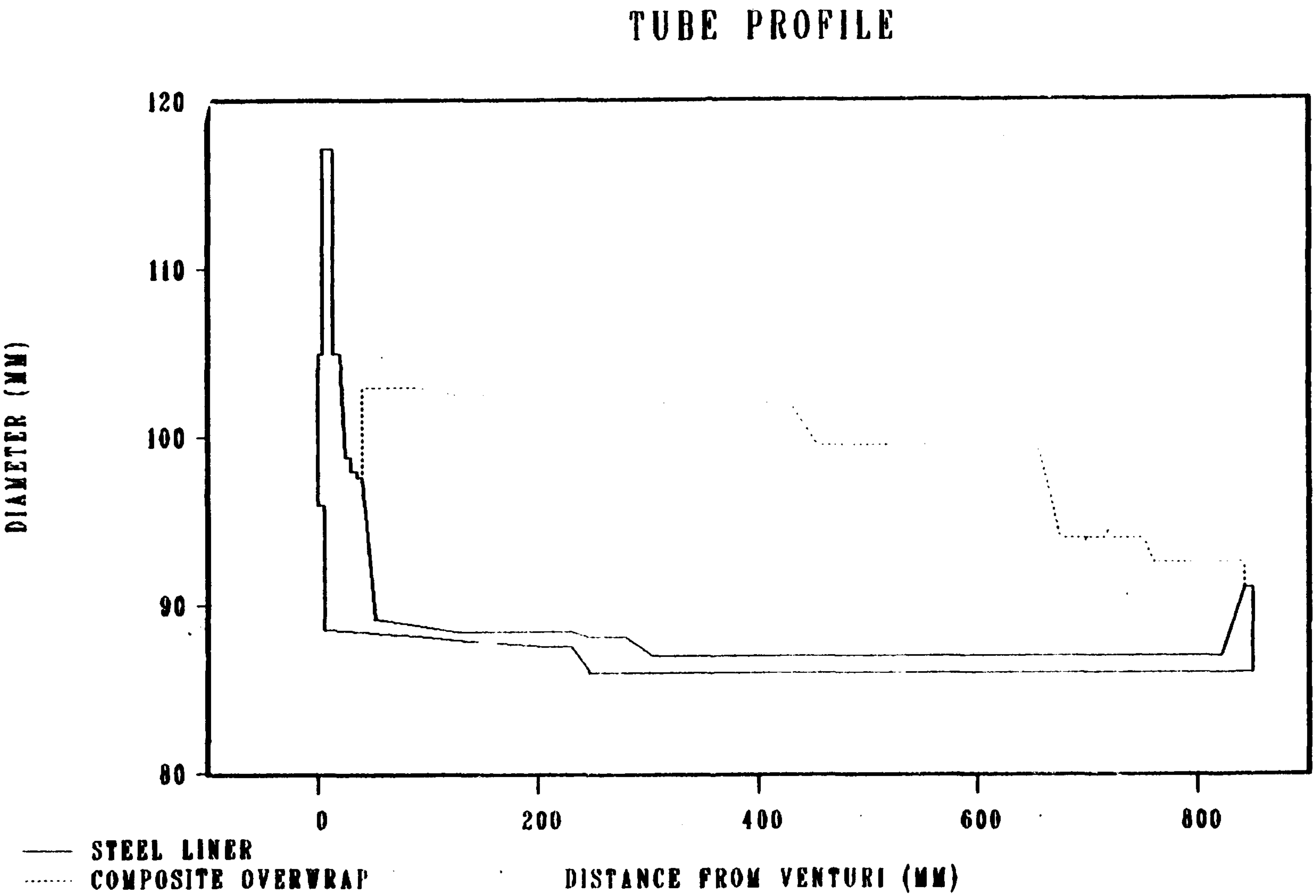


Figure 3. Tube profile.

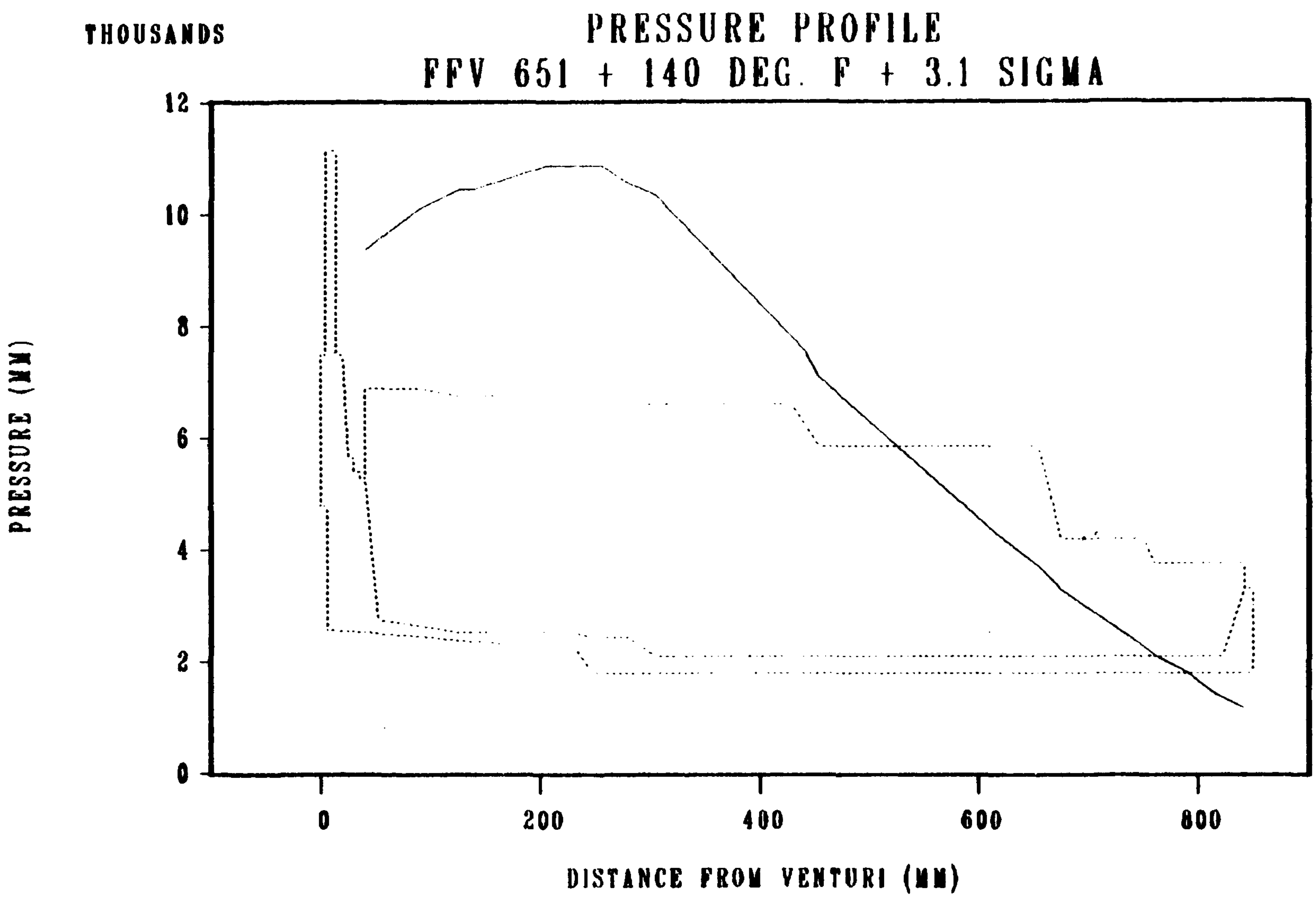


Figure 4. Pressure profile.

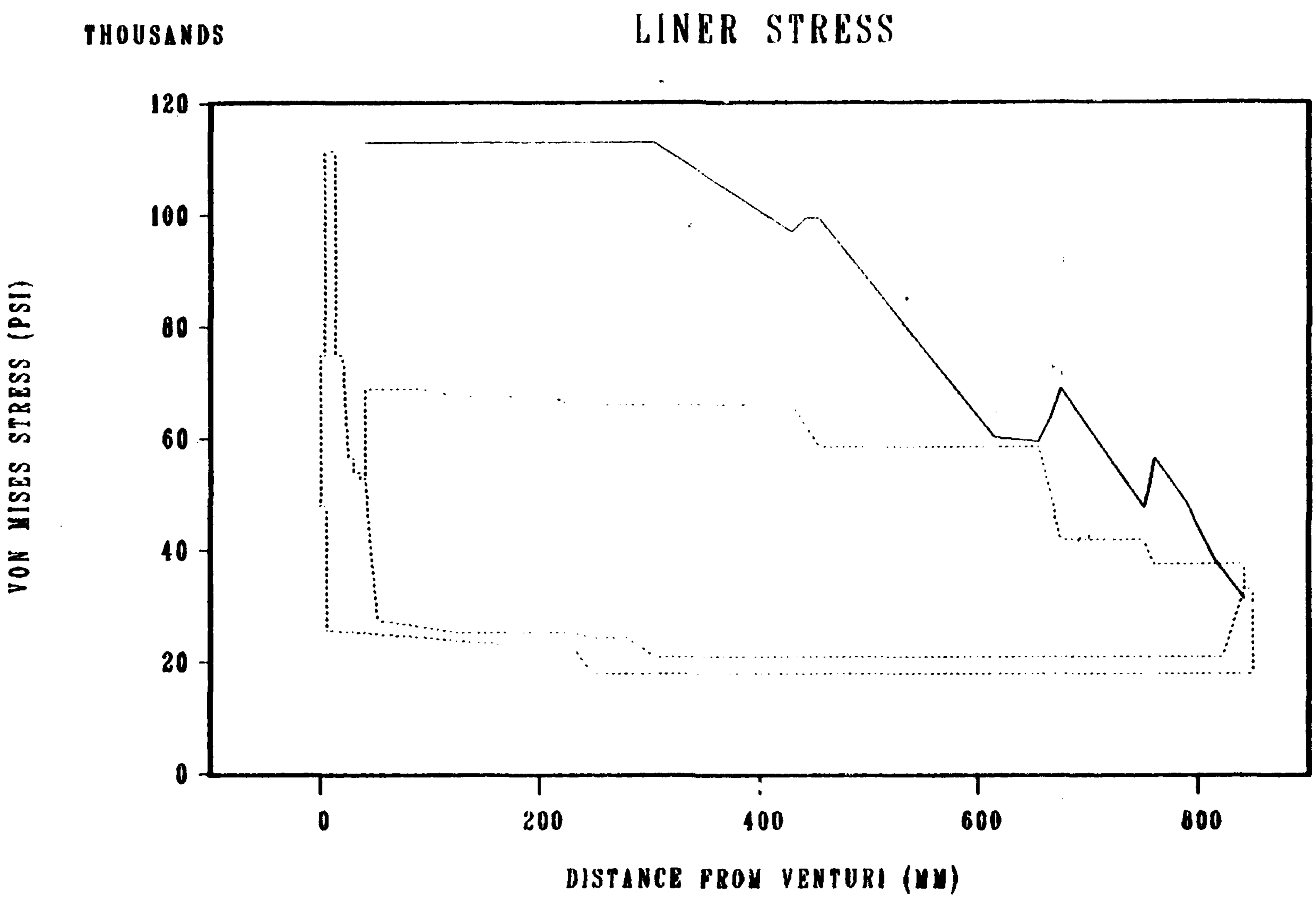


Figure 5. Stress analysis of steel liner.

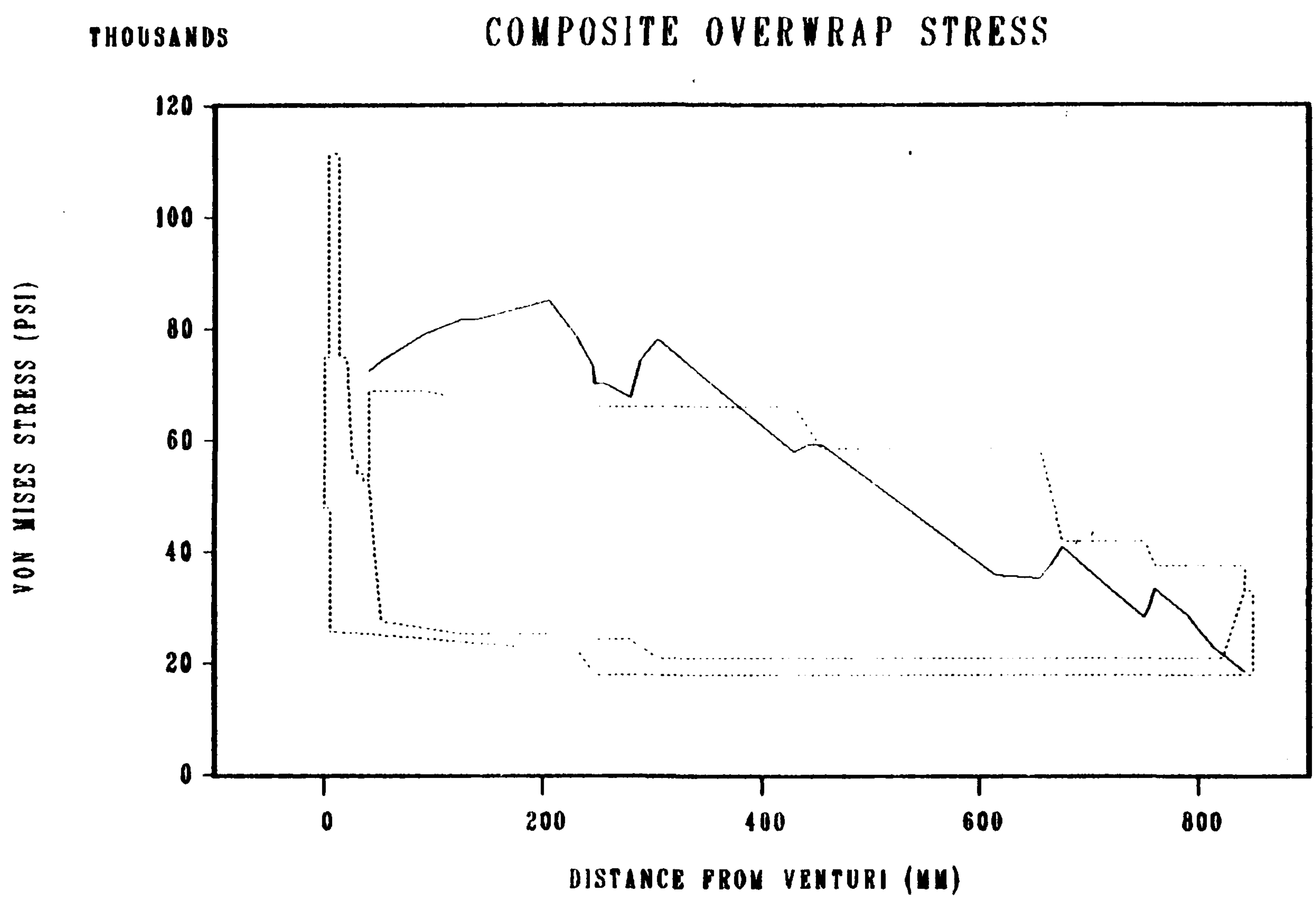
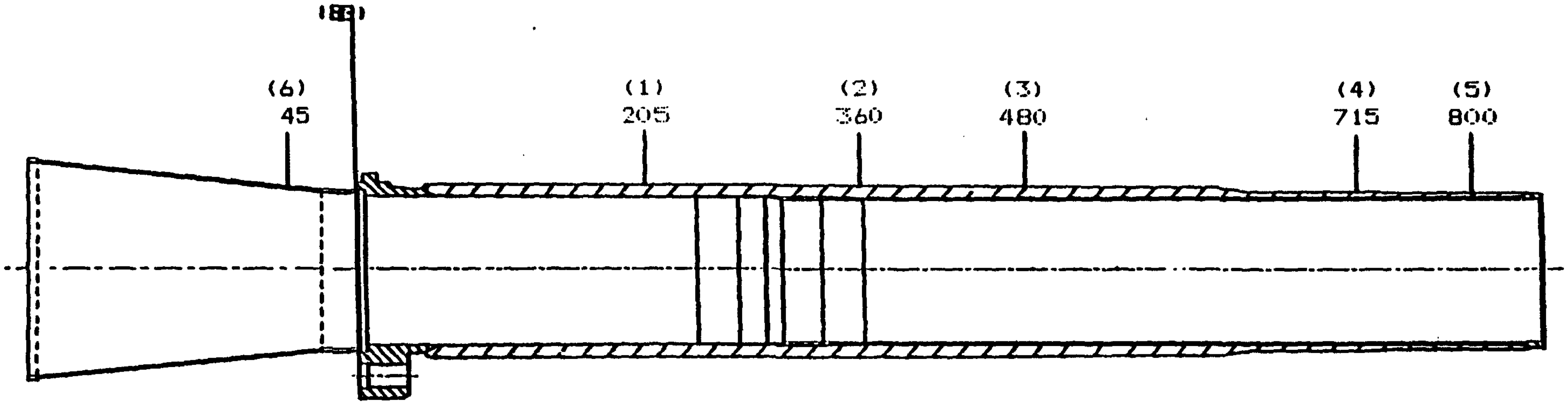


Figure 6. Stress analysis of composite jacket.



LOCATION NUMBER	GAGE NUMBER
1.	1,2,3 (blue)
2.	4,5,6
3.	8,9,10
4.	11,12,13
5.	14,15,16
6.	1,2,3 (yellow)

Figure 7. Strain gage locations.

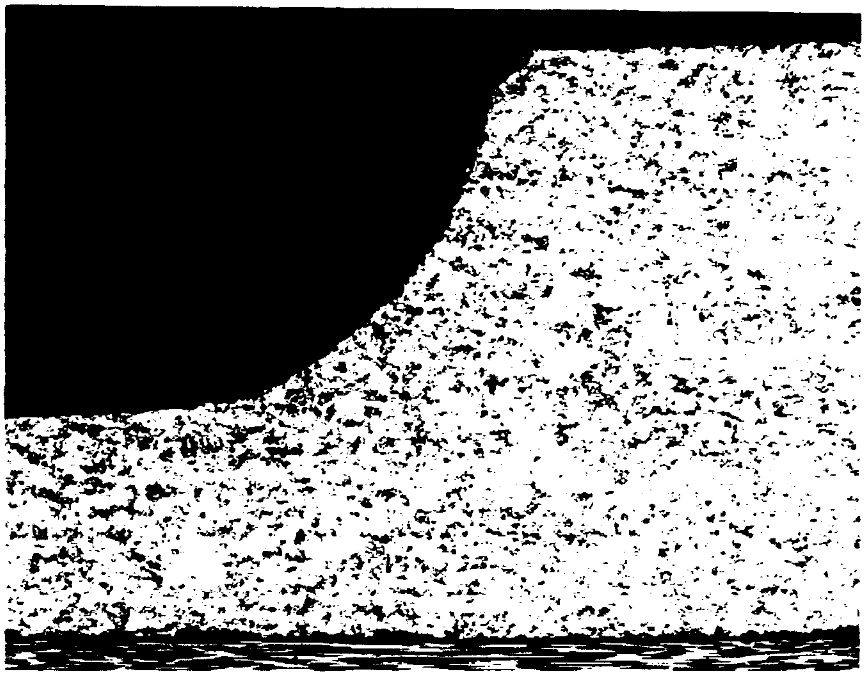


Figure 8. Photomicrograph of steel liner.

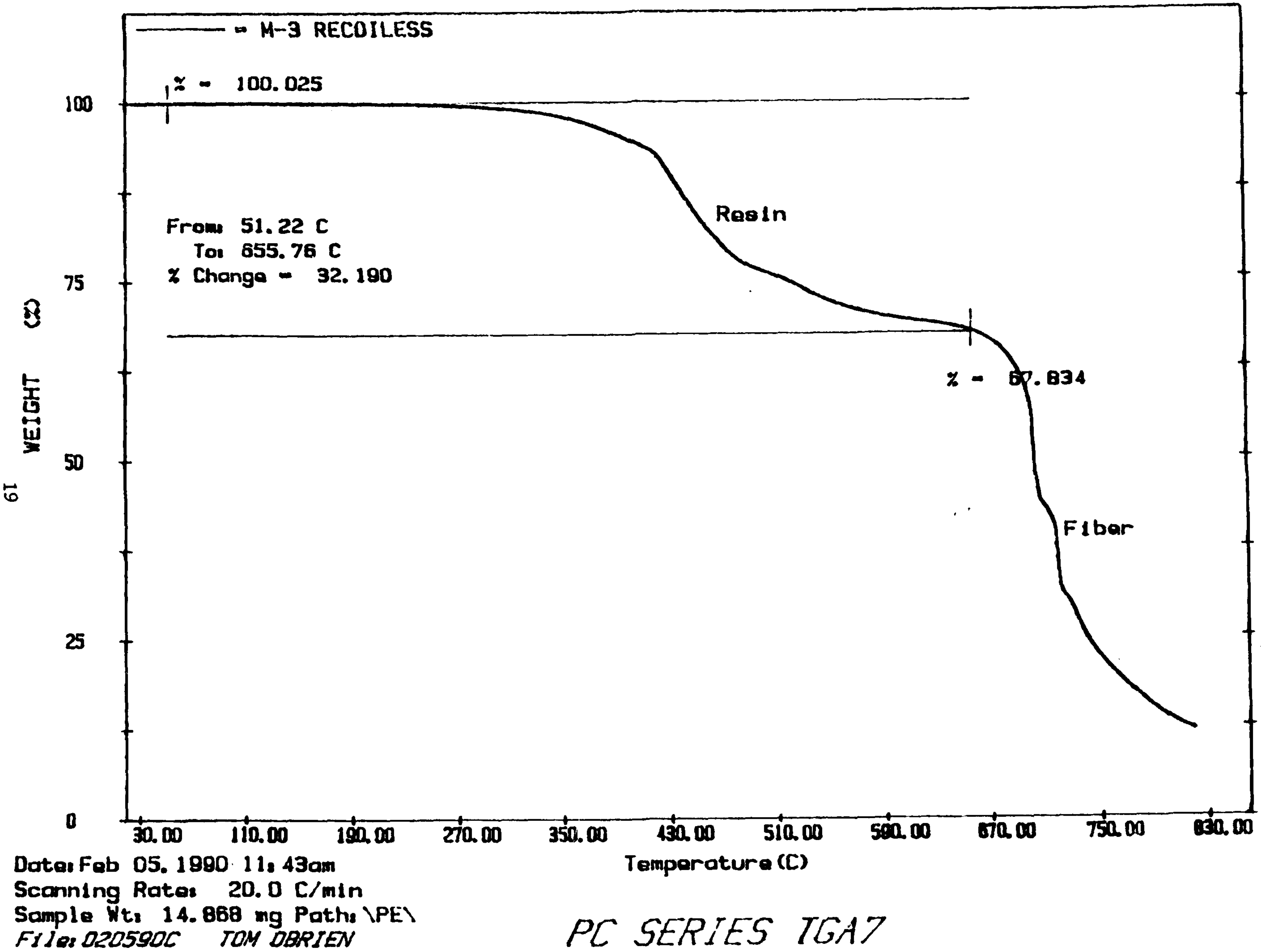


Figure 9. Thermogravimetric analysis of composite jacket.

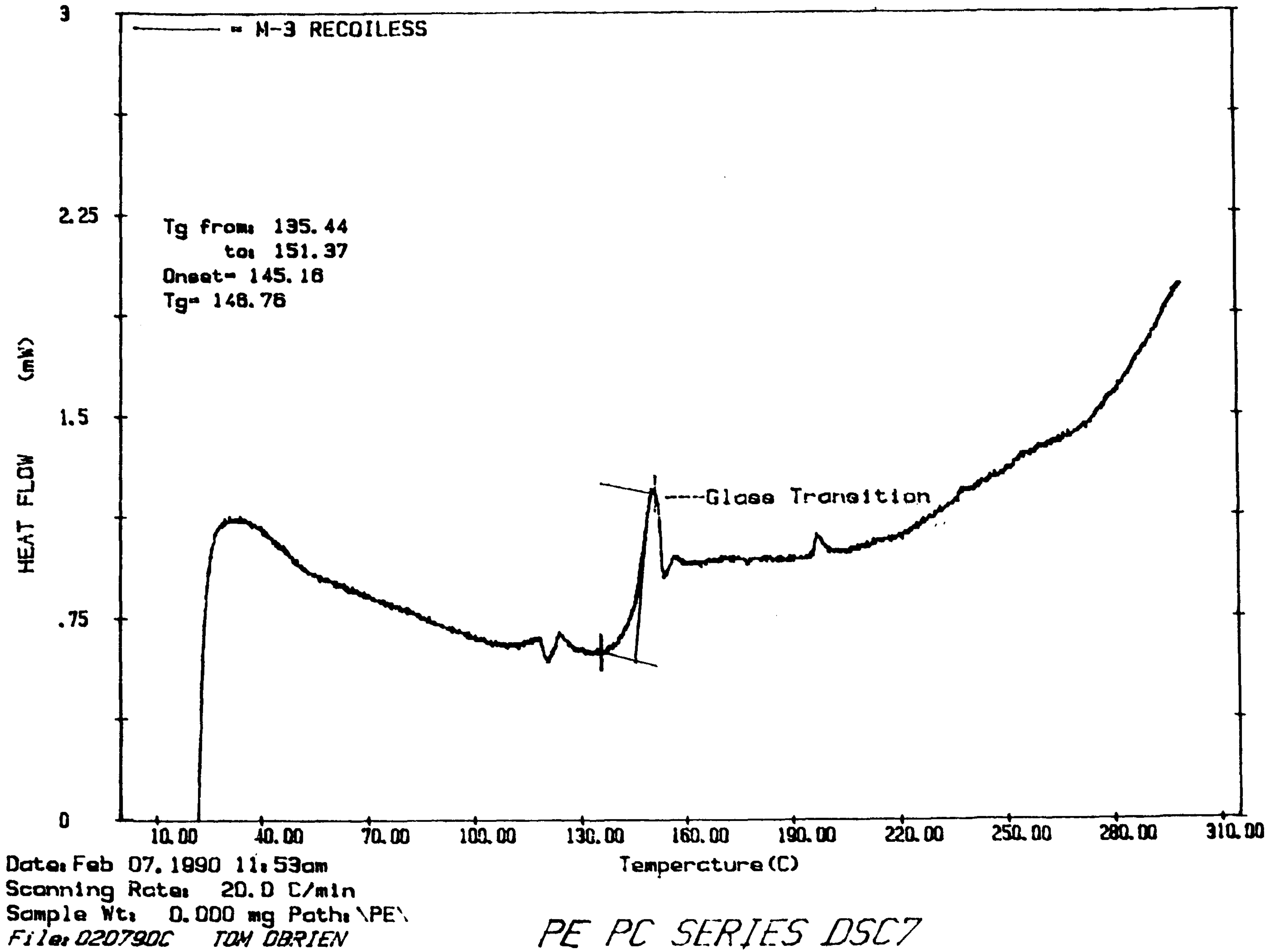


Figure 10. Differential scanning calorimetry of composite jacket.

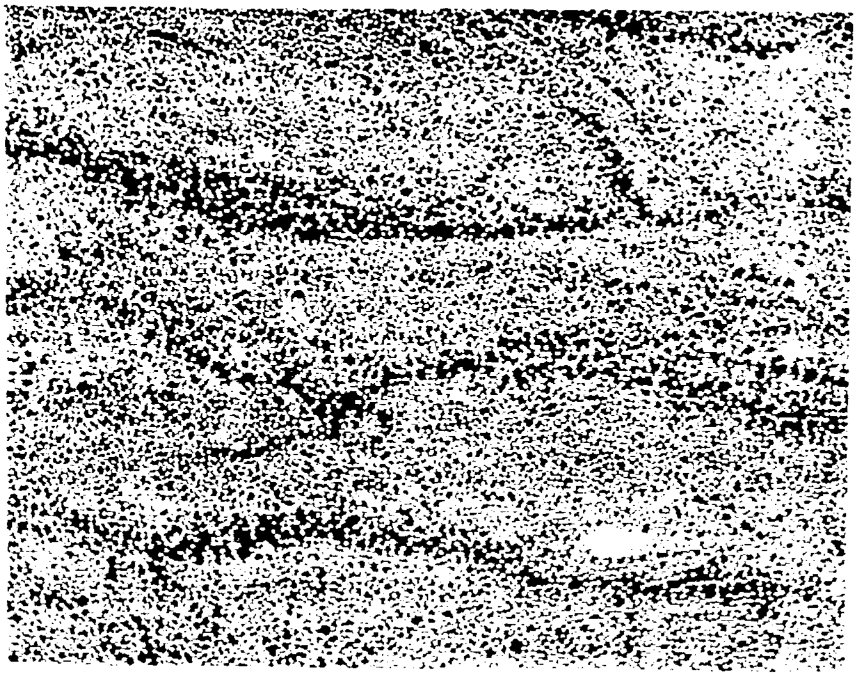


Figure 11. Composite jacket, hoop fiber cross section.

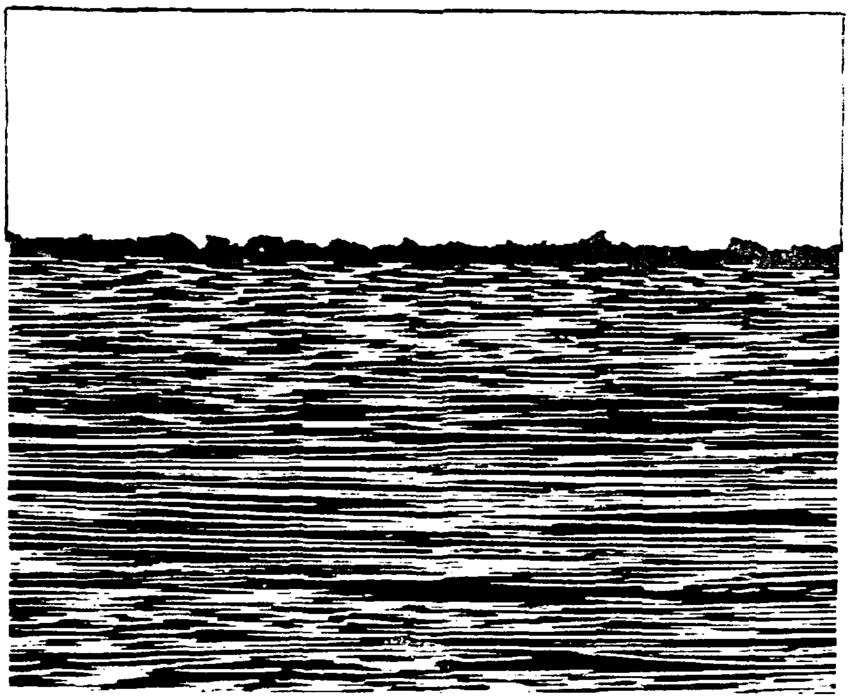


Figure 12. Composite jacket, steel liner interface.

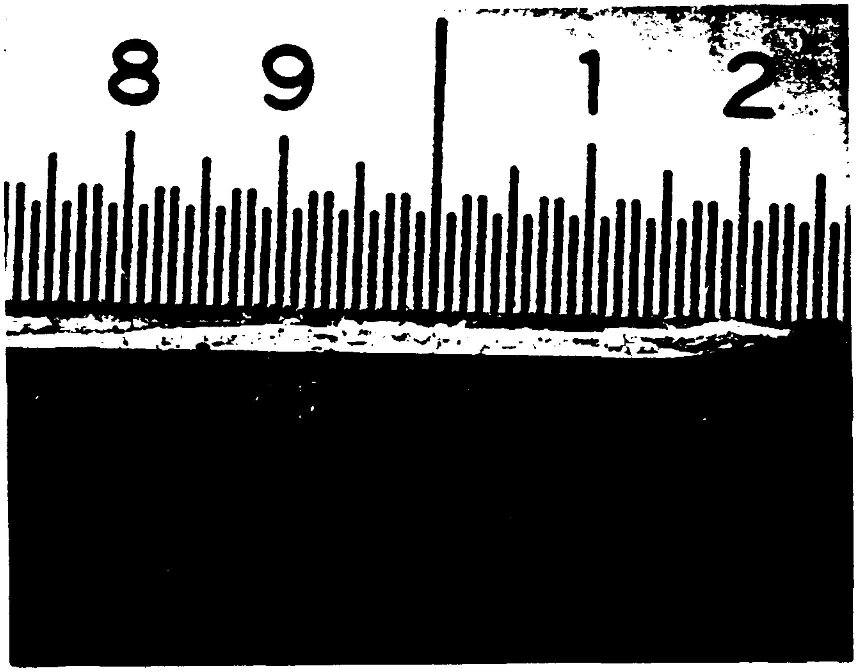


Figure 13. Fracture surface, tube SN 14003.

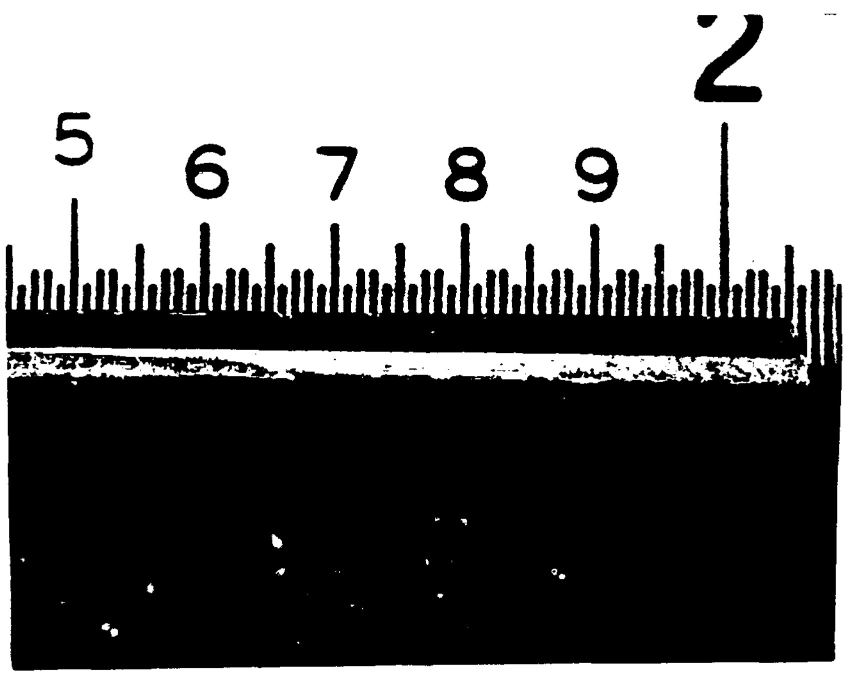


Figure 14. Fracture surface, tube SN 14002.

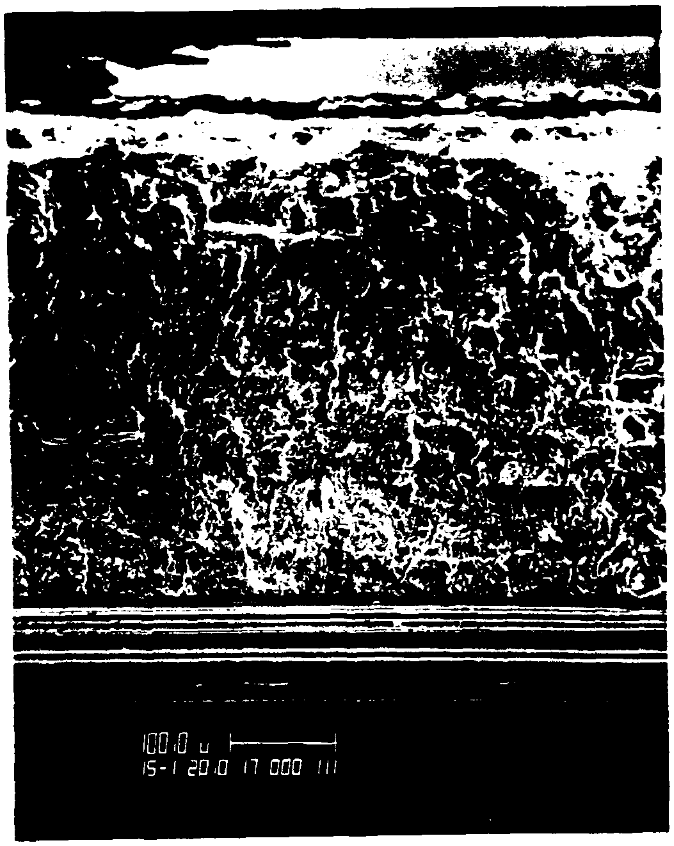


Figure 15. Fracture surface, tube SN 14002 (150X).

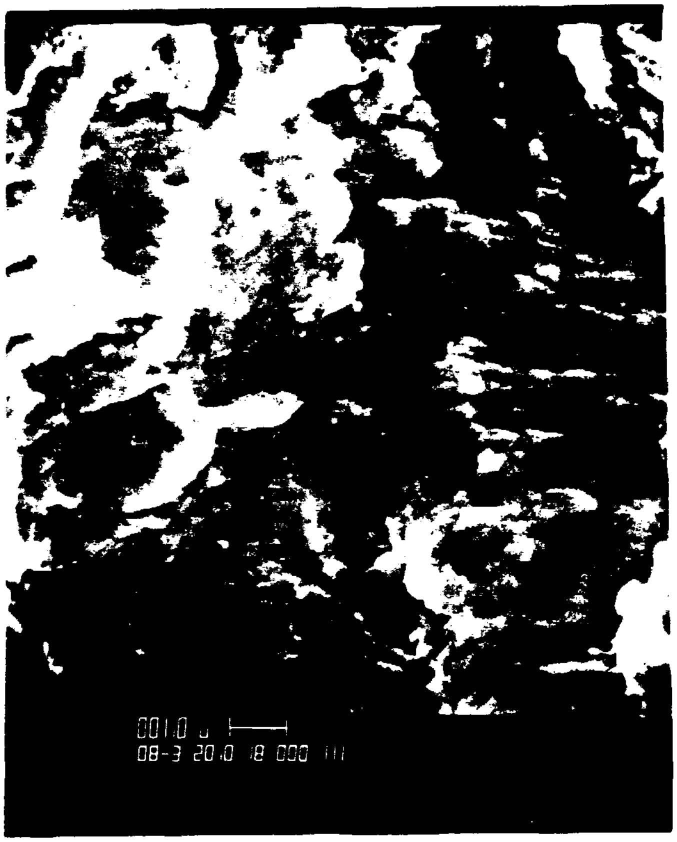


Figure 16. Fracture surface, tube SN 14002 (8000X).

APPENDIX

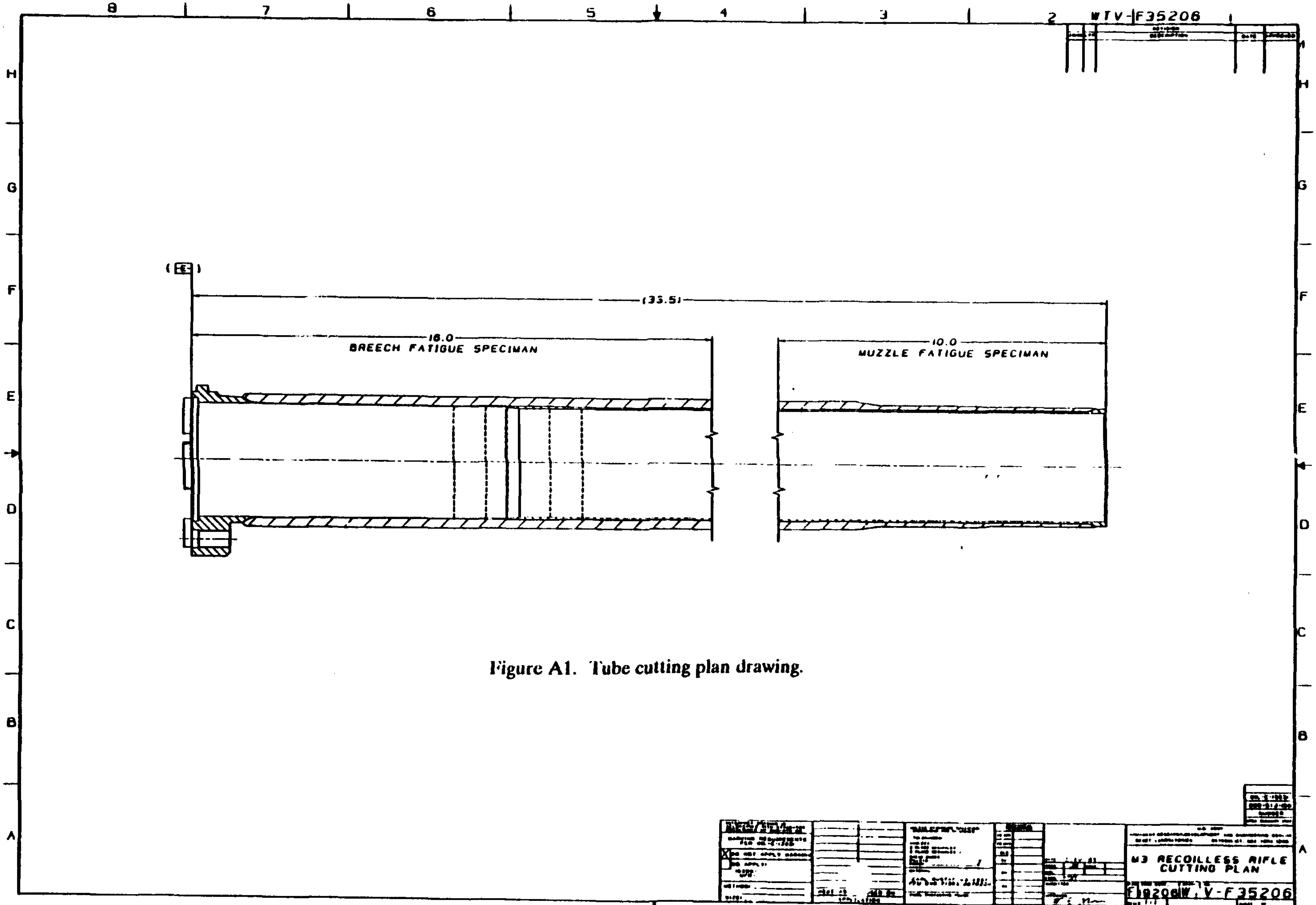


Figure A1. Tube cutting plan drawing.

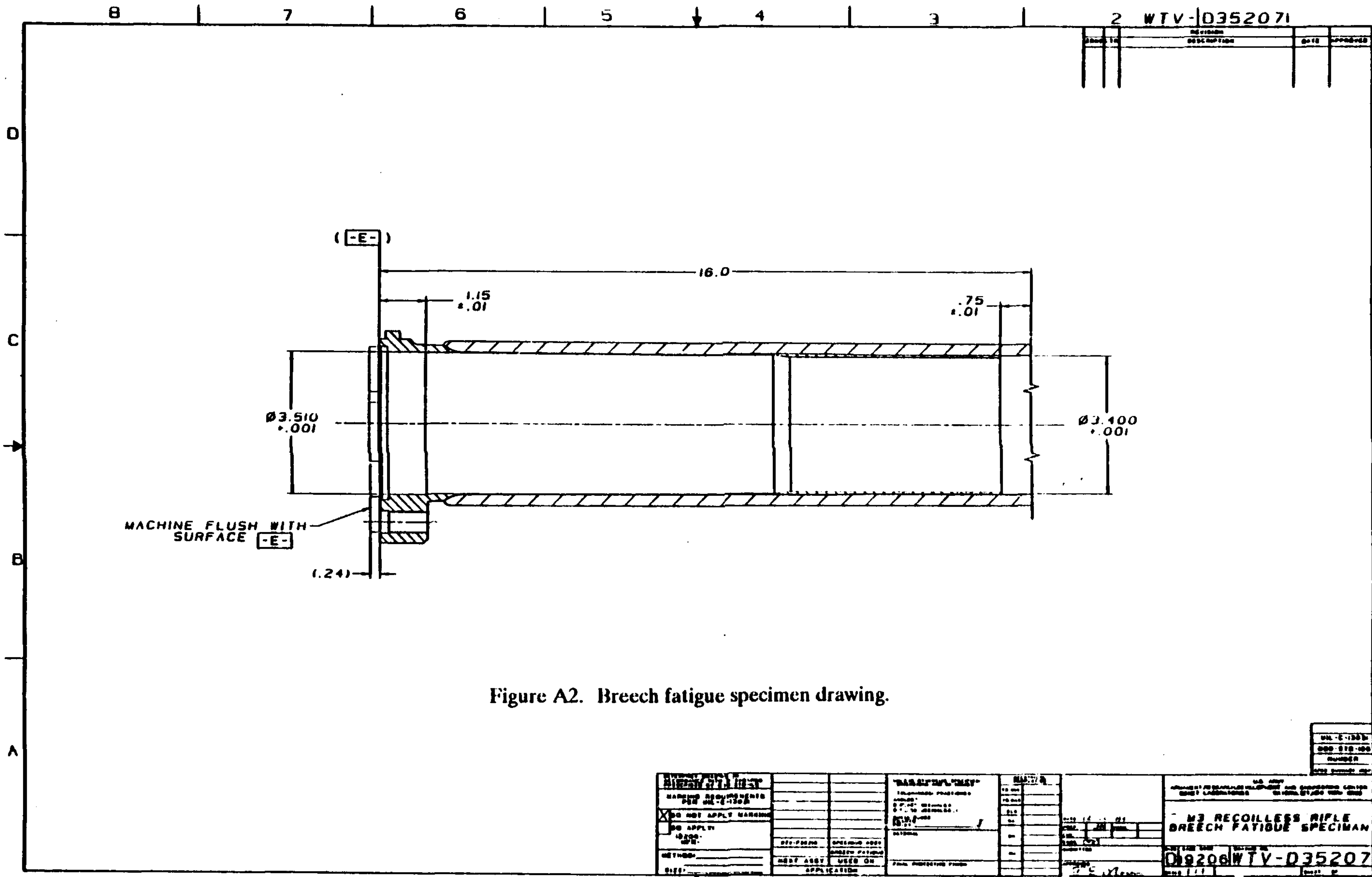


Figure A2. Breech fatigue specimen drawing.

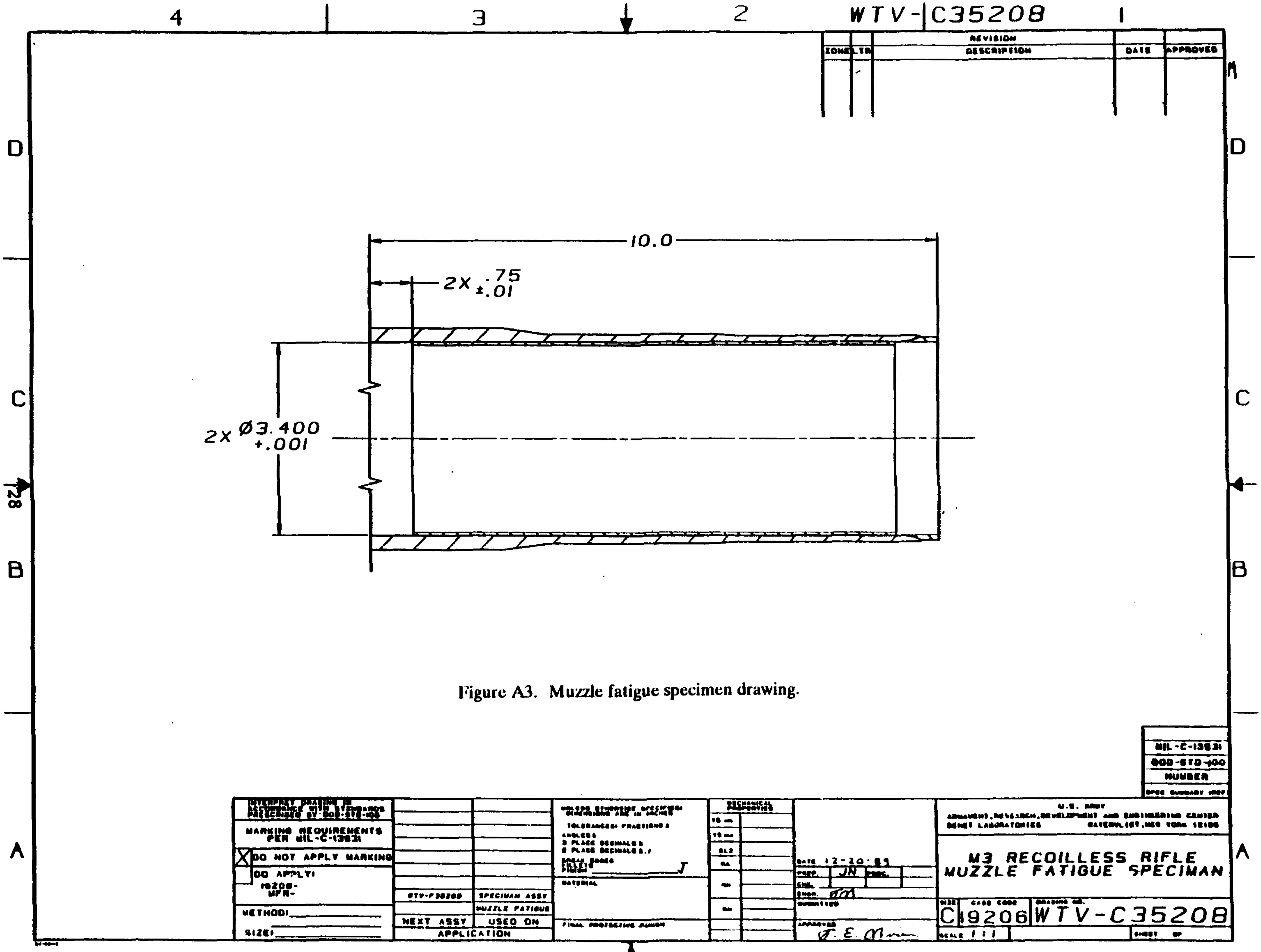


Figure A3. Muzzle fatigue specimen drawing.

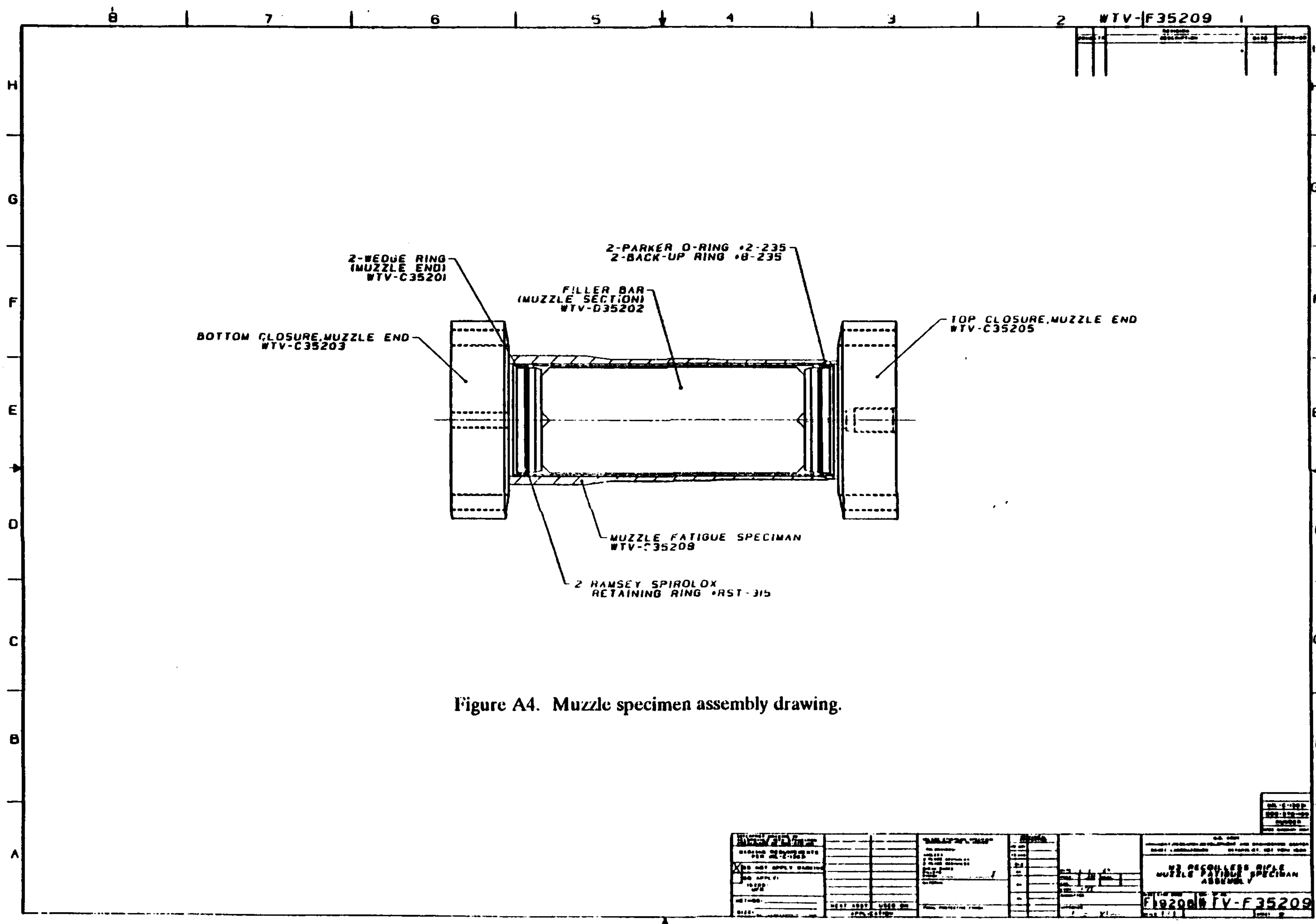


Figure A4. Muzzle specimen assembly drawing.

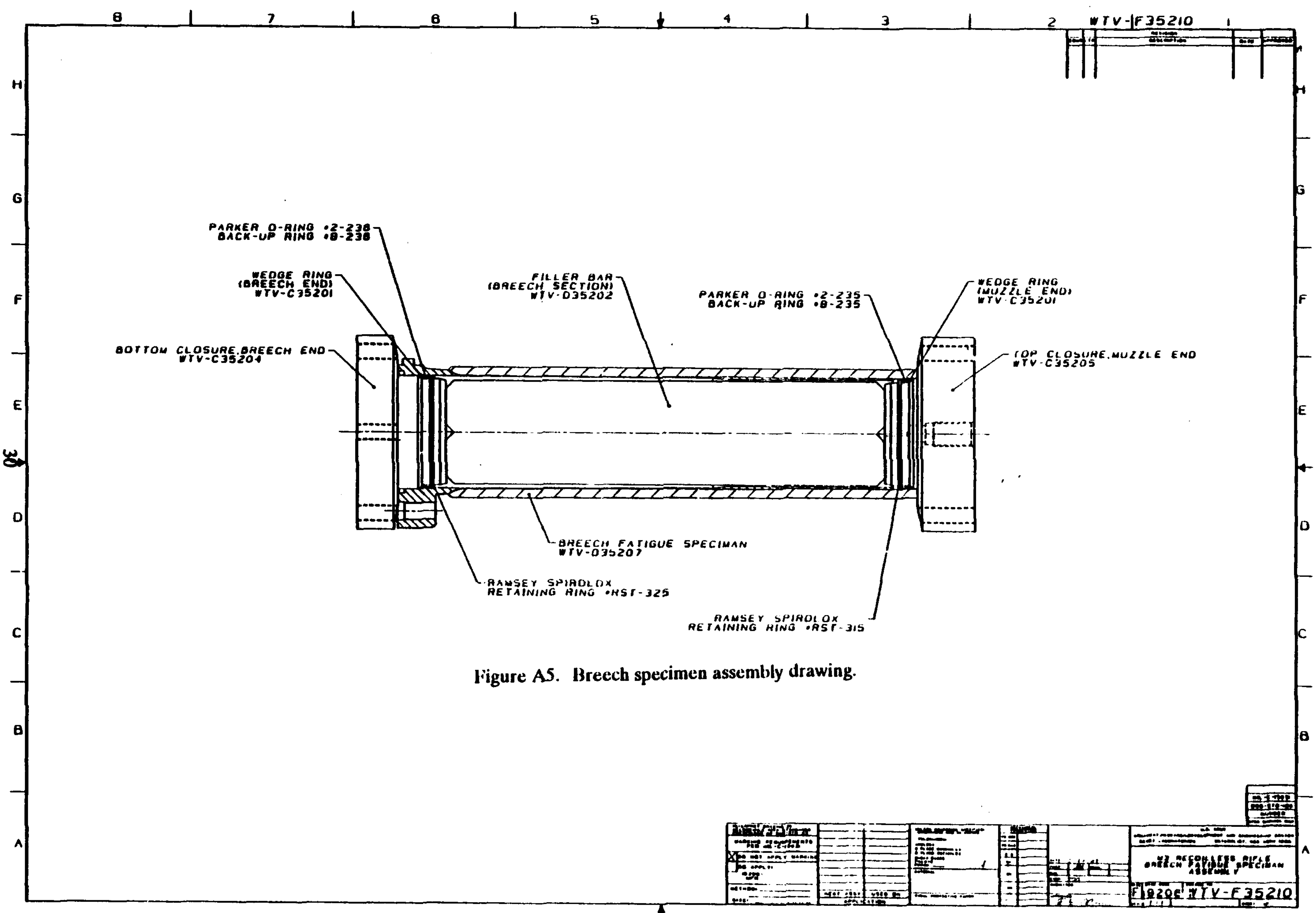


Figure A5. Breech specimen assembly drawing.

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