EVALUATION OF RUPTURED DOT-E-7235 CYLINDER

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INTRODUCTION

A cylinder received by NIST was reported to have ruptured, in service, while being filled. The cylinder that ruptured, along with auxiliary equipment used to fill the cylinder, and two example cylinders of the same design type were submitted to NIST by the U. S. Department of Transportation (DOT) Office of Hazardous Materials Technology for evaluation. The objective of the NIST evaluation was to document the condition of the ruptured cylinder, to compare the ruptured cylinder with cylinders of similar design, and, if possible, to determine the cause of the rupture.

DOCUMENTATION OF THE ITEMS RECEIVED FOR EVALUATION

GENERAL DOCUMENTATION OF ALL PARTS RECEIVED: A general documentation of the cylinders and auxiliary equipment received by NIST was carried out. The objectives of this documentation were:

1. To identify and document the general condition of all parts "as received" -- for example damage, corrosion, deformation, abrasion etc.

2. To document any identification or markings on the cylinders "as received".

3. To compare the ruptured cylinder with example cylinders of the same design type that did not fail.

Fourteen items were received by NIST for documentation and evaluation. These items are identified in Table I. The items to be documented and evaluated were: a portable "Eagle Air System" (Item 1) that was used for filling the cylinder that ruptured (Fig. 1), two example cylinders (Items 2A and 10A) that were of the same design type as the cylinder that ruptured (Fig. 2 and 3), two valve systems (Items 2B and 10B) from the example cylinders (Fig. 4 and 5), and all of the pieces and the valve system (Items 3A, 3B, 3C, 4, 5, 6, 7, 8, and 9) from the ruptured cylinder (Fig. 6, 7, 8, 9, 10, 11, 12, and 13). Detailed evaluation was carried out only on the parts from the ruptured cylinder (Items 3A and 3B). The other parts and cylinders were documented for the record only and no further evaluation of these parts (i.e. the valves, air system, example cylinders) was carried out.

DOCUMENTATION OF THE Ruptured CYLINDER: The general condition of the ruptured cylinder received by NIST is shown in Figure 6 (Item 3A). The rupture of the cylinder resulted in the cylinder breaking into two pieces (Items 3A and 3B) as shown in Figures 6 and 7, respectively. A portion of the head of the cylinder (Item 3B) was removed as a result of the rupture. The rest of the cylinder (Item 3A) remained intact (Fig. 6) with no significant secondary tearing or deformation of the cylinder.

The U.S. Department of Transportation (DOT) requires that high pressure cylinders have markings on the cylinder body or head that show the type of cylinder, the maximum service pressure, the name of the manufacturer, the date of manufacture (first hydrostatic test), the cylinder serial number, and the date that any of the required retests were conducted. Markings on the body of the cylinder (Fig. 14) show that the cylinder was manufactured to the requirements of U. S. (DOT) exemption number E-7235 (Ref. 1) issued to Luxfer U.S.A. Ltd. Markings on the base of the cylinder confirmed that the cylinder was manufactured by Luxfer U.S.A. Ltd.

DOT-E-7235 type cylinders are constructed of a seamless aluminum liner with hoop-wrapped fiberglass over-wrapping. The marked maximum service pressure of the cylinder that ruptured is 4500 psi. (Fig. 6).

Markings on the head of the cylinder show that the serial number for this cylinder is WA 6933 (Fig.15). Other markings on the head of this cylinder show that the elastic expansion value at the time of manufacture was EE-480 (this value is referred to during the hydrostatic retest). The number "4" next to an upright arrow on the head of the cylinder is the first part of the marking showing the date of the first hydrostatic test which is taken as the date of manufacture of the cylinder (the other part of the date of first hydrostatic test is on part 3B). The "4" indicates the month as April. The upright arrow is the symbol for Authorized Testing Inc. which is the DOT independent inspector for Luxfer U.S.A. Ltd. The other marking on this section of the head is an "S" which is part of the name Scott who was the ordinal purchaser of the cylinder. Figure 16 shows more details of the markings on the head of the Item 3A part of the cylinder. These markings show that the cylinder was retested, as required by DOT, in 1981 and 1986.

The rest of the markings on the head of the cylinder are shown on the section of the cylinder head that came off during the rupture (Item 3B) that is shown in Figure 17. The markings on this section of the head show the markings "COTT" which is the rest of the name of the ordinal purchaser, i.e., SCOTT and the year of manufacture, which is "77" for 1977. This section also shows the date of the last retest which is 1990.

In summary, the markings on the body and head of the cylinder show that the cylinder that ruptured was manufactured to DOT exemption E-7235 in April 1977 and had a maximum allowed service pressure of 4500 psi. The cylinder was retested, as required, in 1981, 1986, and 1990. It should be noted that cylinders manufactured under DOT exemption E-7235 have a maximum service life of fifteen (15) years (Ref. 1). Therefore because this cylinder was manufactured in April 1977, it should have been removed from service and not refilled after April 1992.

In addition to the markings on the head of the cylinder, Figure 15 shows that the cylinder that ruptured had not been fitted with a steel neck ring as required by the DOT notice of August 15, 1985 (Ref. 2). The absence of a neck ring is seen by the yellow paint to the very end of the neck on the cylinder and by the lack of any machining on the neck that would be required before a neck ring could be fitted (Fig. 15). There was no physical evidence that the cylinder which ruptured had ever had a neck ring or had been machined in preparation for fitting a neck ring.

For comparison, a typical DOT-E-7235 cylinder of the same design which had been retrofitted with a steel neck ring is shown in Figure 18. In Figure 18, the neck ring is visible as the shiny silver colored attachment on the neck of the cylinder. The purpose of the steel neck ring is to prevent rupture of the cylinder when cracking occurs in the shoulder of the cylinder. When cracking occurs in the shoulder of cylinders manufactured according to DOT exemption E-7235, the cylinders have been shown to only leak when they are fitted with a neck ring but to rupture when the neck ring is not present.

<u>DOCUMENTATION OF THE EXAMPLE CYLINDERS:</u> In addition to the ruptured cylinder, two example cylinders (Items 2A and 10A) manufactured under DOT exemption E-7235 were also submitted to NIST by the U. S. Department of Transportation (DOT) Office of Hazardous Materials Technology. These example cylinders were reported to be from the same source as the ruptured cylinder. One of the example cylinders (Item 10A) is shown in Figure 18. For comparison with the ruptured cylinder, the example cylinder shown in Figure 18 (Item 10A) is properly fitted with a steel neck ring as required by the DOT regulations (Ref. 2). Figure 18 also shows that in addition to the neck ring a label entitled "RETROFITTED" is attached to the cylinder at the time the neck ring was fitted to the cylinder. This label was not required by the DOT regulations but was put on at the time the neck ring was fitted at the discretion of the manufacturer. Figure 18 shows that the neck ring is clearly visible on a cylinder that has been retrofitted with a neck ring and leaves no doubt that the ruptured cylinder never was fitted with a neck ring.

METALLURGICAL EVALUATION OF THE RUPTURED CYLINDER

METALLURGICAL EVALUATION: A metallurgical evaluation of the cylinder that ruptured was carried out by NIST. The objectives of this evaluation were:

1. To identify the specific material in the cylinder that ruptured.

2. To identify the origin of the rupture and to characterize the physical features of origin of the rupture.

3. To identify the microstructural features of the mode of rupture.

CHEMICAL ANALYSIS OF THE RUPTURED CYLINDER: A quantitative chemical analysis of samples taken from the head of the ruptured cylinder was conducted to determine the chemical composition of the cylinder metal and to determine if the aluminum cylinder liner was in compliance with the requirements of DOT exemption E-7235. Duplicate samples were taken from the head of the ruptured cylinder and were analyzed using the ASTM test method E607 - 90 (Ref. 3) for the major alloying elements and ASTM test method E663-91 (Ref. 4) for the content of lead. These results of this chemical analysis are shown in Table 2. The chemical composition of these samples conforms to the composition requirements for the Aluminum Association alloy designated AA6351. This is the aluminum alloy required for the construction of the liner cylinders manufactured under DOT exemption E-7235. Therefore, the material in the cylinder liner is in compliance with the DOT exemption E-7235.

GENERAL CHARACTERIZATION OF THE RUPTURED CYLINDER: Photographs were taken of the ruptured part of the cylinder to identify the size, shape, and fracture appearance of the origin of the rupture. As shown in Figure 19, the rupture appears to initiate at the shoulder of the cylinder and propagate around cylinder head and cause the cylinder head to tear off. On closer examination of the shoulder of the cylinder, as shown in Figure 20, there appears to be shoulder cracks on each side of the threaded region of the cylinder. These shoulder cracks are believed to be the origin of the rupture which then propagated around the head of the cylinder and down to the region of the cylinder body that was wrapped with fiberglass. Figure 21 shows that the region of the cylinder shoulder at the base of the threaded region has a different, more shiny, appearance than the remainder of the fracture surface. This shiny region is believed to be the preexisting cracked region that led to the final rupture.

FRACTOGRAPHIC ANALYSIS OF THE RUPTURED CYLINDER: Detailed examination of the surface of the fractured region of the cylinder shoulder that is believed to be the origin of the rupture was carried out using a scanning electron microscope. The purpose of this examination was to determine if cracks existed in this region prior to the final rupture of the cylinder and to identify the type of any cracks that were found.

A specimen was cut from the cylinder shoulder, as shown in Figure 22, for examination in the scanning electron microscope. The entire surface of this specimen was examined to characterize the type of fracture that occurred. The fracture surface of this specimen in the lower left corner (Fig. 22) near the bottom end of the threads is shown in Figure 23. At this location, the fracture surface was characteristic of a type of intergranular, ductile fracture known as sustained-load-cracking (SLC) that has been found to occur in type AA6351 aluminum alloy (Ref. 5). This type of cracking occurs over time when the metal is stressed at a high level as it is in these type of cylinders. This region of the cylinder shoulder is believed to be the origin of the final rupture of the cylinder.

Examination of the fracture surface of this specimen (Fig. 22) in the lower right corner (Fig. 24) shows a different type of fracture surface that is characteristic of general overload type of ductile fracture. This region of the fracture surface is typical of fracture propagation during the final stage of rupture of the cylinder and is not characteristic of the SLC type of cracking.

CONCLUSIONS

1. The ruptured cylinder was manufactured according to DOT exemption E-7235

2. The aluminum part of the ruptured cylinder was determined to be aluminum alloy AA6351 which complied with chemical composition requirements of DOT exemption E-7235.

3. The ruptured cylinder was not fitted with a steel neck ring as required for DOT exemption E-7235 cylinders.

4. DOT E-7235 cylinders have a maximum permitted life of fifteen (15) years. The ruptured cylinder was manufactured in April 1977 and therefore should have been removed from service and not refilled after April 1992.

5. The origin of rupture was believed to be due to cracks in shoulder of the cylinder that are typical of sustained-load-cracking (SLC) which has been found to occur in alloy AA6351 from which this cylinder was made.

REFERENCES

1. U.S. Dept. of Transportation, Exemption DOT-E-7235, April 1, 1976.

2. "High Pressure Composite Hoop Wrapped Cylinders 4500 p.s.i.g. Marked Service Pressure: Cylinders - (85-4)" Federal Register Vol. 50, No. 158, August 15, 1985.

3. "Standard Test Method for Optical Emission Spectrometric Analysis o Aluminum Alloys by the Point-to-Plane Technique, Nitrogen Atmosphere", ASTM E607-90, American Society for Testing and Materials annual book of ASTM Standards, Vol. 03.06, 1994.

4. "Standard Practice for Flame Atomic Absorption Analysis", ASTM E663-86(91), American Society for Testing and Materials annual book of ASTM Standards, Vol. 03.06, 1994.

5. "Pb-Induced Solid-Metal Embrittlement of A;-Mg-Si Alloys at Ambient Temperatures", Y.S. Kim, N.J.H. Holyrod, J.J. Lewandowski; Proceedings of Environment-Induced Cracking of Metals, pp. 371--377, Published by the National Association of Corrosion Engineers, 1989.

TABLE 1

ITEMS RECEIVED FOR DOCUMENTATION AND EVALUATION

ITEM NO.	DESCRIPTION
1	Portable Eagle Air System with Case
2A	Scott Air Pak Cylinder (Exemplar)
2B	Valve System Removed from Item 2A
3A	Scott Air Pak Cylinder Ruptured at Neck
3B	Fragment of Scott Air Pak Cylinder - Item 3A
3C	Valve System with Attached Hose from Item 3A
4	Metal Fragments Recovered from Ruptured Cylinder
5	Metal Fragments Recovered from Ruptured Cylinder
6	Fiberglass from Ruptured Cylinder
7	J-shaped Piece of Metal from Ruptured Cylinder
8	Piece of Metal Recovered from Ruptured Cylinder
9	Piece of Metal Recovered from Ruptured Cylinder
10A	Scott Air Pak Cylinder (Exemplar)
10B	Valve System Removed from Item 10A (Exemplar)

TABLE 2

CHEMICAL COMPOSITION OF SPECIMENS FROM RUPTURED CYLINDER

CHEMICAL ELEMENT	SAMPLE # 1 (Weight %)	SAMPLE # 2 (Weight %)
Silicon	0.91	0.88
Copper	< 0.05	< 0.05
Magnesium	0.71	0.69
Iron	0.22	0.22
Titanium	< 0.05	< 0.05
Zinc	< 0.05	< 0.05
Manganese	0.52	0.52
Lead	0.003	0.003
Tin	< 0.05	< 0.05
Nickel	< 0.05	< 0.05
Chromium	< 0.05	< 0.05
Bismuth	< 0.0001	< 0.0001
Aluminum	Remainder	Remainder

FIGURE 1 PORTABLE EAGLE AIR SYSTEM WITH CASE -- ITEM 1

FIGURE 2 SCOTT AIR PAK CYLINDER (EXEMPLAR) -- ITEM 2A

FIGURE 3 SCOTT AIR PAK CYLINDER (EXEMPLAR) -- ITEM 10A

FIGURE 4 VALVE SYSTEM REMOVED FROM ITEM 2A

FIGURE 5 VALVE SYSTEM REMOVED FROM ITEM 10A

FIGURE 6 SCOTT AIR PAK CYLINDER THAT RUPTURED AT NECK -- ITEM 3A

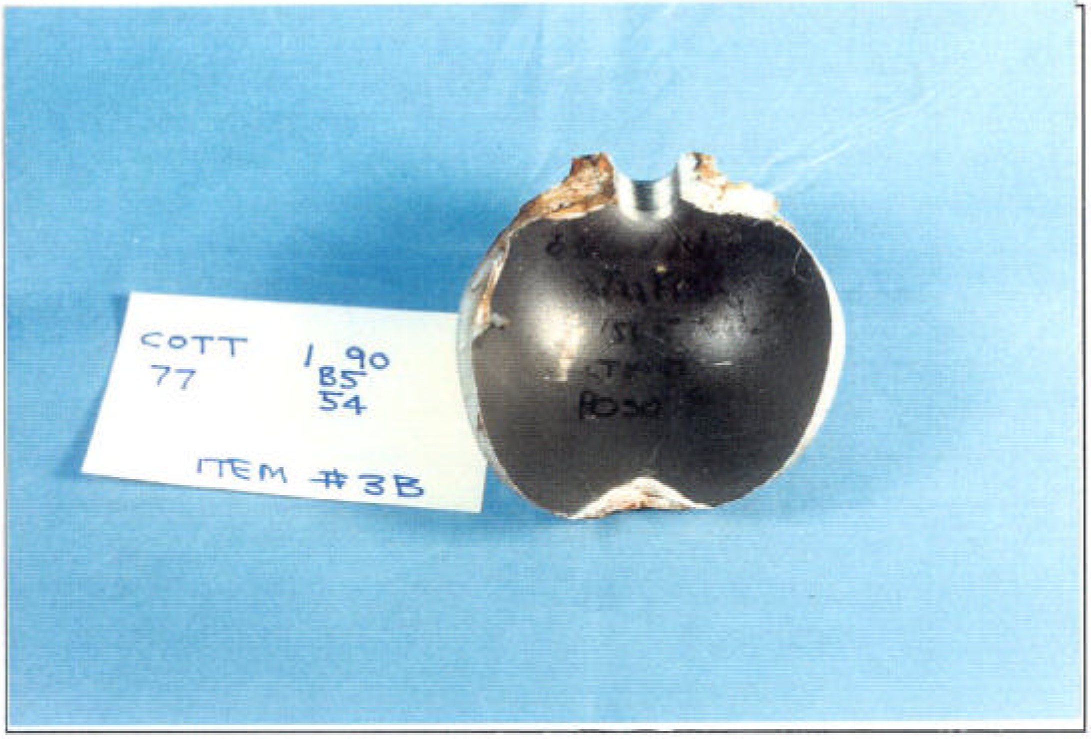

FIGURE 7 FRAGMENT OF SCOTT AIR PAK CYLINDER THAT RUPTURED -- ITEM 3A

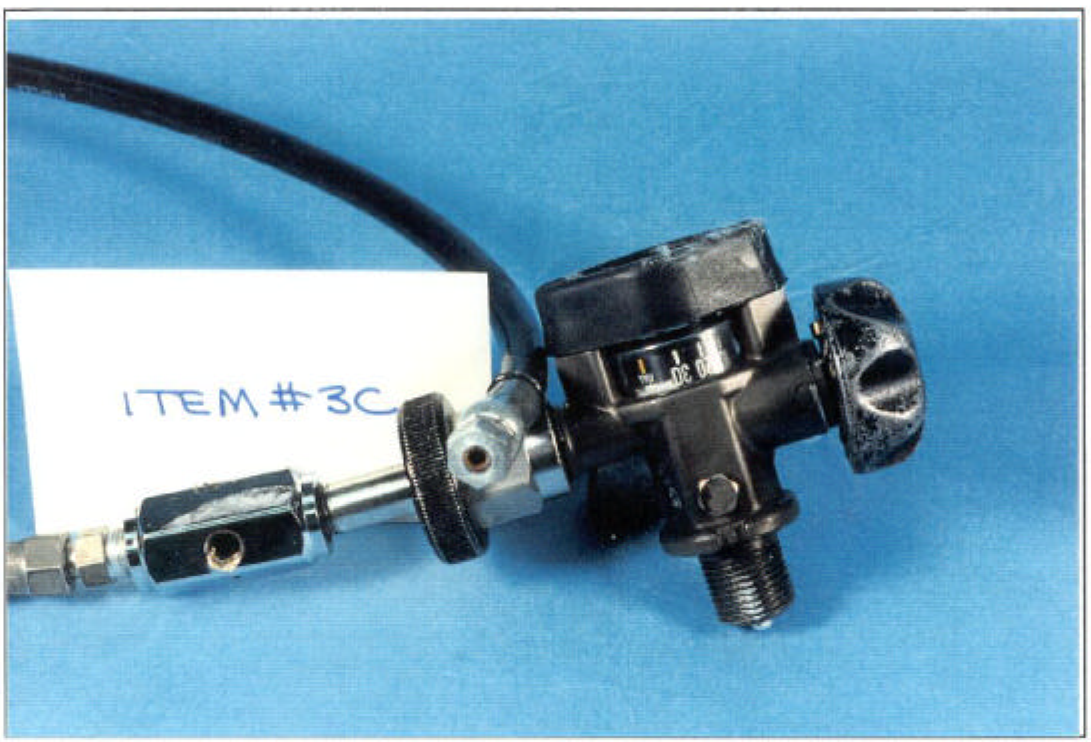

FIGURE 8 VALVE SYSTEM WITH ATTACHED HOSE FROM ITEM 3A

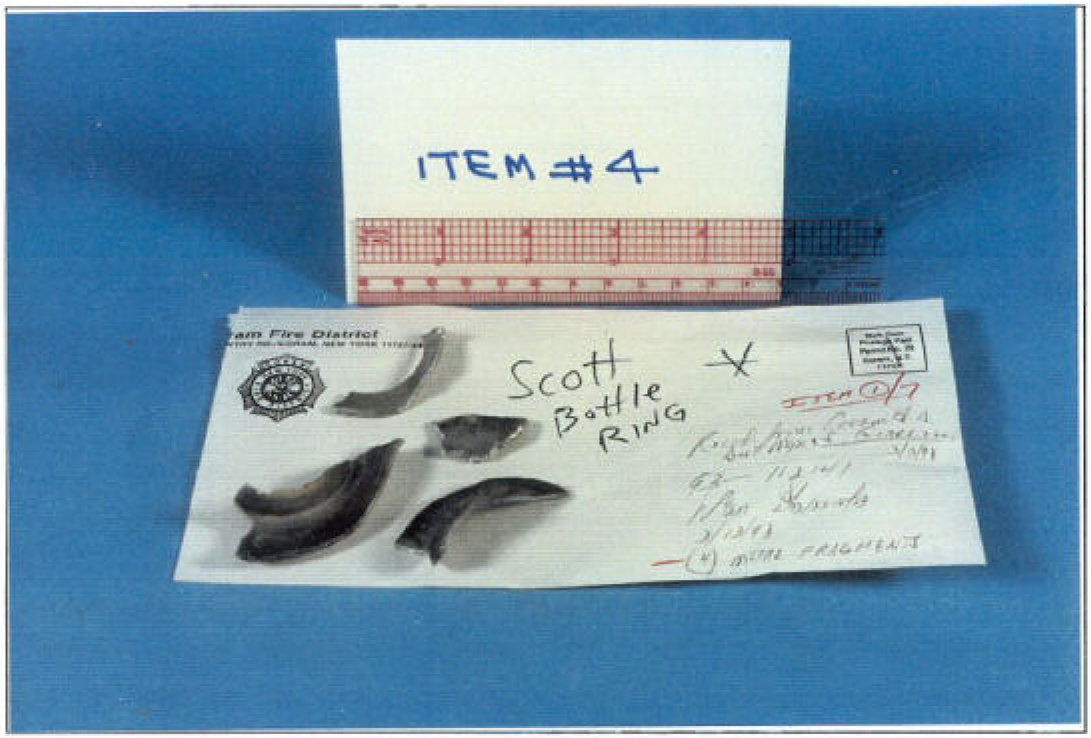

FIGURE 9 METAL FRAGMENTS RECOVERED FROM THE RUPTURED CYLINDER -- ITEM 4

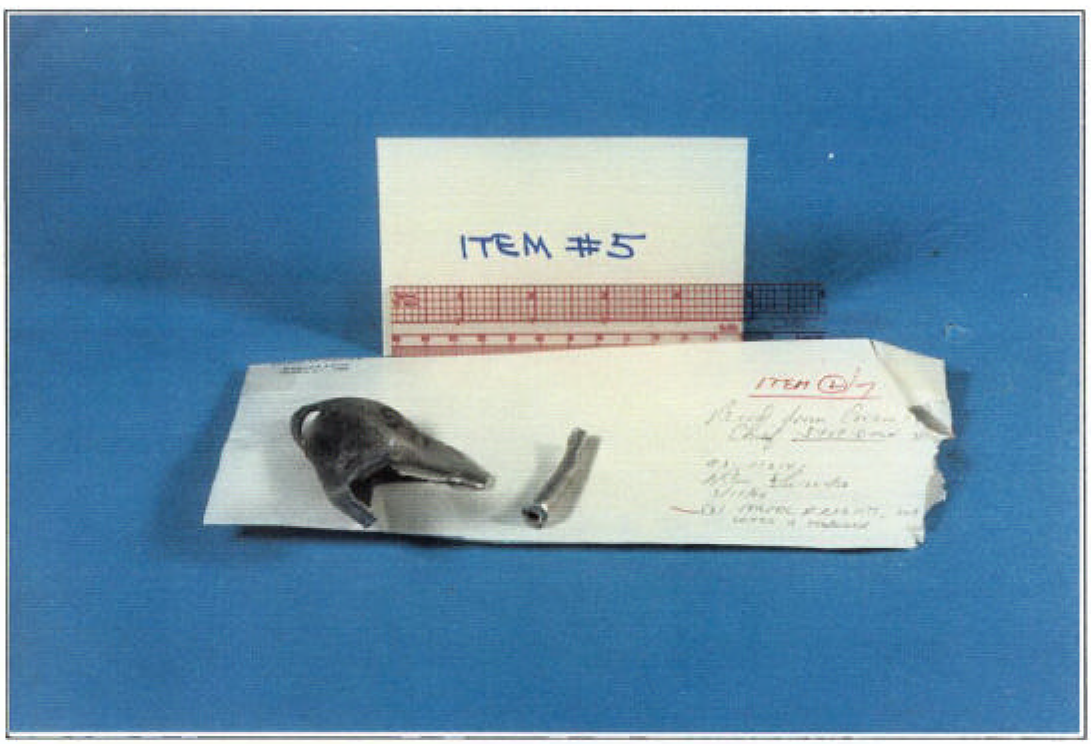

FIGURE 10 METAL FRAGMENTS RECOVERED FROM THE RUPTURED CYLINDER -- ITEM 5

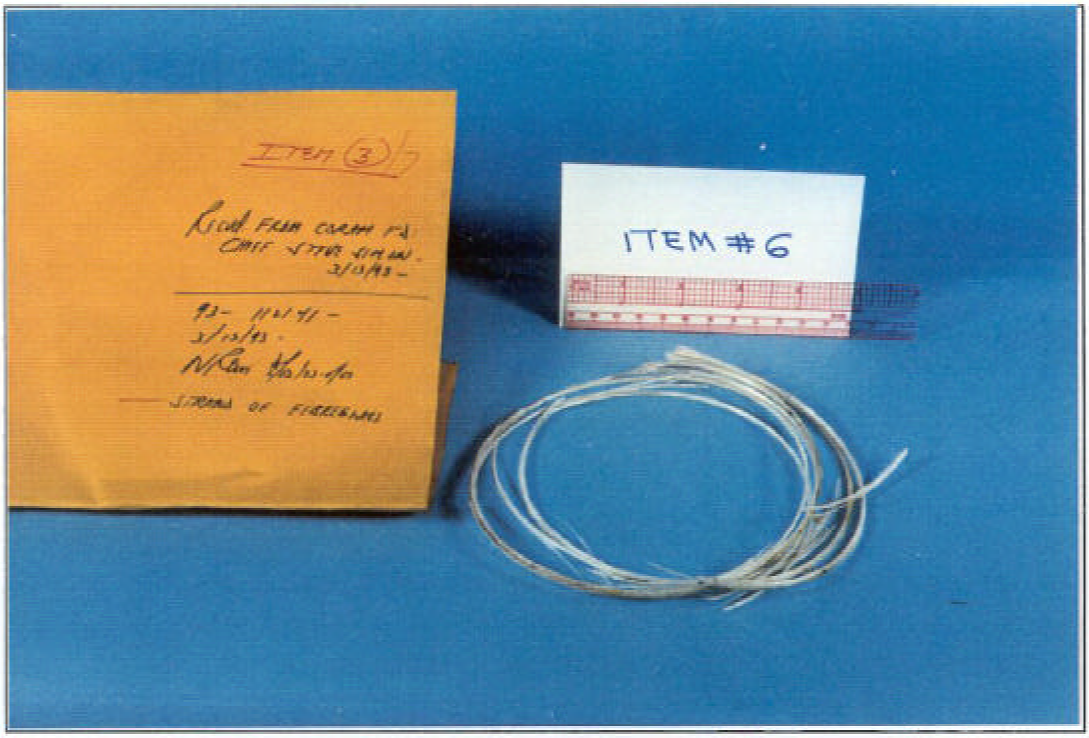

FIGURE 11 FIBERGLASS FROM THE RUPTURED CYLINDER -- ITEM 6

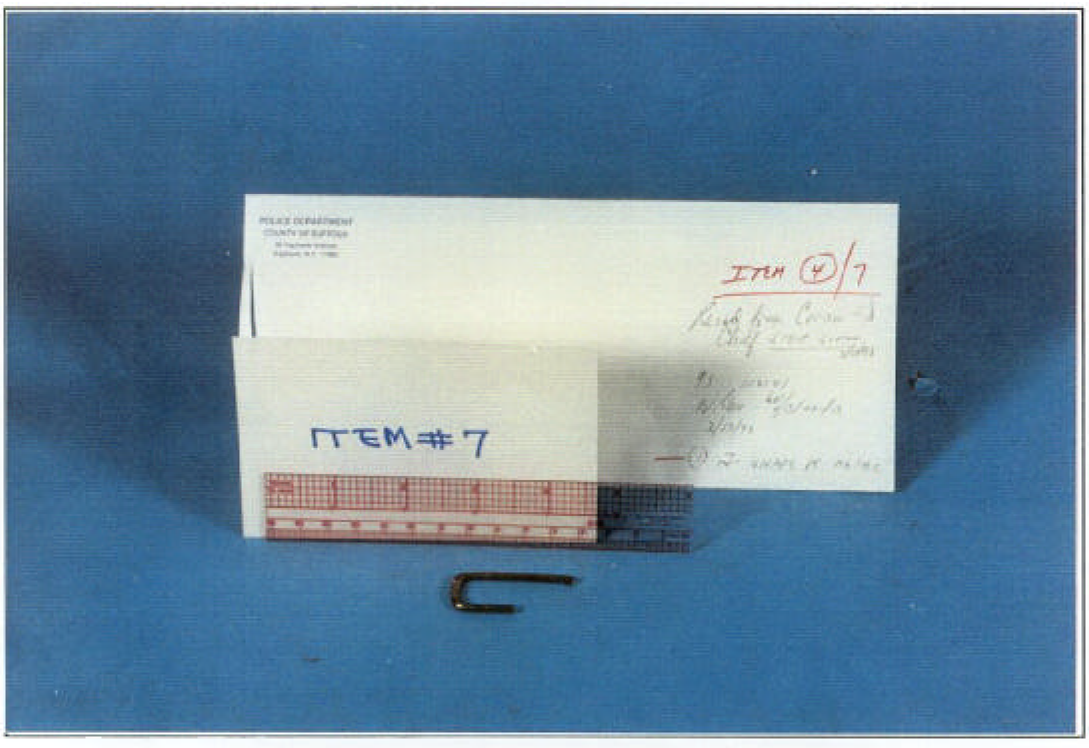

FIGURE 12 J-SHAPED PIECE OF METAL FROM THE RUPTURED CYLINDER -- ITEM 7

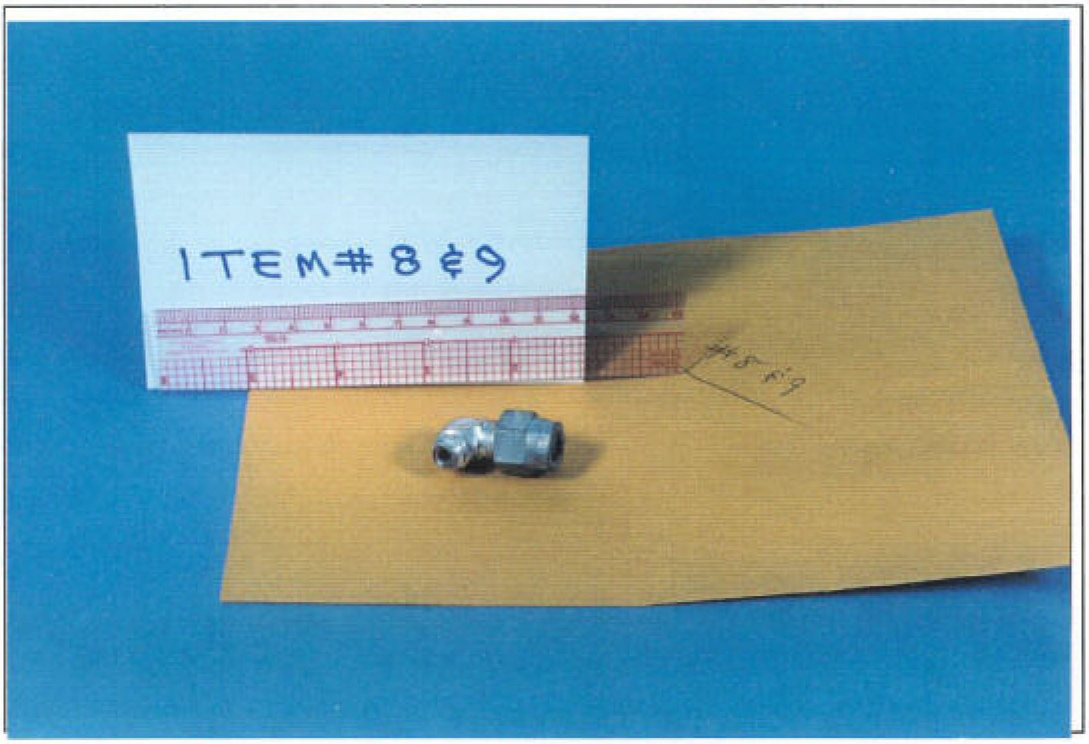

FIGURE 13 PIECES OF METAL RECOVERED FROM THE RUPTURED CYLINDER -- ITEMS 8 AND 9

FIGURE 14 MARKING IDENTIFYING THE RUPTURED CYLINDER AS A TYPE DOT-E-7235

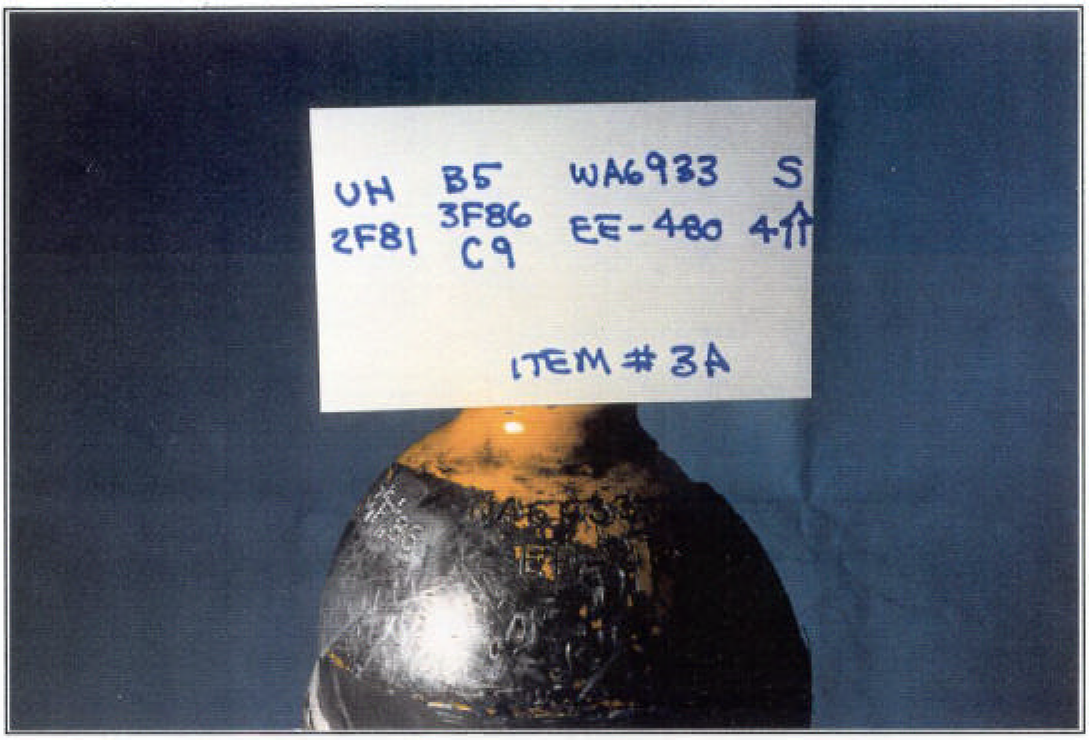

FIGURE 15 MARKINGS ON THE HEAD OF THE RUPTURED CYLINDER SHOWING THE SERIAL NUMBER -- ITEM 3A

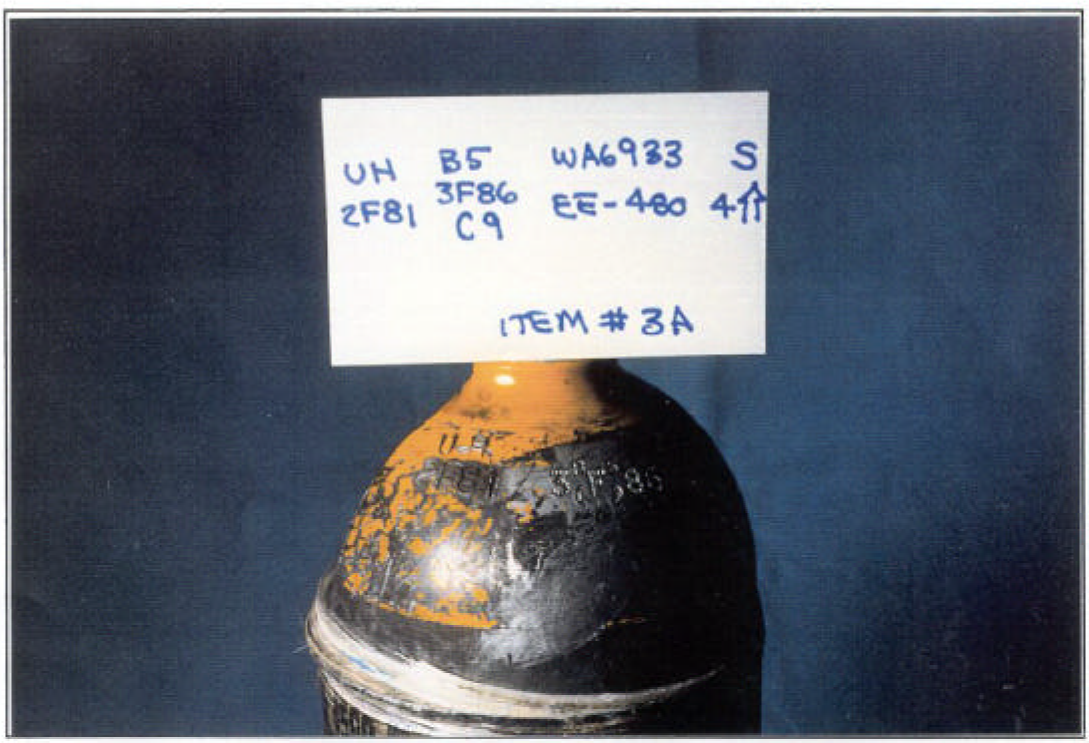

FIGURE 16 MARKINGS ON THE HEAD OF THE RUPTURED CYLINDER SHOWING THE DATE OF RETESTS -- ITEM 3A

FIGURE 17 MARKINGS ON THE HEAD OF THE CYLINDER THAT RUPTURED SHOWING THE YEAR OF MANUFACTURE -- ITEM 3B

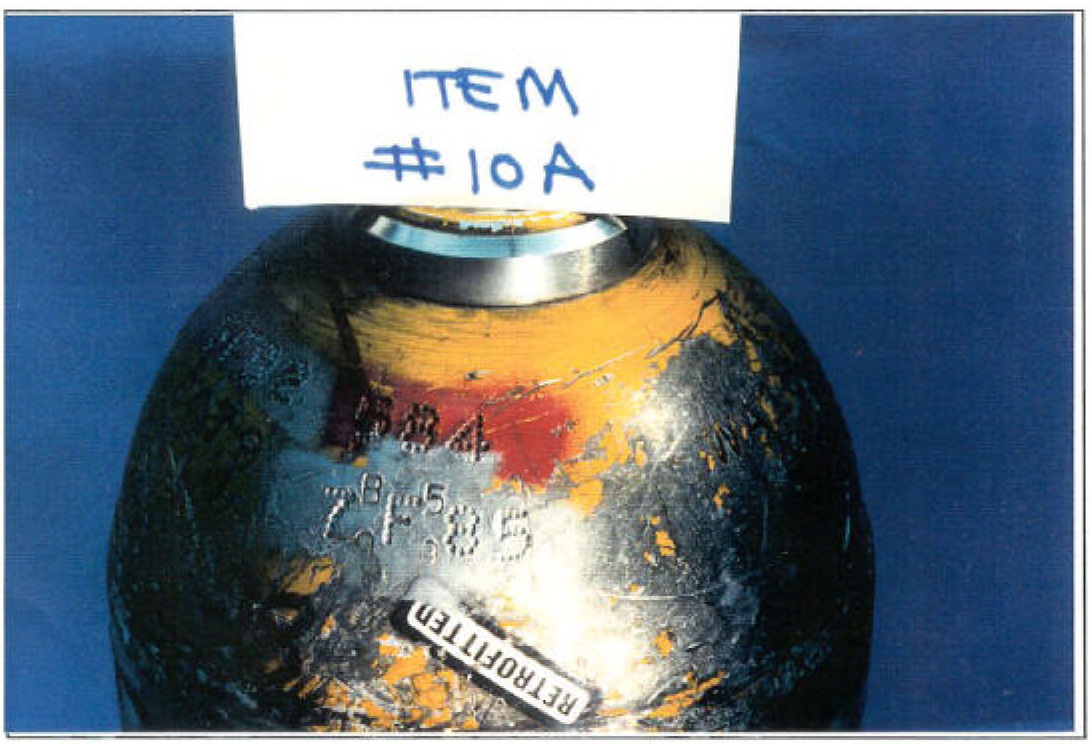

FIGURE 18 EXEMPLAR CYLINDER FITTED WITH STEEL NECK RING -- ITEM 10A

FIGURE 19 FRACTURE APPEARANCE OF THE HEAD OF THE RUPTURED CYLINDER -- ITEM 3A

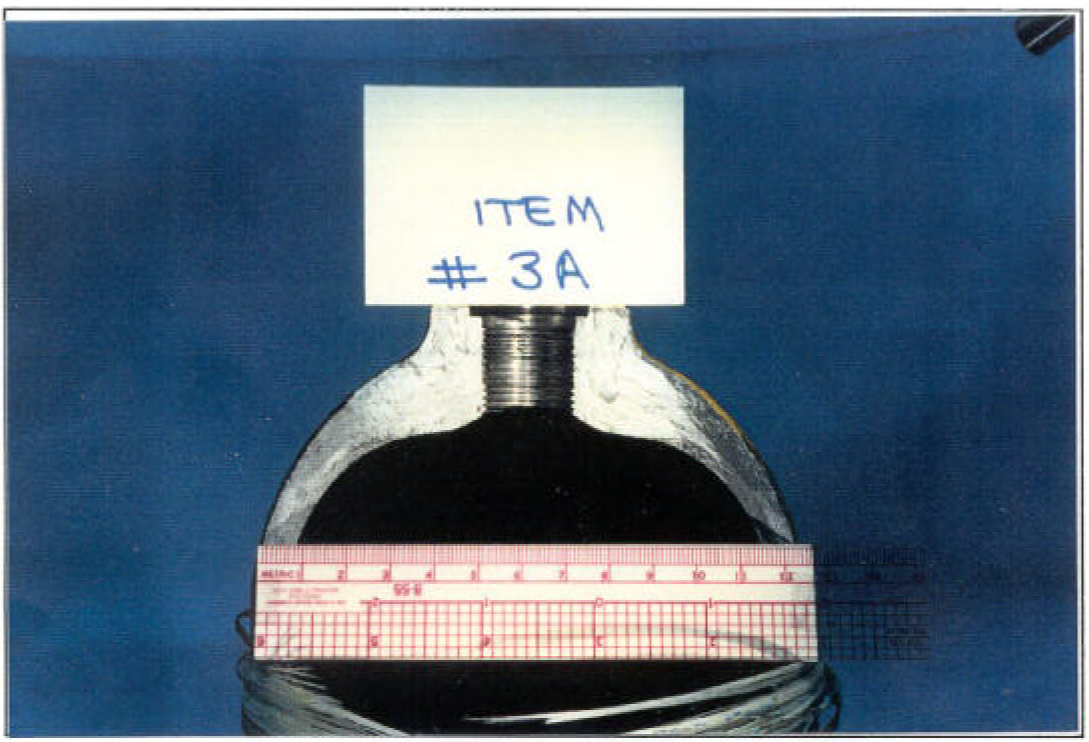

FIGURE 20 HEAD OF THE RUPTURED CYLINDER SHOWING LOCATION OF CRACKS IN THE SHOULDER OF THE CYLINDER HEAD -- ITEM 3A

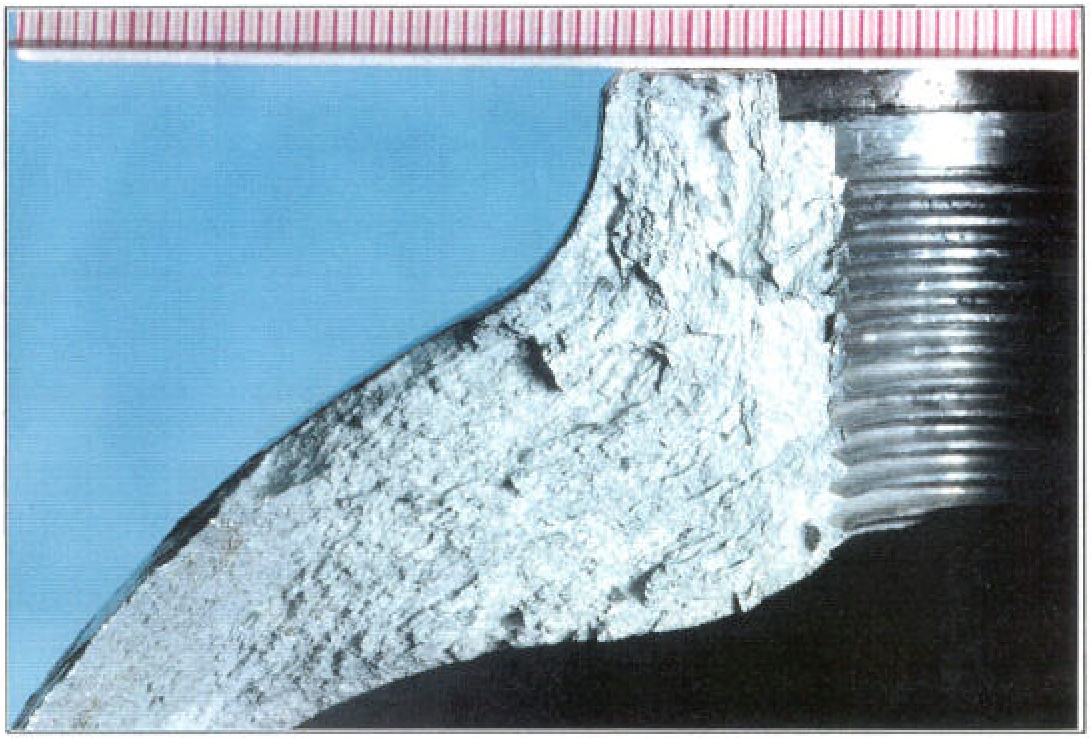

FIGURE 21 CLOSE UP PHOTOGRAPH OF THE CRACKED REGION OF THE CYLINDER HEAD -- ITEM 3A

FIGURE 22 SPECIMEN FROM THE SHOULDER OF THE RUPTURED CYLINDER USED FOR MICROSCOPIC EXAMINATION

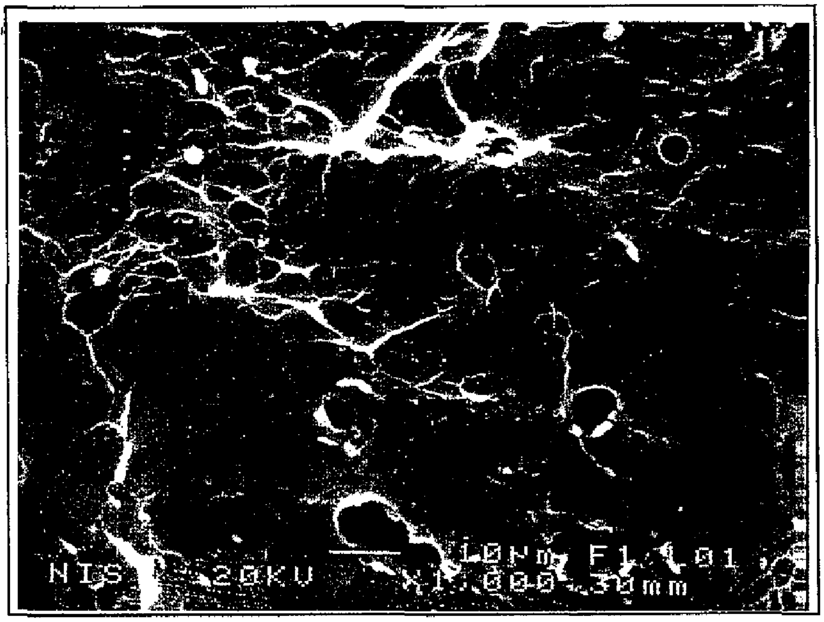

FIGURE 23 FRACTURE SURFACE OF THE SHOULDER OF THE RUPTURED CYLINDER THAT SHOWS SUSTAINED-LOAD-CRACKING (MAG. 1000X) -- ITEM 3A

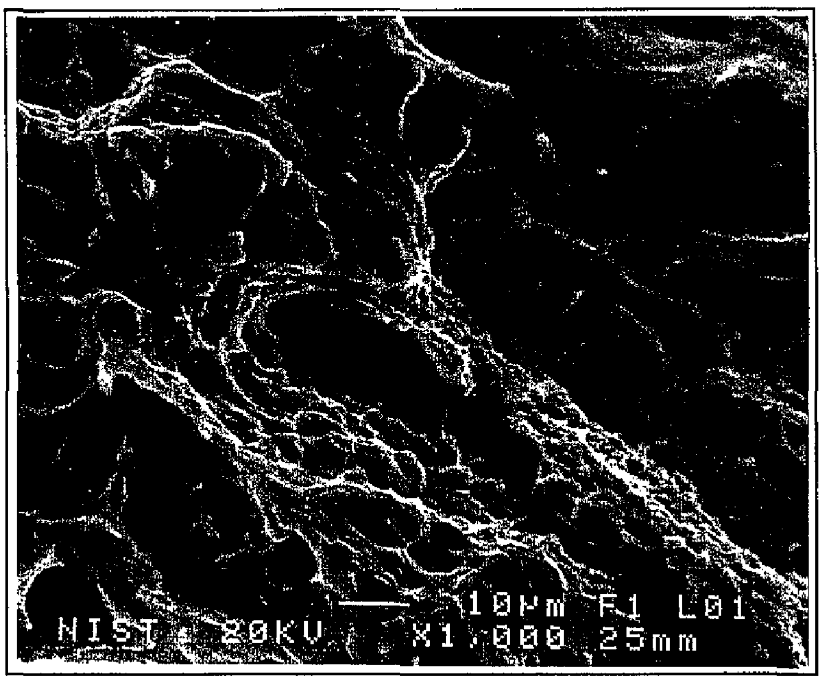

FIGURE 24 FRACTURE SURFACE OF THE SHOULDER OF THE RUPTURED CYLINDER THAT SHOWS DUCTILE TEARING TYPE OF FRACTURE (MAG. 1000X) -- ITEM 3A