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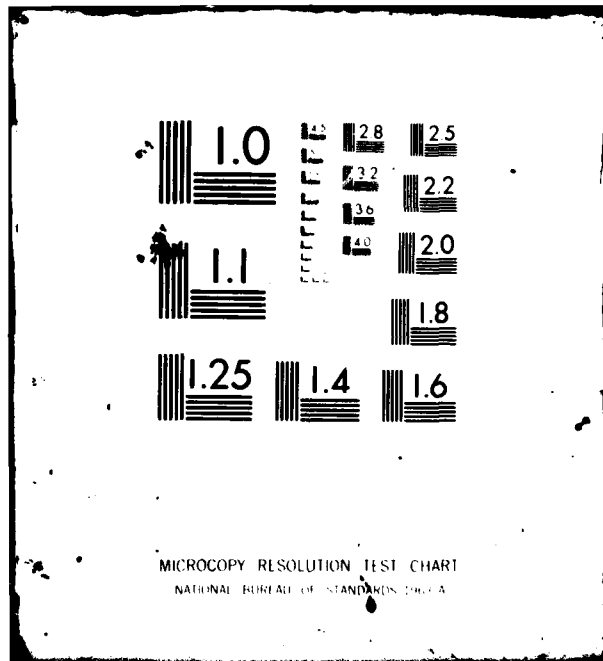
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ENGINEERING MODELS OF BALLISTIC PERFORATION AT HIGH VELOCITIES. (U)  
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| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                      | READ INSTRUCTIONS<br>BEFORE COMPLETING FORM                                             |
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| 20. Abstract<br>This report presents the results of ballistic tests consisting of 10 shots of long rod penetrators, made from SAE 4140 steel, on target plates: 50.8mm and 75.0 mm thick PHA, and 133.5mm 5083 H-115 aluminum. Impact and residual velocities as well as residual length of the penetrator have been measured. The target plates were sectioned and etched around the perforation cavities and subjected to close inspection. Mechanical properties of penetrator and targets were measured and a split Hopkinson pressure bar arrangement has been set up.<br><br>A new five stage engineering model of perforation of a metal target by a rigid projectile has been developed which does not rely on empirical factors. |                                      |                                                                                         |

Abstract

This report presents the results of ballistic tests consisting of 10 shots of long rod penetrators, made from SAE 4140 steel, on target plates: 50.8 mm and 75.0 mm thick RHA, and 133.5 mm 5083 H-115 aluminum. Impact and residual velocities as well as residual length of the penetrator have been measured. The target plates were sectioned and etched around the perforation cavities and subjected to close inspection. Mechanical properties of penetrator and targets were measured and a split Hopkinson pressure bar arrangement has been set up.

A new five stage engineering model of perforation of a metal target by a rigid projectile has been developed which does not rely on empirical factors.

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The main effort during this period was devoted to detailed examination of the results of a series of ballistic tests. These tests consisted of 10 shots of specially prepared long rod penetrators made from SAE 4140 steel (Note: not SAE 4340 steel as erroneously reported in the previous Annual Technical Report of Sept. 1979) on target plates of homogeneous armor steel (RHA) and 5083-H115 aluminum alloy. Thicknesses of the RHA plates were 75.0 mm and 50.8 mm and the aluminium target consisted of 3 plates in contact, each of 44.5 mm, for a total thickness of 133.5 mm. Impact was normal to the plate with impact velocities ranging from 1356 to 1560 m/s. Eight of the shots were successful in supplying useful information.

The tests were conducted in a well instrumented ballistic range which provided pre-impact velocity measurements by photo-cells and X-ray photographs of the projectile immediately prior and after perforation by flash radiographic equipment. After completion of the ballistic tests, the target plates were sectioned and etched around the perforation cavities which were then subjected to close inspection. Mechanical property tests were also made on the projectile and target materials. Since the perforation process occurs at very high rates of loading, mechanical properties at those rates would be useful in the analytical modelling. This data can be obtained by means of a split Hopkinson pressure bar (Kolsky bar).

A split Hopkinson pressure bar arrangement for longitudinal loading has been built. The loading is achieved by firing a short cylinder against the free end of the loading bar. Instead of using an air gun to drive the

projectile, a rifle whose barrel was replaced by a thick walled cylinder ( $3/4"$  I.D.) is being used. The velocity of the projectile, which is controlled by varying the amount of powder in the cartridge, is measured just prior to impact by a photocell. Plane impact is ensured by inserting the ( $1/2"$   $\phi$ ) loading bar slightly into the barrel where the projectile is still guided.

Most of the experimental work with the Hopkinson bar until now has been to eliminate the noise from the measuring system. These efforts seem to have been successful and the recorded pulses are fairly "clean".

A second type of Hopkinson bar; a torsional or Kolsky bar, is being built. It has a simple loading device for introducing the torque into the loading bar and is expected to be ready for use during the coming year of research.

The output signals from the strain-gauges bridges are recorded in a digital oscilloscope (Explorer II, by Nicolet). Presently the signals are transferred to an XY recorder to be analyzed manually. A proper interface has been ordered recently (IEEE-488), which will enable us to transfer the recorded pulse directly from the oscilloscope to a minicomputer for further analysis.

When the measured residual velocities following perforation are extrapolated to zero by an analytical procedure, an estimate could be obtained for the ballistic limit velocity,  $V_L$ , for the projectile and the various target plates. For the steel plates,  $V_L$  for the 75.0 mm thickness was obtained

to be 1325 m/s, while that of the 50.8 mm steel target plate was  $V_L = 1150$  m/s. In the case of the aluminium targets, the test data was not sufficient for a reasonable estimate of  $V_L$ .

Some of the more important results of the various tests and examinations are attached to this report as an Appendix. The attached figures and tables consist of the following:

Fig. 1 - Geometry of projectile of SAE 4140 steel.

Table I - Penetrator: Material composition.

Table II - Penetrator: Mechanical properties.

Table III - Target plates: Mechanical properties.

Table IV - Projectile velocity characteristics prior to impact.

Table V - Contact time, residual velocity, and physical and geometrical characteristics after perforation.

Table VI - Dimensions of projectile entrance and exit holes in the target plates.

Figs. 2,3 - Cavity profiles in steel target plates showing hardness ( $R_c$ ) measurements.

Fig. 4 - Cavity profile in an aluminium target.

Fig. 5 - Hole profile after perforation of 50.8 mm RHA target.

Fig. 6 - Hole profile after perforation of 75 mm RHA target.

Fig. 7 - Hole profile after perforation of 133.5 mm AL 5083 H-115 target.

Fig. 8 - Hole profile after perforation of 133.5 mm AL 5083 H-115 target.

Fig. 9 - Characterization of the final deformation and hole dimension for Table VII.

Table VII - Characteristic parameters measured for defining the final target deformation.

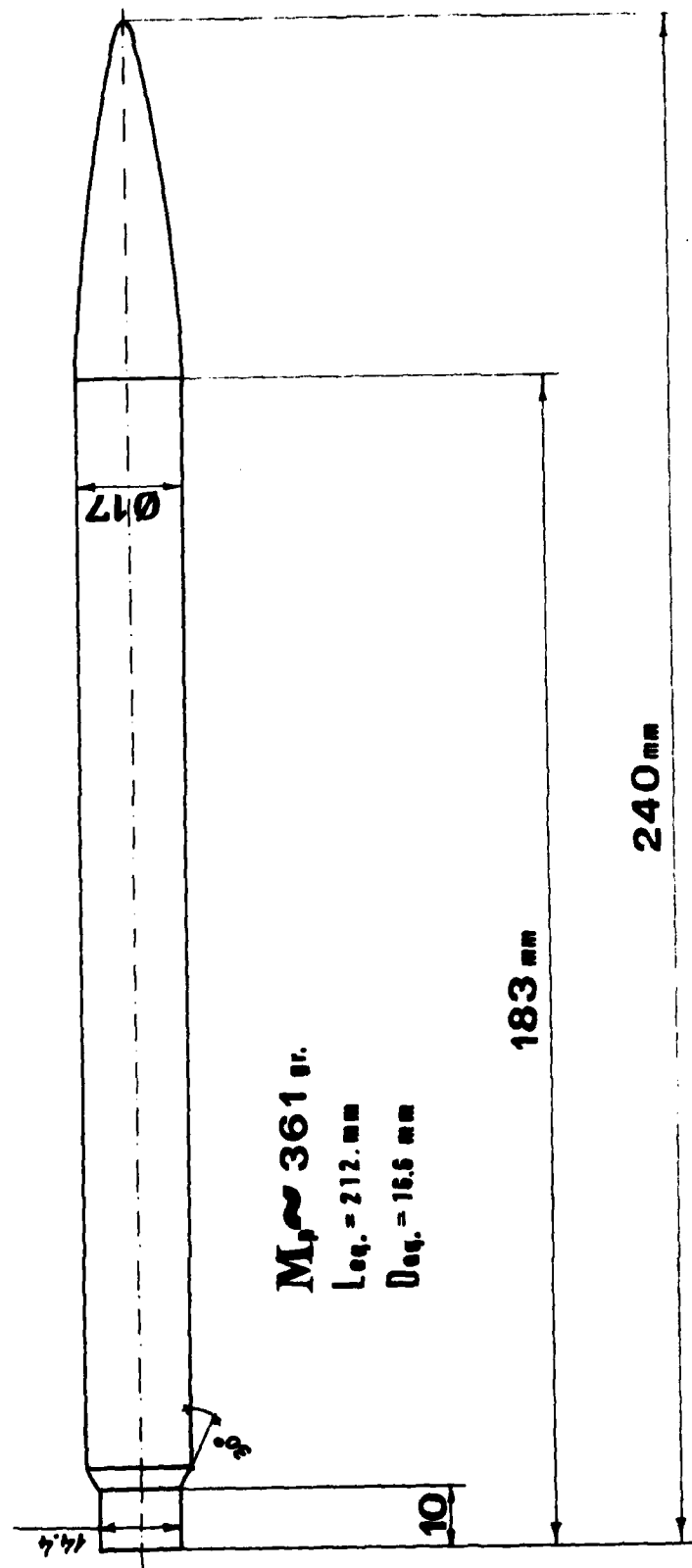
This examination of the results of the ballistic tests is intended to serve as a physical basis and motivation for the development of an engineering model of the perforation process at high impact velocities. The test results, especially the residual velocities and residual projectile lengths, will also serve as reference data for subsequent comparison with analytical predictions. The model would include the effects of erosion of the projectile and of plastic deformation and inertia of the projectile and target.

At the present time, a new five stage engineering model of perforation of a metal target by a rigid projectile has been developed. The initial stage relies on an assumed velocity field for a plastically deforming medium with a moving boundary (the indenter), where the unknown parameters are determined from the upper bound theorem of plasticity modified to include dynamic effects. Subsequent deformation stages include the development of a bulge at the rear surface of the target, the extension of the bulge, the development of a plug and a shear zone, and the ejection of the projectile and plug following material failure. This model is an improvement over that of Awerbuch and Bodner as it does not rely on any empirical factors and is more suitable for extension to the case of projectile erosion.

A paper describing this model is presently being prepared for publication (by Ravid and Bodner).

The personnel who worked on the research program during this period are: - Prof. S.R. Bodner, Assoc. Prof. J.M. Lifshitz, and Mr. Moshe Ravid and Mr. Ezra Scher, graduate students.

Figure 1 : - STEEL S.A.E - 4140  
PENETRATOR



**Table I** : Penetrator Material Description. SAE 4140 [EN 19A]

| Symbol | C    | Si   | Mn   | P     | S     | Cr   | Mo   |
|--------|------|------|------|-------|-------|------|------|
| [%]    | 0.41 | 0.21 | 0.72 | 0.015 | 0.022 | 1.06 | 0.22 |

**Table II** : Mechanical Properties of Penetrator Material.

| Yield Stress<br>$\sigma_p$ | Ultimate Stress<br>U.T.S. | Elongation<br>$\epsilon_{max}$ | Impact Test<br>IZOD  |
|----------------------------|---------------------------|--------------------------------|----------------------|
| $Kg \cdot f/mm^2$          | $Kg \cdot f/mm^2$         | %                              | $Kg \cdot f \cdot m$ |
| 78 - 80                    | 90 - 91                   | 22 - 24                        | 11 - 13              |

**Table III** : Target Plates and Mechanical Properties of Target Material.

| Plate Material | Plate Thickness | Mechanical Properties - (*) |                   |                  |
|----------------|-----------------|-----------------------------|-------------------|------------------|
|                |                 | Yield Stress                | Ultimate Stress   | Max. Strain      |
|                | T               | $\sigma_p (\sigma_{0.2})$   | U.T.S.            | $\epsilon_{max}$ |
|                | mm              | $Kg \cdot f/mm^2$           | $Kg \cdot f/mm^2$ | %                |
| R.H.A. (**)    | 50.8            | 86                          | 97-98.7           | 15.1-15.3        |
| R.H.A. (**)    | 75              | 80-85                       | 91.3-98.6         | 15.3             |
| AL-5083 H-115  | 44.5            | 11-12                       | 26.2-28.2         | 15.8-18.3        |

(\*) At Strain-Rate of  $\sim 0.1 \text{ Sec}^{-1}$  for Steel and  $\sim 0.6 \text{ Sec}^{-1}$  for Aluminum Plates (obtained on M.T.S. machine, 25 ton capacity).

(\*\*) According to MIL-S-12560B (ORD)

Table IV : Summary of Before Target Penetration Results and Analysis.

| Round Number | Target Description. | Striking Velocity (m/sec)   |                             |                        | Trajectory Components (Degree) |          | Impact Angle (Degree Rotation) | Yaw Components (Degree) |          | Yaw Angle (Degree) |
|--------------|---------------------|-----------------------------|-----------------------------|------------------------|--------------------------------|----------|--------------------------------|-------------------------|----------|--------------------|
|              |                     | Photo-electric Cell Results | Flash X-ray Average Results | Mean Striking velocity | Horizon-tal                    | Vertical |                                | Horizontal              | Vertical |                    |
| 11           | 75 mm               | 1560                        | 1550                        | 1555                   | -0.29                          | 0.87     | ~ 1                            | 0.22                    | 0.04     | 0.23               |
| 12           | R.H.A.              | 1430                        | 1454                        | 1442                   | -                              | 0.74     | ~ 1                            |                         | 0.25     | ~ 0.3              |
| 13           |                     | 1357                        | 1355                        | 1356                   | -0.06                          | 0.82     | ~ 1                            | -0.55                   | -0.6     | 0.7                |
| 14           | 50.8mm              | 1560                        | 1549                        | 1555                   | -0.31                          | -        | ~ 1                            | 0.74                    | -        | ~ 0.8              |
| 15           | R.H.A.              | -                           | 1461                        | 1461                   | 0.39                           | -        | ~ 1                            | 0.08                    | -        | ~ 0.1              |
| 16           |                     | 1390                        | 1383                        | 1387                   | -0.61                          | -        | ~ 1                            | -0.4                    | -        | ~ 0.4              |
| 19           | 133.5mm             | -                           | 1560                        | 1560                   | -                              | 1.03     | ~ 1                            | -                       | 0.72     | ~ 0.8              |
| 20           | AL5083              | 1391                        | 1387                        | 1388                   | -0.64                          | 0.84     | ~ 1                            | 0.12                    | 0.15     | 0.2                |

Table V : Summary of After Target Perforation Results and Analysis.

| Round Number | Target Description | Penetration Duration (10 <sup>-6</sup> sec) | V <sub>R</sub>            |  | Vertical Trajectory Component (Degree) | Vertical Yaw Component (Degree) | L <sub>R</sub> | M <sub>R</sub> | Penetrator front Deformation |                               |
|--------------|--------------------|---------------------------------------------|---------------------------|--|----------------------------------------|---------------------------------|----------------|----------------|------------------------------|-------------------------------|
|              |                    |                                             | Residual Velocity (M/sec) |  |                                        |                                 |                |                | H <sub>f</sub> Length (mm)   | D <sub>jf</sub> Diameter (mm) |
| 11           | 75mm               | 159                                         | 1342                      |  | -0.8                                   | 0.2                             | 96             | 197            | 12                           | 24                            |
| 12           | R.H.A.             | 239                                         | 1117                      |  | -3.1                                   | 22.9                            | 65             | 117            | 12                           | 19                            |
| 13           |                    | 350                                         | 215                       |  | 7.7                                    | -39                             | 25             | 102            | Plug P.L. 13                 | Plug P.D. 19                  |
| 14           | 50.8mm             | 135                                         | 1405                      |  | -0.6                                   | 3.3                             | 146            | 296            | 9                            | 25                            |
| 15           | R.H.A.             | 163                                         | 1310                      |  | -0.5                                   | 7                               | 129            | 255            | 10                           | 20                            |
| 16           |                    | 182                                         | 1240                      |  | -0.8                                   | 1.8                             | 130            | 259            | 9                            | 23                            |
| 19           | 133.5mm            | 244                                         | 1390                      |  | 1.1                                    | -4.3                            | 138            | 303            | 10                           | 23                            |
| 20           | AL5083             | 270                                         | 1218                      |  | 0.1                                    | 0.4                             | 136            | 270            | 14                           | 22                            |

H<sub>f</sub> - Length of forward end of penetrator that is subjected to appreciable plastic deformation.

D<sub>jf</sub> - Maximum diameter of plastically deformed forward end of projectile.

Table VI - Summary of Target Hole Dimension Measurements

| Round Number | Target Description | D <sub>i</sub><br>Target Entrance Hole Average Diameter (mm) | D <sub>e</sub><br>Target Exit Hole Average Diameter (mm) | Exit Circumferential Fracture            |                                       |
|--------------|--------------------|--------------------------------------------------------------|----------------------------------------------------------|------------------------------------------|---------------------------------------|
|              |                    |                                                              |                                                          | D <sub>fr</sub><br>Average Diameter (mm) | P <sub>fr</sub><br>Average Depth (mm) |
| 11           | 75mm               | 20                                                           | 37                                                       | 61                                       | 16                                    |
| 12           | R.H.A.             | 19                                                           | 36                                                       | 58(Partial)                              | 11                                    |
| 13           |                    | 20                                                           | 37                                                       | 49(Partial)                              | 10                                    |
| 14           | 50.8mm             | 19                                                           | 35                                                       | 55                                       | 9                                     |
| 15           | R.H.A.             | 20                                                           | 36                                                       | 57                                       | 8                                     |
| 16           |                    | 20                                                           | 35                                                       | 47                                       | 9                                     |
| 19           | 133.5mm AL5083     | Depth<br>44.5<br>89<br>133.5                                 | 27<br>38<br>48                                           | Ductile Exit                             |                                       |
| 20           | 133.5mm AL5083     | 44.5<br>89<br>133.5                                          | 22<br>34<br>39                                           | Ductile Exit                             |                                       |

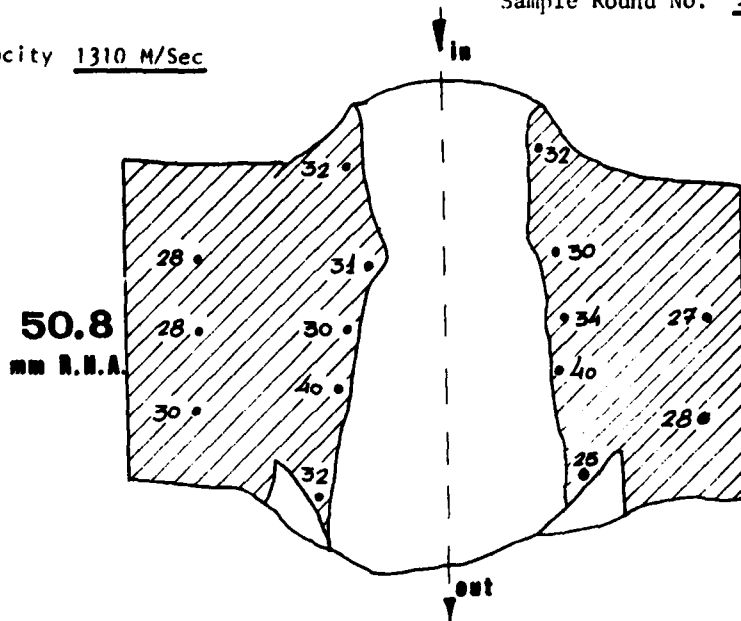
\* D<sub>fr</sub> - Maximum diameter of circumferential fracture region surrounding exit hole (circumferential avg.).

\*\* P<sub>fr</sub> - Depth from rear surface of circumferential fracture region surrounding exit hole (circum. avg.).

Striking Velocity 1461 M/Sec

Sample Round No. 15

Residual Velocity 1310 M/Sec

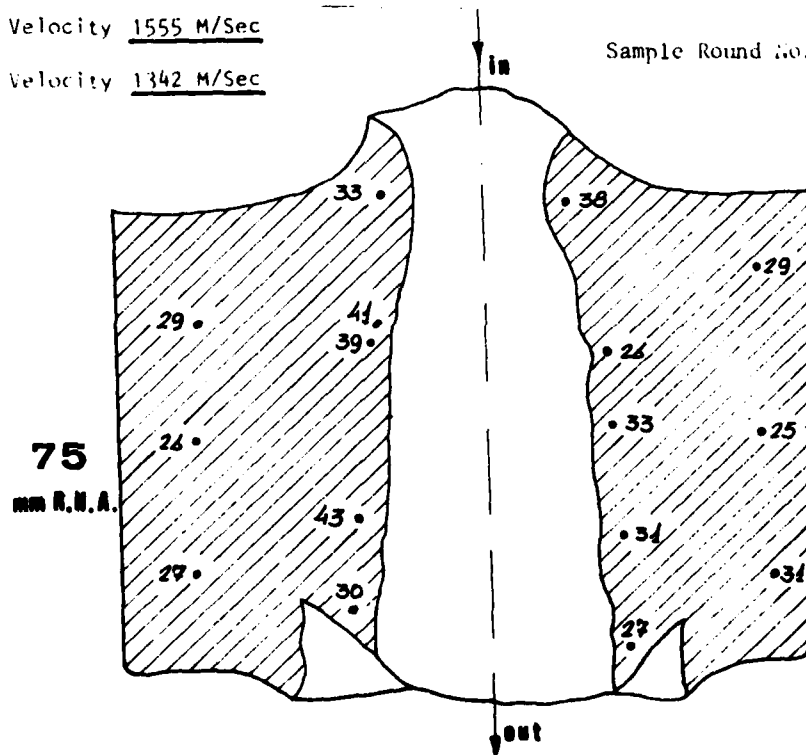


**Figure 2** : Hole Profile After Perforation of 50.8 mm R.H.A Target and Hardness Test (HRC) Measurements.

Striking Velocity 1555 M/Sec

Sample Round No. 11

Residual Velocity 1342 M/Sec



**Figure 3** : Hole Profile After Perforation of 75 mm R.H.A. Target and Hardness Test (Rc) Measurements.

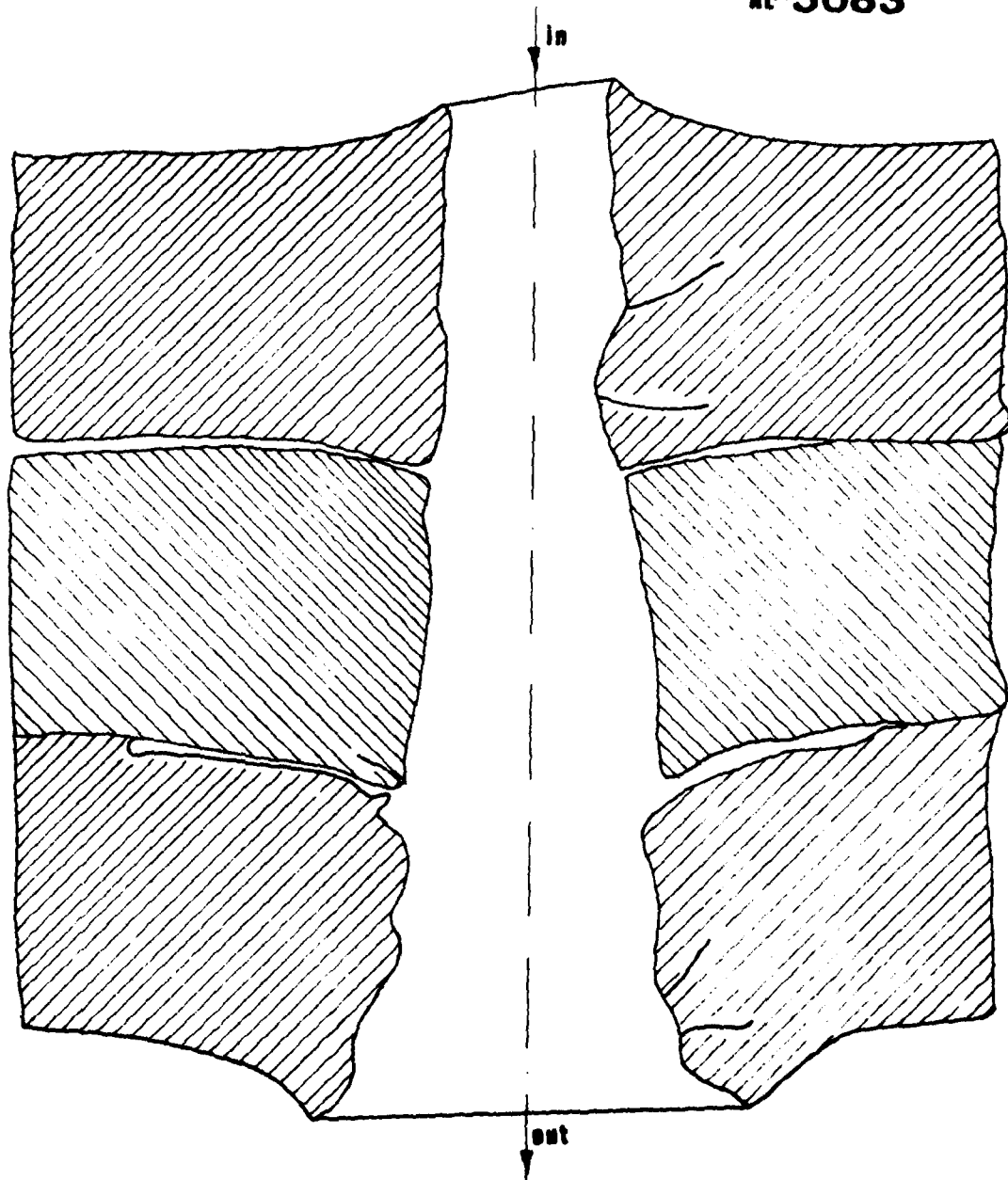
Striking Velocity 1560 M/Sec

Sample Round No. 19

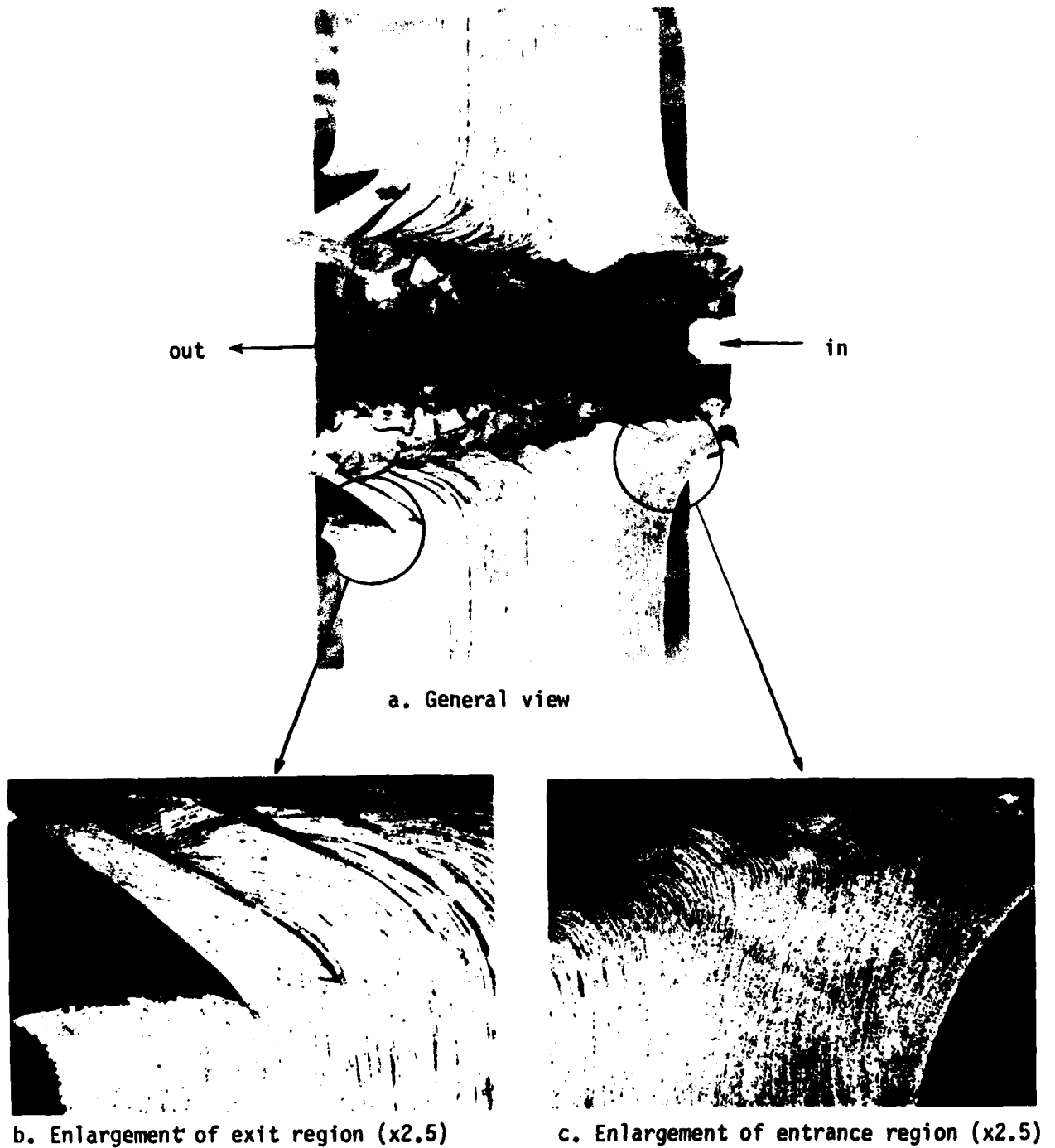
Residual Velocity 1390 M/Sec

**133.5 mm**

**AL-5083**

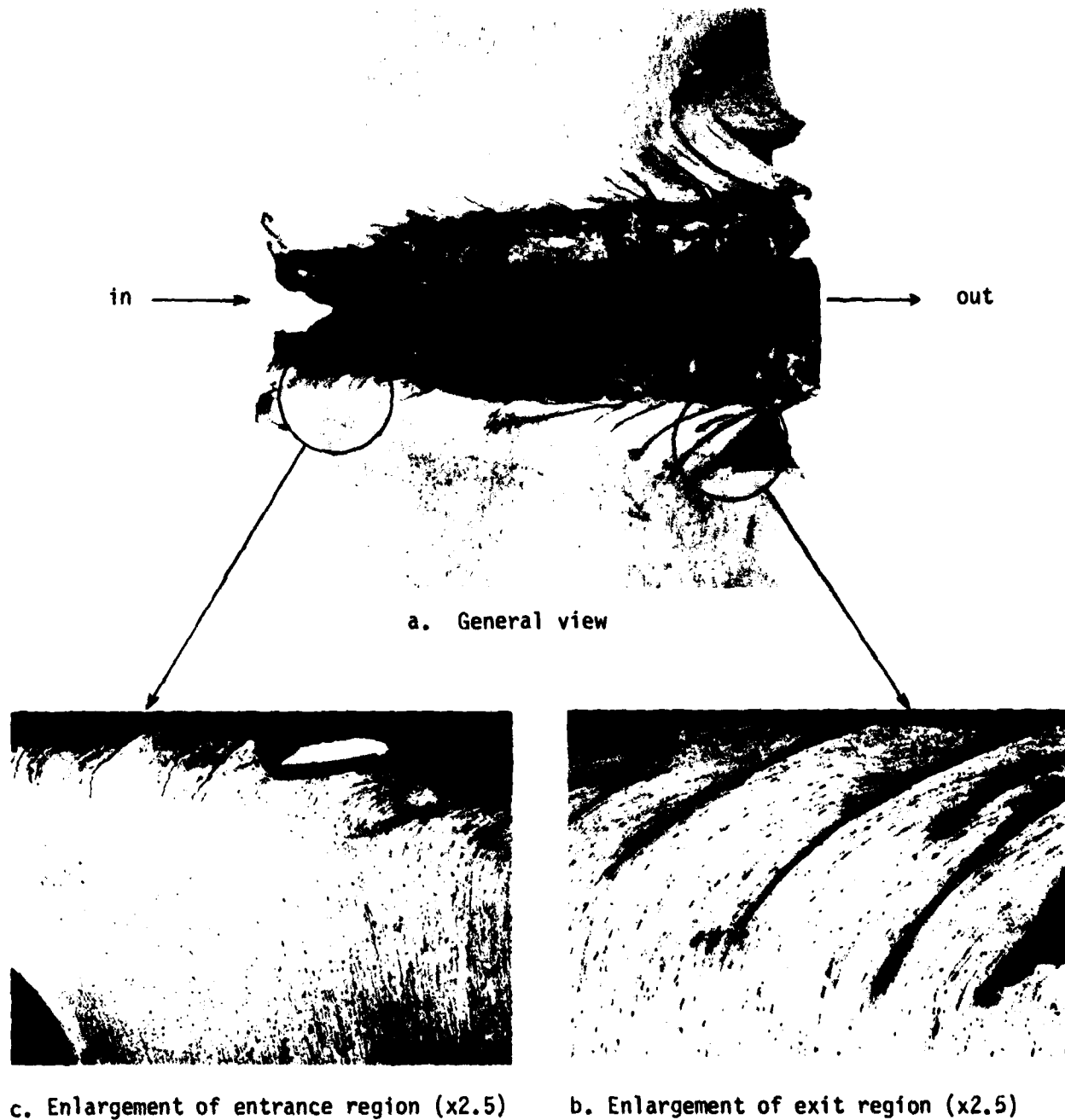


**Figure 4** : Hole Profile, After Perforation of 133.5 mm AL 5083 H-115  
Target (3 x 44.5 mm)



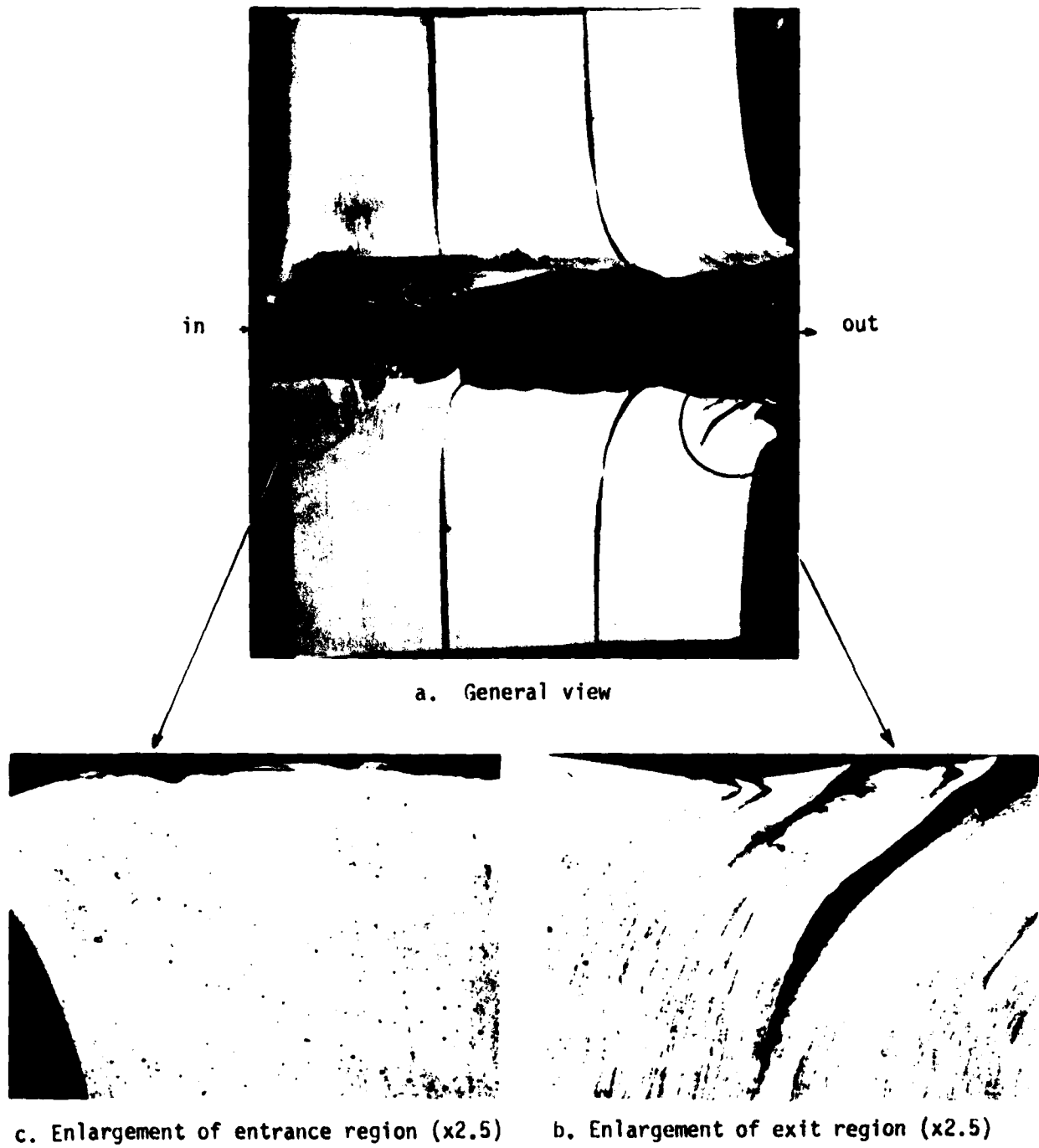
Etching: boiling 50% HCl

**Figure 5:** Hole profile after perforation of 50.8 mm R.H.A. target.  
(Round No. 15;  $V_s = 1461$  m/sec;  $V_R = 1310$  m/sec;  $L_R = 129$  mm)



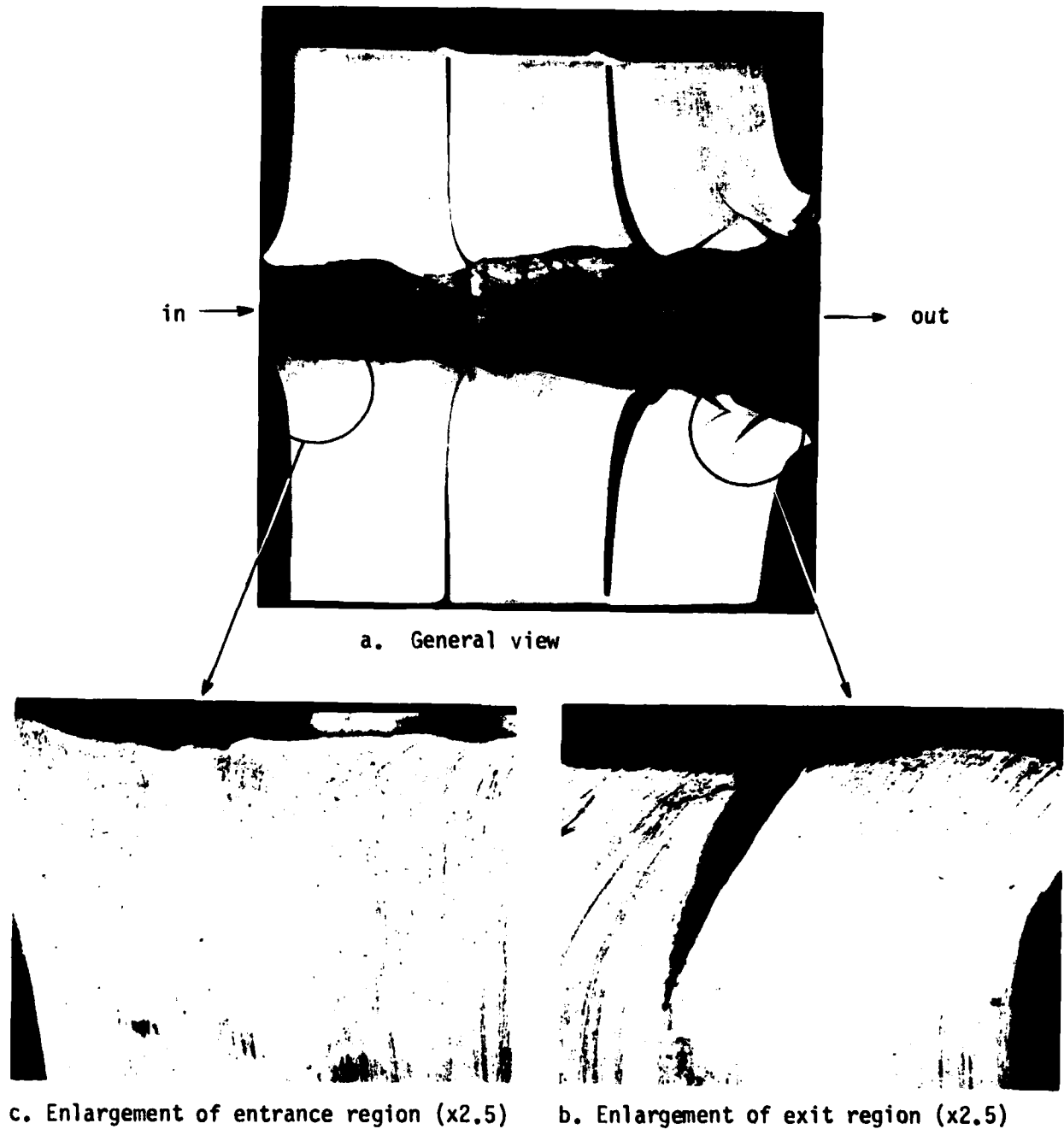
Etching: boiling 50% HCl

Figure 6: Hole profile after perforation of 75 mm R.H.A. target.  
(Round No. 11;  $V_s = 1555$  m/sec;  $V_R = 1342$  m/sec;  $L_R = 96$  mm)



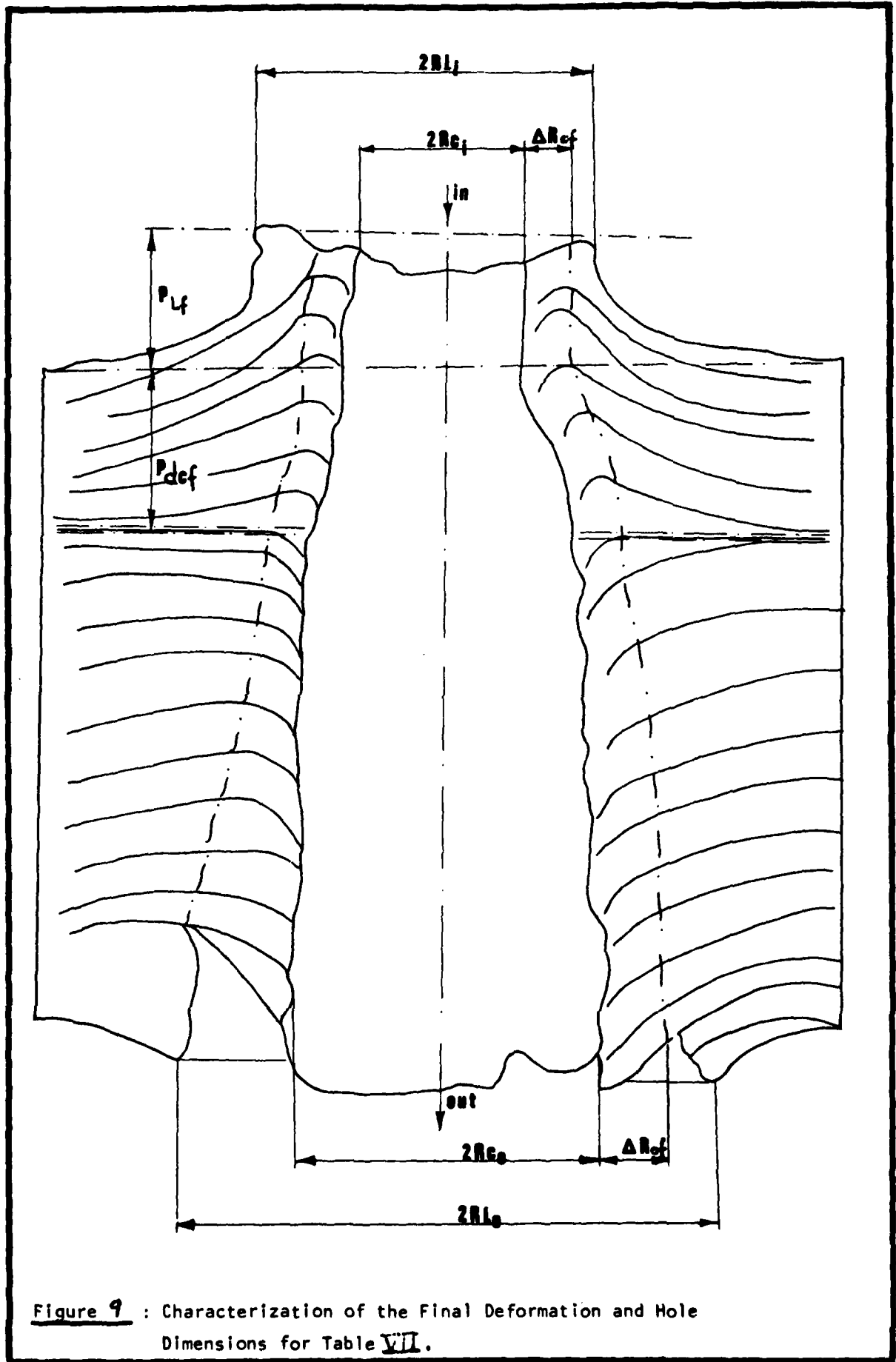
Etching: Feric Chloride + HCl + Alcohol

**Figure 7:** Hole profile after perforation of 133.5 mm Al 5083 H-115 target.  
(Round No. 20;  $V_s = 1388$  m/sec;  $V_R = 1218$  m/sec;  $L_R = 136$  mm)



Etching: Feric Chloride + HCl + Alcohol

**Figure 8:** Hole profile after perforation of 133.5 mm AL 5083 H-115 target.  
(Round No. 19;  $V_s = 1560$  m/sec;  $V_R = 1390$  m/sec;  $L_R = 138$  mm)



**Figure 9** : Characterization of the Final Deformation and Hole Dimensions for Table **VII**.

**Table VII:** Characteristic Parameters Measured for Defining the Final Target Deformation.

| Round Number | Target Description | Entrance Lips- $P_{Lf}$<br>(mm) | Depth of Entrance Deformation- $P_{def}$<br>(mm) | Radial Clearance for Sheared Regions (mm) |                         |
|--------------|--------------------|---------------------------------|--------------------------------------------------|-------------------------------------------|-------------------------|
|              |                    |                                 |                                                  | $\Delta R_{cf}$<br>Entrance               | $\Delta R_{of}$<br>Exit |
| 15           | 50.8mm<br>R.H.A.   | 8.8 - 10.8                      | 11.1 - 14.8                                      | 3.4                                       | 8.3- 8.4                |
| 11           | 75mm<br>R.H.A.     | 9.0 - 12.1                      | 13.4 - 15.9                                      | 3.5-4.5                                   | 10.4-10.8               |
| 20           | 133.5mm<br>AL5083  | 7.8 - 10.4                      | 17.8 - 18.0                                      | 5.1                                       | 12.6-14.1               |
| 19           |                    | 9.5 - 11.5                      | 19.9 - 20.7                                      | 5.8-6.5                                   | 11.6-12.9               |

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