A gas leak was detected on a 56-in. (1.4-m) cross-country underground gas pipeline from a small orifice on the bottom of an indentation. The pipeline had an epoxy primer and a hot polyethylene coating, and was only four years old. Metallurgical tests on the hole and theoretical calculations indicated that the pipeline had been penetrated by a bullet before being coated. This may be the first such case recorded, and would have been difficult to prove if an explosion had taken place.

Figure 1 shows a close-up of the hole. It reveals signs of impact from a foreign object, probably a bullet, and the splashing effect of white metal around it. The straight cut line was made with a saw. After excavation and removal of the PE coating, the grey, sandblasted pipe surface started to rust upon exposure to the atmosphere, whereas the splashed metal region remained bright. The hole had a cylindrical portion measuring ~12 mm in diameter, and had penetration of nearly 14 mm through the pipe. There was no sign of impact on the coating exterior. It was clear, therefore, that the impact had occurred before coating application.

There have been reports of an above-ground pipeline being shot accidentally (e.g., the Trans-Alaska Pipeline on October 4, 2001\(^2\)). Obviously, this case is different, as the pipe was shot before coating was applied. It would have been difficult to prove this type of incident if an explosion had taken place. This case emphasizes the need for careful inspection of the pipe before being coated to prevent the incidence of such failures.

**Results**

Figure 2 shows the typical scanning electron microscopy (SEM) micrograph of the splashed region around the hole, which indicated a melted state. Some porosity and microcracks occurred in this region. Figure 3 shows SEM/energy dispersive x-ray analysis (EDXA) of this region, along with that of the adjacent unaffected surface of the pipeline for com-
parison. The close similarity of these two analyses indicate that the splashed region is composed of steel. The presence of O, Si, Ca, and Al in these regions can be attributed to the rust and other corrosion products formed from contact with atmospheric moisture. The same tests were performed on the cross-section of the splashed region. Figures 4 and 5 show a SEM micrograph and EDXA of the base steel and splashed region, respectively. The difference between the two micrographs is evident, as the base steel is in wrought condition with a uniform microstructure (Figure 4), whereas the splashed region has an irregular microstructure containing a high amount of black second-phase material, probably oxide particles (Figure 5). A comparison of EDXA of the base steel and the splashed regions in Figures 4 and 5 indicate that the steel in the splashed region is made from the base steel.

Figure 6 shows an optical micrograph of the splashed region cross-section in unetched condition. Three different zones are evident from this micrograph—a banded bottom layer, a homogenous grey middle layer, and a top white layer. The banded bottom layer is the typical base steel microstructure; the homogenous middle layer consists of martensite and lower and upper bainite (i.e., heat-affected zone [HAZ]); and the top layer is made from high-carbon martensite.

Figure 7 shows the results of microhardness profile measurements on these regions, including the change in hardness from the base to the HAZ and splashed region. There is a gradual increase in hardness of the base metal (from ~200 hardness, Vickers [HV]) to the HAZ region (~400 HV), and an abrupt increase in hardness in the top or splashed region (>400 HV). These results support the theory that the high-energy impact of a steel bullet was involved. The energy of the bullet was high enough to penetrate ~14 mm into the steel and produce the liquid steel that is splashed around the hole. The heat of the impact caused a HAZ region similar to a welding process. The maximum hardness of ~400 HV in the HAZ is compatible with the hardness

![FIGURE 1](image1.png) Evidence of the impact of a foreign object on a gas pipeline.

![FIGURE 2](image2.png) SEM micrograph of the splashed region around the hole.

![FIGURE 3](image3.png)

### Table 1: EDXA Results

<table>
<thead>
<tr>
<th>Element</th>
<th>K Ratio</th>
<th>Wt%</th>
<th>At%</th>
</tr>
</thead>
<tbody>
<tr>
<td>O K</td>
<td>0.0631</td>
<td>6.307</td>
<td>18.367</td>
</tr>
<tr>
<td>Al K</td>
<td>0.0137</td>
<td>1.372</td>
<td>2.369</td>
</tr>
<tr>
<td>Si K</td>
<td>0.0228</td>
<td>2.276</td>
<td>3.775</td>
</tr>
<tr>
<td>Ca K</td>
<td>0.0111</td>
<td>1.110</td>
<td>1.290</td>
</tr>
<tr>
<td>Fe K</td>
<td>0.8894</td>
<td>88.936</td>
<td>74.199</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100.000</td>
<td>100.000</td>
</tr>
</tbody>
</table>

(a) : SEM/EDXA of splashed region, b) SEM/EDXA of the region adjacent to the splashed region (unaffected surface of the pipeline).
The splashed steel cooled rapidly and transformed to martensite, along with super-cooled steel. The high hardness of >1,000 HV in the splashed region is related to the very high cooling rate experienced by the splashed liquid, which causes amorphous steel with unusual properties such as hardness and corrosion resistance. This can also explain why the surface of the hole would not rust upon exposure to the atmosphere, as was mentioned earlier.

In order to prove that the incident was caused by a gunshot, the following calculation was made: A steel bullet from a typical weapon measures 12.5-mm in diameter, has a weight of \( M = 40 \) grams, and has a velocity of \( V = 850 \) m/s. The kinetic energy of the bullet (0.5 \( MV^2 \)) is equal to 14,450 J. Taking the average specific heat of low-carbon steel, \( C_p = 473 \) J/kg·K, and the latent heat of Fe fusion at its melting point, \( H = 254.9 \) J/g, the bullet energy is equal to thermal energy required to melt 15.8 g of steel.

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**References**

FIGURE 7

Microhardness profile measurements of the three regions shown in Figure 6.


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