Metallurgical Analysis of High Pressure Gas Pipelines Rupture

F. Hasan[1] and F. Ahmed[1]

[1] *Department of Metallurgical and Materials Engineering, University of Engineering and Technology Lahore.*

Abstract

On 6 July 2004, two parallel-running gas pipelines (18-inch and 24-inch diameters), in the main transmission network of SNGPL (a gas company in Pakistan) were ruptured. The ruptures occurred in the early hours of the morning about 8 miles downstream of the compressor station AC-4. The ruptures were indicated by the increased gas flow at the outlet of AC-4 [1], first at about 0648 hours and then again about 20 minutes later. The gas escaping from the ruptured lines had caught fire, and the flames had also 'affected' a third parallel-running pipeline of 30-inch diameter, lying next to the 24-inch line.

The metallurgical examination of the two ruptured lines showed that the 24-inch line was ruptured with the help of an explosive device that had been placed on the underside of the pipe. An examination of the 18-inch line showed that this pipe had failed as a result of the heating of the pipe-wall, presumably, by the flame emanating from the 24-inch line. These two observations clearly suggested that the 24-inch line was the first to rupture (by explosives), and the fire following this rupture had heated the 18-inch pipe to a temperature where its yield strength was unable to support the inside gas pressure. The 20 minutes time interval between the two ruptures was obviously the time taken by the 18-inch pipe to be heated upto the level where it started to yield.

The 30-inch line lying next to the 24-inch line was affected to the extent that its coating had been burnt-off over a length of about 40-50 feet. However, the pipe did not exhibit any signs of de-shaping or deformation what-so-ever. A replica metallographic examination indicated that the microstructure of the pipe was not measurably affected by the heat. It was thus decided not to replace the 'affected' part of the 30-inch pipe, but only to re-coat this affected portion.

Key words: Rupture; Fire; Yield; Polyethylene Coating

1. Introduction

Sui Northern Gas Pipeline Limited (SNGPL) of Pakistan has a large network of high-pressure gas-transmission pipelines. The main transmission lines, which supply the gas to the northern part of the country, are of 18, 24 and 30 inch diameter. For most part of the transmission network, these lines have been laid parallel to each other, at a lateral distance of about 20 ft [2].

Since January 2003, the high-pressure gas lines in Pakistan have been attacked many times by saboteurs for reasons that cannot be a part of this paper. On 6 July 2004, two parallel-running gas pipelines were ruptured in the area of Uchh-Sharif and it was suspected that the ruptures were the result of a sabotage activity. These ruptures occurred in the early hours of the morning about 8 miles downstream of the compressor station AC-4. The first rupture occurred at 0648 hours, which was indicated by an increased gas flow at the outlet of AC-4 [1]. Then, after a time interval of about 20 minutes another increase in the gas-flow was observed, indicating that a second line had also been ruptured. It took another few minutes to establish that the 18 and 24 inch diameter lines had been ruptured. An examination of the rupture site, carried out about 2 hours after the incident, showed that the gas escaping from the ruptured lines had caught fire, and the flames had also 'affected' a third pipeline of 30-inch diameter, lying next to the 24-inch line.

This paper constitutes the failure analysis of the ruptures of 18 and 24 inch diameter pipelines. The paper also includes the results of the metallurgical examination of the fire-affected

Corresponding Author: F. Hasan (drfaiz@uet.edu.pk)

30-inch diameter line, on the basis of which it was decided that it was safe not to replace the affected portion of the this line.

2. Location and Geometry of the Rupture

Figure 1 below is an illustration of the layout of the three pipelines, as well as the manner in which the 18 and 24 inch lines had ruptured. The location of the rupture was about 8 miles downstream of the Gas Compressor Station AC-4. The mechanical characteristics and the operating parameters of the two ruptured lines as well as the 30-inch diameter line are summarized in Table 1.

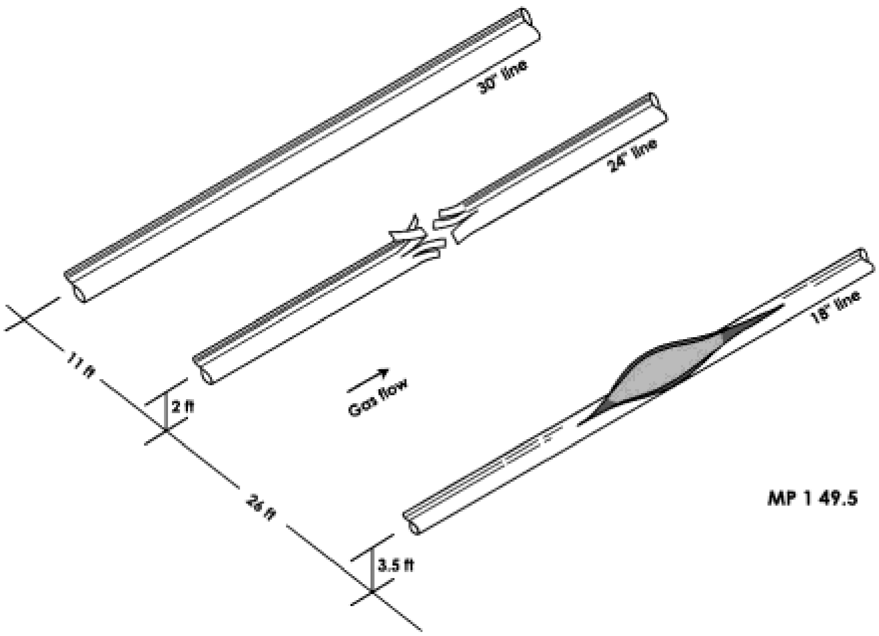


Figure 1: A schematic illustration of the layout of three pipelines, also indicating the manner in which the 18 and 24 inch lines had ruptured. The rupture-location was about 8 miles downstream of the compressor station AC-4.

Table 1: Mechanical and operating data of the Pipelines [1].

	18-inch Dia Line	**24-Inch Dia Line**	**30-Inch Dia Line**
Nominal dia of pipe	18-inch	24-inch	30-inch
Wall thickness	0.438 inch	0.438 inch	0.562 inch
Grade	Carbon Steel Yield = 52,000 psi UTS = 68,000 psi	Carbon Steel Yield = 56,000 psi UTS = 71,000 psi	Carbon Steel Yield = 60,000 psi UTS = 75,000 psi
Operating Pressure (max)	1440 psig	1440 psig	1440 psig
Pressure (line tested at)	2160 psig	1840 psig	2020 psig
Discharge Pressure at AC-4 (at the time of first rupture)	1100 psig	1100 psig	1100 psig
Date of Commissioning	Jan 1995	Oct 1987	May 1993
Type of Coating	Bitumen	Bitumen	P.E. Coating
Horizontal Distance between lines	26 ft. between 18″ and 24″		11 ft. between 24″ and 30″
Vertical Distance between lines	18″ line was 1.5 ft. above the 24″ line		30″ line was 2.0 ft. below the 24″ line

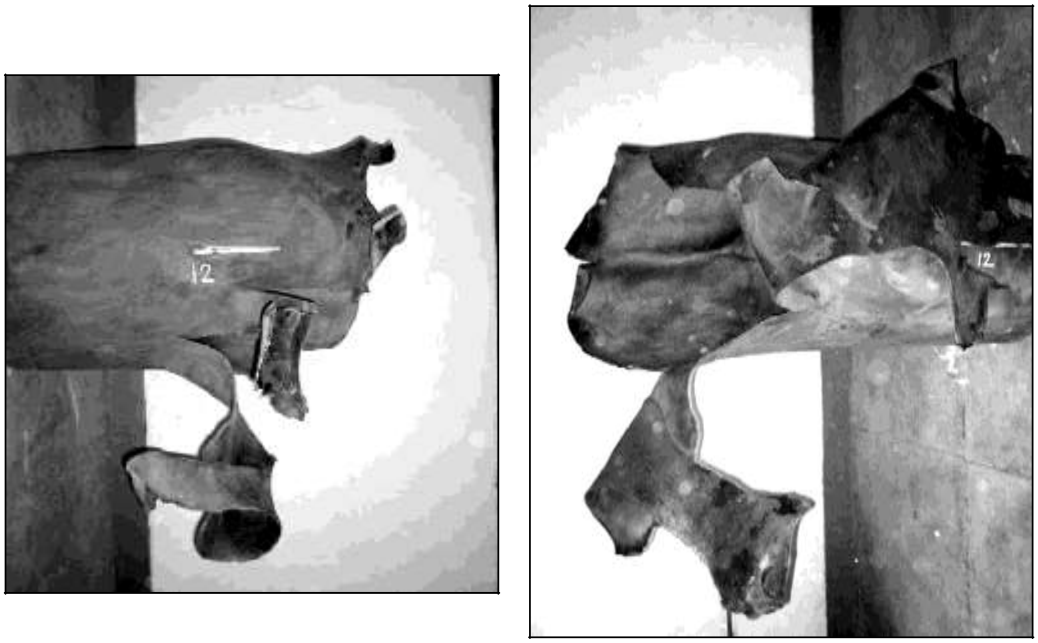


Figure 2: Photographs of the two broken ends of the 24-inch pipe, taken from the 12 o'clock angle.

3. 24-inch Diameter Pipeline

The geometrical configuration of the 24-inch diameter ruptured line is illustrated in Figure 1, while the photographs of the broken ends of this pipe are given in Figure 2. As indicated by Figures 1 and 2, the 24-inch pipe had broken apart by the force of the blast. The inward 'dents' at the 7 o'clock position* on both the broken ends of the pipe indicated that the explosive device had been placed beneath the pipe. Figure 3 shows the 7 o'clock position dent on one of the broken ends. (*The clock position represents the position of the pipe section looking along the gas-flow.)

An interesting feature of the rupture may be noticed in the photograph shown in Figure 4. This portion of the 24-inch pipe approximately corresponds to 1 o'clock position, i.e. almost exactly opposite to the 7 o'clock. An outward dent observed at this location suggests that either a portion of the explosive device or a part of the broken pipe from the lower side of the pipe had gone on to hit the opposite (upper) wall of the pipe from inside. It may be mentioned that no broken part of the pipe or any foreign object was recovered either from the site or from inside the pipe.

A closer examination of the entire fracture surface revealed that if the cracked and bent (or folded) portions of the two pipe-ends (shown in Figure 2) were straightened and matched with each other, it would be found that the pipe had lost no material from its walls. Further, it would be revealed that the underside of the pipe had cracked both longitudinally as well as circumferentially by the blast, and that the cracked portions there-from had gone on to hit the upper wall from inside producing the dent seen in Figure 4.

The regions around the fracture show severe bending (or denting) of the pipe-wall, as may be seen in Figures 2, 3, and 4. The geometrical configuration of the ruptured pipe provides considerable information about the forces/stresses involved in the fracture. A careful analysis of the broken edges of the rupture opening clearly reflects that such a damage to the pipe could not be the result of excessive gas pressure, or any shortcoming or fault in the pipe material. On the contrary, a logical interpretation of the heavily bent broken edges is that the pipe was attacked by some explosive device planted on the pipe.

On the basis of above observations, it has been concluded that the rupture of the 24-inch line was caused by an explosive device placed beneath the pipe at about 7 o'clock position.

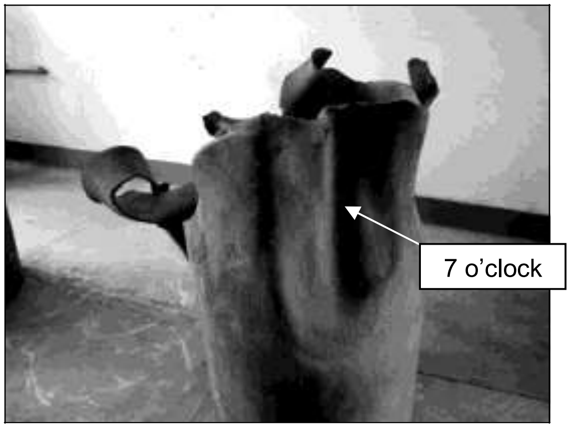


Figure 3: The large 'inward dent' at 7 o'clock position on the 24-inch ruptured pipe.

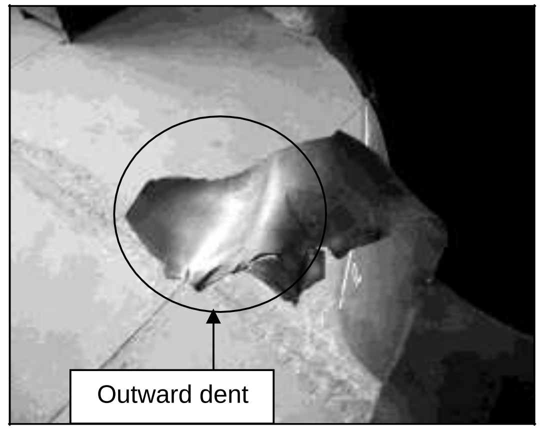


Figure 4: The outward dent at about 1 o'clock position on the 24-inch pipe

4. 18-inch Diameter Pipeline

A schematic illustration of the rupture of 18-inch line has been given above in Figure 1. Photographs of the ruptured pipe are given in Figure 5. As shown by the Figures 1 and 5, the pipe had fractured longitudinally, with the crack located at about 10.30 o'clock position.

The most significant feature of the fracture surface, as shown in Figure 5(b), was the thinning of the fracture-edge over a length of about 24 inches. The circumferential perimeter of the pipe at the location of thinned wall was measured to be 147 cm, while that measured at the un-cracked region was 144 cm. These observations clearly suggest that the pipe had yielded plastically before fracturing under the influence of the inside gas pressure.

It was imperative to suspect that the localized plastic yielding of the 18-inch pipe must have been connected to the flame from the 24-inch pipe. In order to verify this, samples taken from selected locations on the affected regions of the 18-inch pipe were prepared for metallographic examination. One of the microstructures, given in Figure 6a, was taken from a location, where a sizeable thinning of the pipe-wall (like that seen in Figure 5 b) had taken place.

For comparison, a micrograph of a sample taken from 18-inch pipe from a location that was well remote the affected region of the pipe is given in Figure 6b. This microstructure essentially consists of ferrite and a very small proportion of pearlite. The grain size of the ferrite phase was measured to be around ASTM Size 9-10.

A comparison of the microstructure of Figure 6a with that of Figure 6b shows that the distribution of the pearlite phase has been noticeably modified. The pearlitic areas in the original microstructure of Figure 6b can no more be observed in Figure 6a, which clearly indicates that the steel must have been heated upto the austenitic region of iron-carbon phase-diagram. Heating to austenite would once dissolve the pearlite phase which would then precipitate out with a distribution depending upon the cooling rate [3]. It reflects that the temperature at some locations must have exceeded 800-850^{o}C.

The high temperature tensile data of low-carbon steels shows that at 750-800°C the yield strength drops to about one third of its room-temperature value [4]. Accordingly, taking into account the wall-thickness, the diameter, and the yield-strength of the 18-inch pipe (see Table 1), simple calculations would show that a gas pressure of 700-750 psi could have caused the yielding of the pipe-wall. This estimate matches quite well with the gas pressure of about 700 psi, which was reportedly observed at the outlet of AC-4 [1] about 20 minutes after the first rupture was indicated by the increased gas flow. It must be kept in mind that the above calculations are only a very rough estimate aimed at establishing a correlation between the gas-pressure and the temperature of pipe-wall at the time of failure. Nevertheless, these calculations do convincingly indicate that the temperature of the 18-inch pipe over a small region, under the influence of the heat from 24-inch pipe

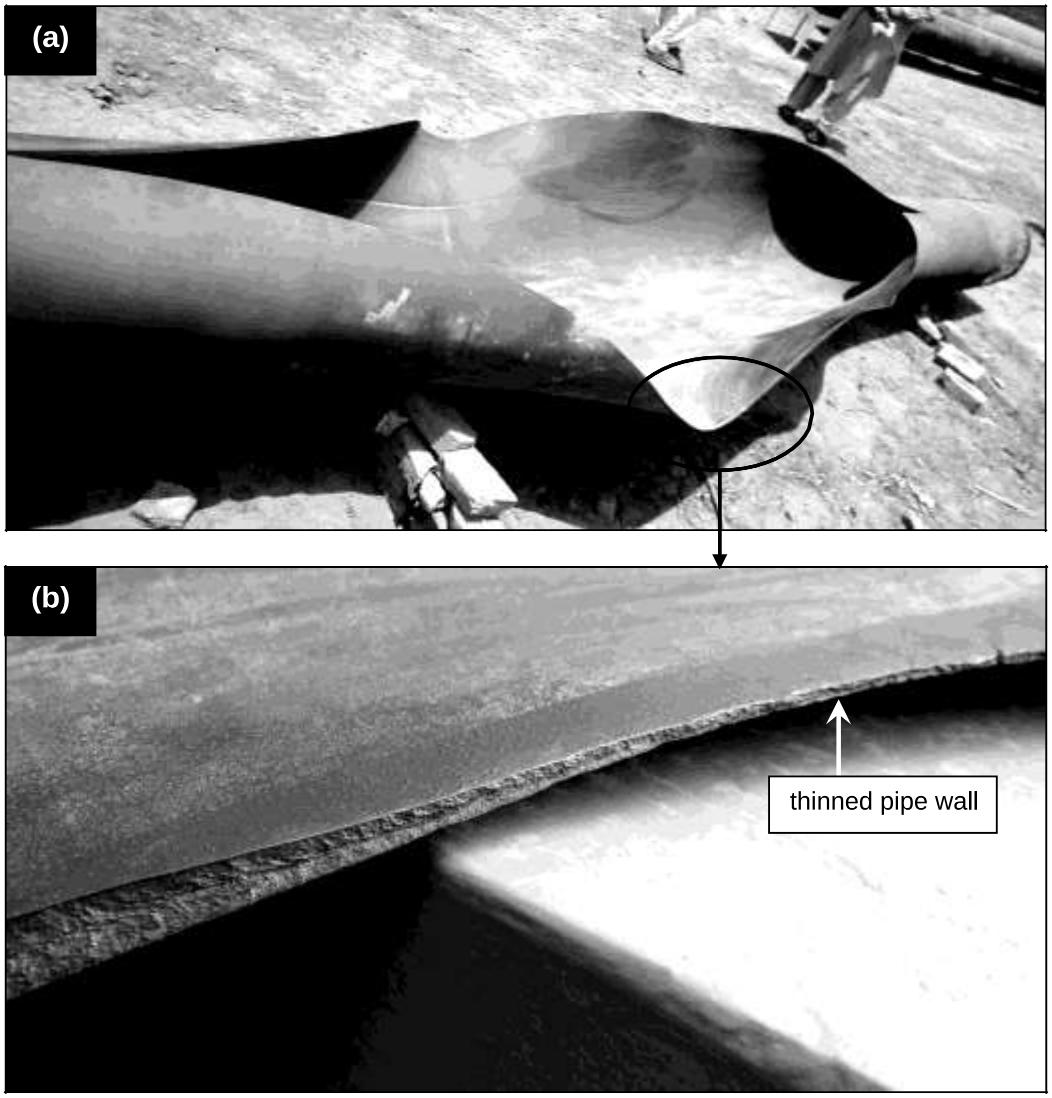


Figure 5: Photograph of the 18-inch ruptured pipe is shown in (a), while a magnified view of the encircled portion is shown in Figure 5 (b) The thinned portion of the pipe-wall on the 18-inch pipe may be noted in Figure 5b.

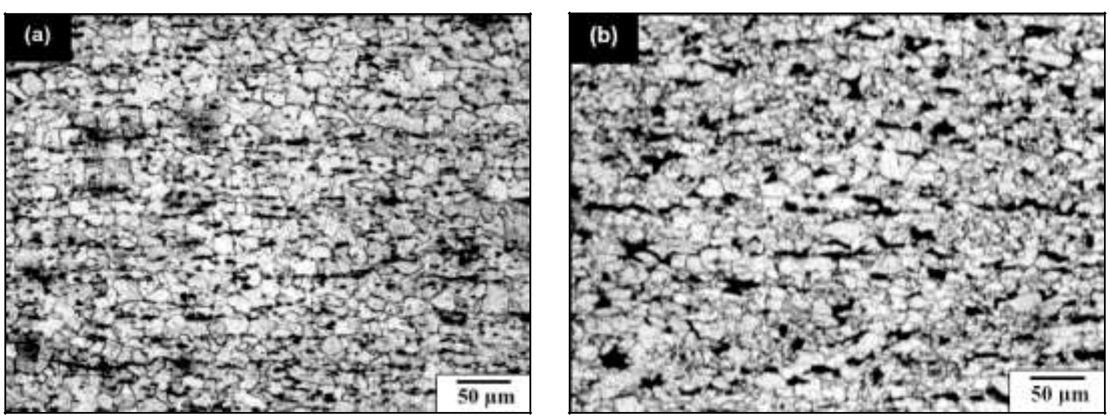
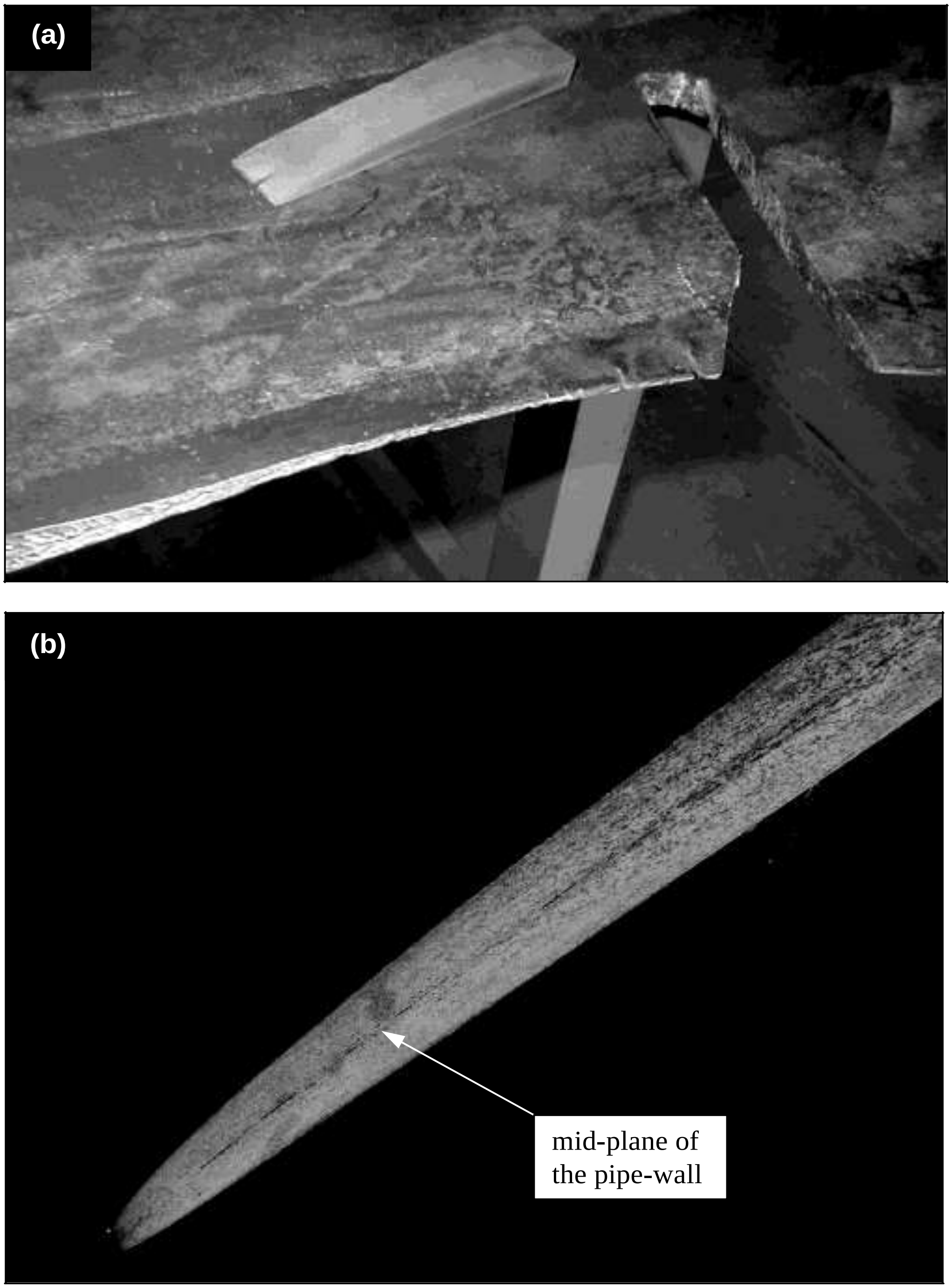


Figure 6: Microstructures taken from the thinned (heated) region of the pipe (a), and in (b) from an un-affected portion of the 18-inch pipe showing that the microstructure has been measurably changed.

flame, had exceeded 800-850°C, where a gas pressure of around 700 psi was able to cause the yielding of the pipe-wall.

A sample taken from the pipe-wall for macro-examination, shown in Figure 7a, illustrated that the pipe-wall had fractured in typical tensile mode. A magnified view of the same specimen (Figure 7b) clearly shows that the thinning of the wall was entirely due to the tensile straining of the heated portion of the pipe-wall. The thinned edge of the specimen was also observed using SEM (see Figure 7c). This fractograph is typical of ductile fracture [5] showing that pipe had fractured in a tensile mode.



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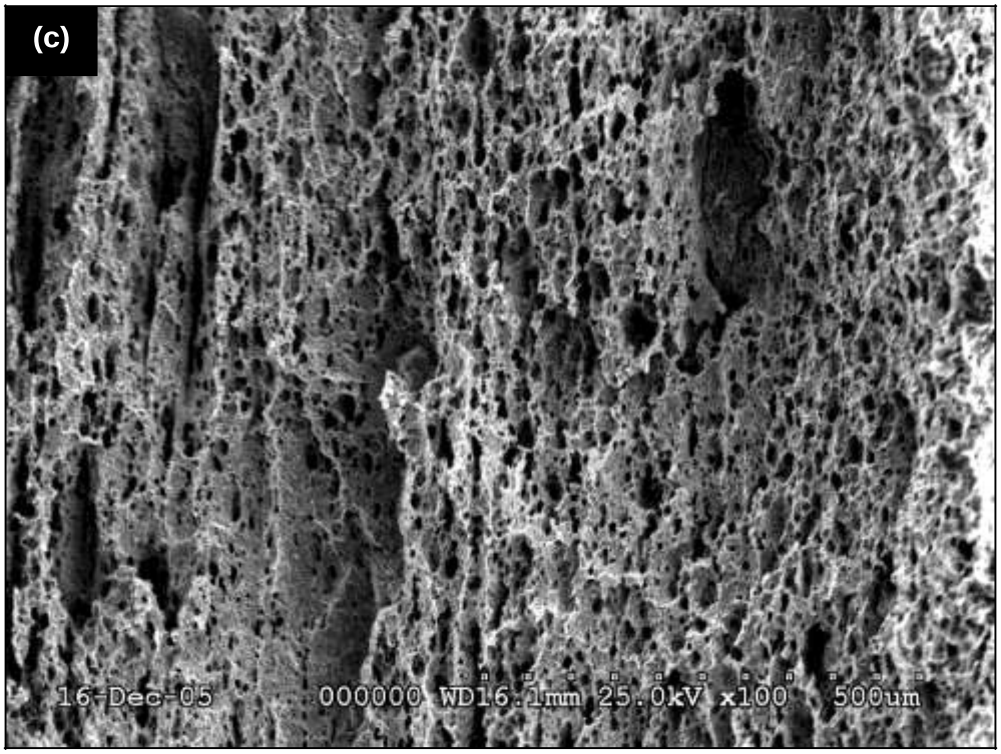

Figure 7: (a) A sample taken from the pipe for macro-etching showing the profile of the thinned wall along the fracture line, and in (b) the mid-plane of the pipe wall revealed by the macro-etching (c) SEM fractograph showing that the sample had fractured in tensile mode.

5. 30-inch Diameter Pipeline

The 30-inch pipe was affected by the fire to the extent that its coating, on the side facing the 24-inch pipe, had been burnt. Photographs taken from the affected region are shown in Figure 8. It was noted that although the 'black' poly-ethylene (PE) upper layer had been burnt off, the presence of inner 'off-white' resin layer suggested that the temperature of the pipe surface had possibly not exceeded about 200°C, which in turn would reflect that little damage must have been done to the pipe steel.

Additionally, the visual examination of the pipe did not show any sign of distortion, deformation, or de-shaping what-so-ever. It was on this basis that the SNGPL engineers had decided not to replace the affected portion of the 30-inch pipe. However, the pipe was left un-coated, so that any metallurgical examination could be carried out.

Accordingly, it was decided to take 'metallographic replicas' of the pipe surface both from the affected region as well as from the un-affected region, and compared. The replicated microstructures taken by the Struers Rubber Replica method [6] are shown in Figure 9. It may be pointed out that taking the replica from the pipe surface proved a very difficult exercise for two reasons; (a) the continuous flow of sand and dust onto the pipe-surface during the metallographic preparation, and (b) the temperature of the pipe surface.

A comparison of the microstructures of the affected and the un-affected regions (Figures 9 a & b respectively), shows that no measurable change in the microstructure of the pipe material has been caused by its heating. Figures 9a & b successfully indicate that there is no difference in the two microstructures on account of both the grain-size as well as the pearlite distribution. This observation, therefore, re-affirmed the decision that the 30-inch pipe was safe for use, and did not need to be replaced.

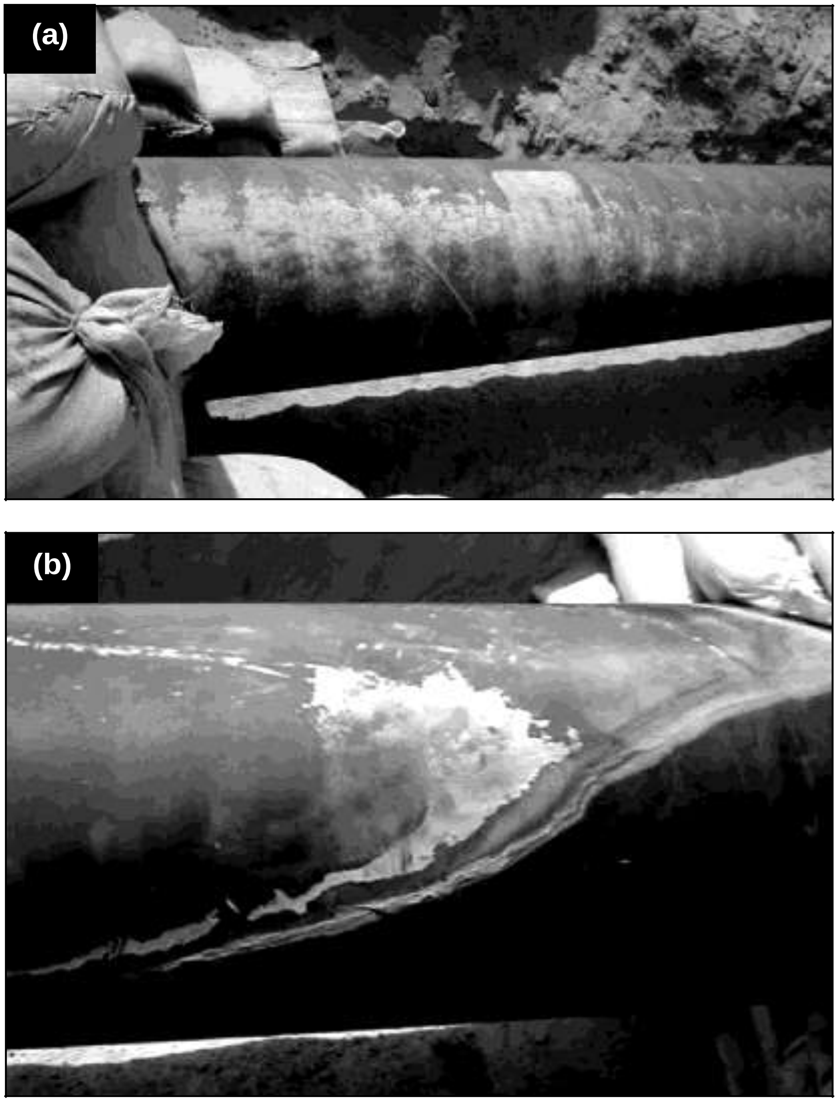

Figure 8: Photographs of the affected portions of the 30-inch line. The 'off-white' layer of epoxy-resin beneath the black polyethylene layer may be noticed.

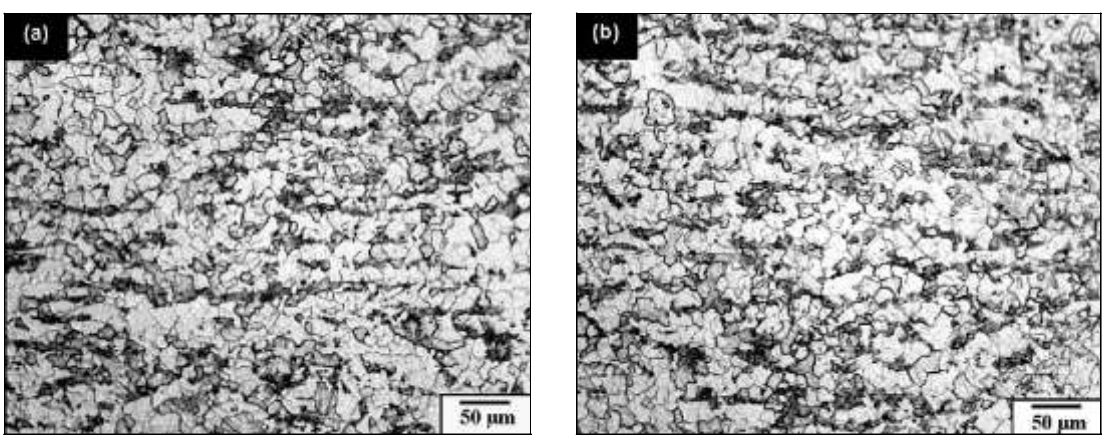

Figure 9: Metallographic replicas obtained from (a) the 'affected' portion of the 30-inch line, and, (b) from the 'un-affected' portion, showing that there was little difference in the two microstructures.

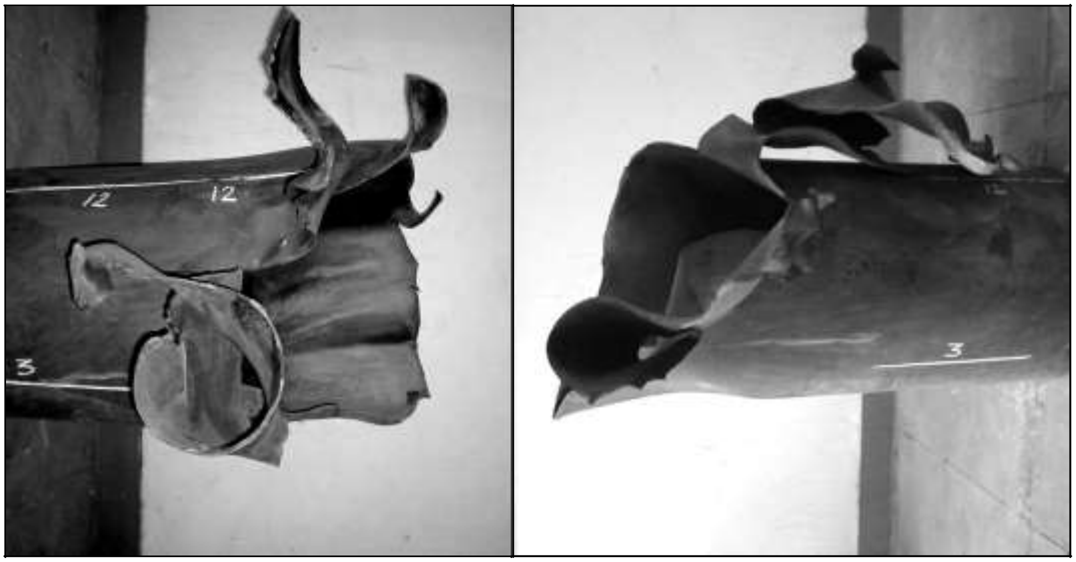

Figure 10: Photographs of the two broken ends of the 24-inch pipe, placed against each other in the same orientation as they were soon after the rupture. The 12 o'clock and the 3 o'clock positions on the two pieces are also indicated. It may be appreciated that in with this positioning of the rupture opening, the gas escaping from the 24-inch pipe would have been preferentially directed toward the 18-inch pipe.

6. Why was the 18-inch line affected so badly compared with the 30-inch line?

An important question that needs to be analyzed is: "why was the damage to 18-inch line so extensive compared with that to the 30-inch line". This question becomes even more intriguing when it is considered that the distance between the 30 and 24 inch lines was only 11 feet, while that between the 24 and 18 inch lines was 26 feet.

The answer to this question can be found in Figure 10, which shows the two broken ends of the 24-inch pipe placed against each other in the same manner as they were following the rupture. The 12 o'clock and the 3 o'clock positions on the two pieces are also indicated. It must be realized that the 18-inch pipe was located towards the 2.30 o'clock direction, and the 30-inch pipe was located opposite to that. It can be easily seen that the profile of the rupture-opening, as shown in Figure 10, was such that the gas jetting out of the rupture-hole would have been preferentially directed towards 2-3 o'clock position, i.e., towards the 18-inch pipe.

Also, as illustrated in Figure 1, the 30-inch line was buried 2 feet below the level of 24-inch pipe, while the 18-inch line was 1.5 feet higher than the 24-inch line. Since the 30-inch pipe was located at a lower vertical elevation compared to the 24-inch pipe, the heat from the upward rising flame form the 24-inch pipe would have had a much lesser effect. This factor may also have had some role in saving the 30-inch line. Additionally, it was also reported that the wind was blowing from west to east, which may have provided further protection to the 30-inch line.

7. Conclusions

1. The 24-inch line was ruptured with the help of an explosive device placed beneath the pipe at about 7 o'clock position. The gas escaping from the 24-inch pipe had caught fire following the rupture.
2. A portion of the 18-inch pipe was heated to about 800-850°C by the flames emanating from the 24-inch line. This had 'weakened' the pipe metal, which then developed a longitudinal yielding under the influence of the inside gas-pressure.
3. The 30-inch line was also affected by the heat, to the extent that its coating was burnt off. However, the replica metallography indicated that no measurable change in the microstructure (and, therefore, the strength) had occurred. It was thus considered safe not to replace the affected portion of the 30-inch pipe.

Acknowledgement

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References

[1] *SNGPL's Pressure and Flow Record at AC-4*, Sui Northern Gas Pipelines, Pakistan.

[2] F. Hasan and J. Iqbal; *Engineering Failure Analysis*, 13(2006) 127–135

[3] Sydney H. Avner; *Introduction to Physical Metallurgy*, Second Edition, McGraw Hill, (1974) 236-240.

[4] ASME; *Pressure vessel and boiler code*, Part D.

[5] ASM Metals Handbook; *Fractography and Atlas of Fractographs*, ASM International, Materials Park, OH, 9(1974).

[6] www.struers.com accessed 15-8-2005