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INVESTIGATION OF PIPELINE FAILURE

by

K. WINTERTON

PHYSICAL METALLURGY DIVISION

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Mines Branch Investigation Report IR 61-149

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K. Winterton*

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SUMMARY OF RESULTS

A metallurgical examination has been made of the causes of a pipeline failure. The pipe used was API-5Lx-Grade X52, and had a diameter of 30 in. and a wall thickness of 3/8 in. A circular patch had been welded on to the exterior of the pipe to repair a leak, at a point corresponding to the junction of a girth weld and a seam weld.

The immediate cause of failure was the welded patch which was used to make the repair, and from which fracture originated. This introduced stress-raising effects because of the change in geometry. In addition, the welding technique resulted in cracking in the heat-affected zone adjacent to the fillet weld around the patch.

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INTRODUCTION

It was reported that a pipeline explosion followed by a fire occurred in May 1961. A double detonation was reported by witnesses, the first presumably due to the sudden escape of gas, and the second to a gas-air ignition. The line had been in service for about two years, but shortly before the explosion occurred, a leak had been discovered by aerial survey and a welded patch repair had been made approximately one week before the failure. Near the location of this patch, catastrophic failure had originated in the pipe. The working pressure of the gas at the time of failure was 920 psi, and the air temperature at a nearby station was reported as 55°F. The pipe used was AP1-5LX=Grade X52, and had a diameter of 30 in. and a wall thickness of 3/8 in.

The damaged section of line was cut out and a new section, about 120 ft in length, was substituted. Finally, this new section was in turn replaced with a more satisfactory pipe installation, prior to hydraulic testing to about 1070 psi of the 18-mile section between valves. At this time, a crack occurred about 10 miles from the first break, several feet in length. After replacement of this newly-damaged pipe, the 18-mile section was tested to approximately 1145 psi and satisfactorily withstood this test.

This report is concerned only with the circumstances of the original failure of the pipe.

The broken pieces of pipe had been taken to a nearby compressor station. A meeting was held at this location in May for the purpose of a preliminary discussion and to inspect the damaged pipe on site. Among those present were:

Mr. W. Scotland, Asst. Chief Engineer, National Energy Board

Mr. D. Midwinter, Pipelines Engineer, National Energy Board

Dr. W. Morgan, Head, Ferrous Metals Section, Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys.

Dr. K. Winterton, Head, Welding Section, Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys.

Mr. H. Adair, Eng. and Met. Division, Ontario Research Foundation.

Mr. Atterbury, Battelle Memorial Institute, and representatives of the pipeline company concerned.

It was stated that the normal technique for making the girth welds involved the use of 5/32 in. dia Lincoln Fleetweld 5 electrodes (E6010) for the root pass, and 3/16 in. dia Shield Arc 85 (E7010) electrodes for the later passes. The same electrodes had been used for the fillet weld around the patch, but in addition a "cold" welding technique had been used, using a low amperage and stringer beads.

GENERAL INSPECTION ON SITE

A view of the damaged pipe on site is shown in Figure 1.

Figure 1 - General view of damaged pipe

It was not difficult to perceive the main course of the fracture. The break had evidently originated close to a circular patch plate of 1/2 in. thickness which had been welded over the leaking location to effect a repair. The crack* had spread in both directions to a distance of about 30 ft, so that the total extent was about 60-70 ft.

In one direction, the crack ran only a few feet before developing the familiar sine-wave pattern. It ran for some distance in this way, finally spiralling around the pipe, and then terminating. In the opposite direction, the crack ran rather straight for about a pipe length, and there was little to be seen of the sine-wave mode of progression; then, after a sudden turn, the crack spiralled around the pipe with a pitch of about 2 ft. It continued for a considerable distance in this way, finally running back on itself and terminating.

It is well known that brittle cracks can attain speeds of around 6000 ft/sec. Cracking can therefore occur faster than the release of stress due to escape of gas. However, close spiralling would reduce the axial component of the cracking speed to a fraction of its normal value. For this reason, it is unusual to see long

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*In this report, the term "crack" has been used to describe the nature of the failure, despite the fact that later examination showed that the fracture had a high percentage of shear. This use of the term, though sanctioned by custom, is admittedly not entirely satisfactory.

lengths of cracking in the spiral mode. Quite frequently, the ends of a fracture in a pipeline are characterized by spiral progression.

As in previous instances, in locations where the crack encountered a weld in its path, the outcome depended on the angle of incidence. At low angles, the crack frequently ran alongside the weld for a short distance before breaking away again to produce a flat-topped wave. At somewhat larger angles, a jog often occurred in the crack as it crossed the weld. When the crack encountered the weld approximately at right-angles, the weld had a negligible influence on the course of cracking.

The exact location of the origin of failure was not immediately clear from a visual inspection, for two reasons. Firstly, a subsidiary crack occurred near the main crack. Secondly, the fracture was not brittle enough except in a few locations to show the chevron patterns that would indicate the direction of cracking. Accordingly, samples of the pipe were marked for examination, taking sufficient material to ensure that the origin was included. These samples were sent to the Physical Metallurgy Division, Mines Branch for further examination.

Two further samples of pipe were taken from the north and south ends of the damaged section, for an examination of the material to ensure that sufficient pipe had been removed to make a satisfactory repair. This examination will be the subject of a separate report.

VISUAL EXAMINATION OF SELECTED SAMPLES

The samples selected for examination are shown in Figure 2.

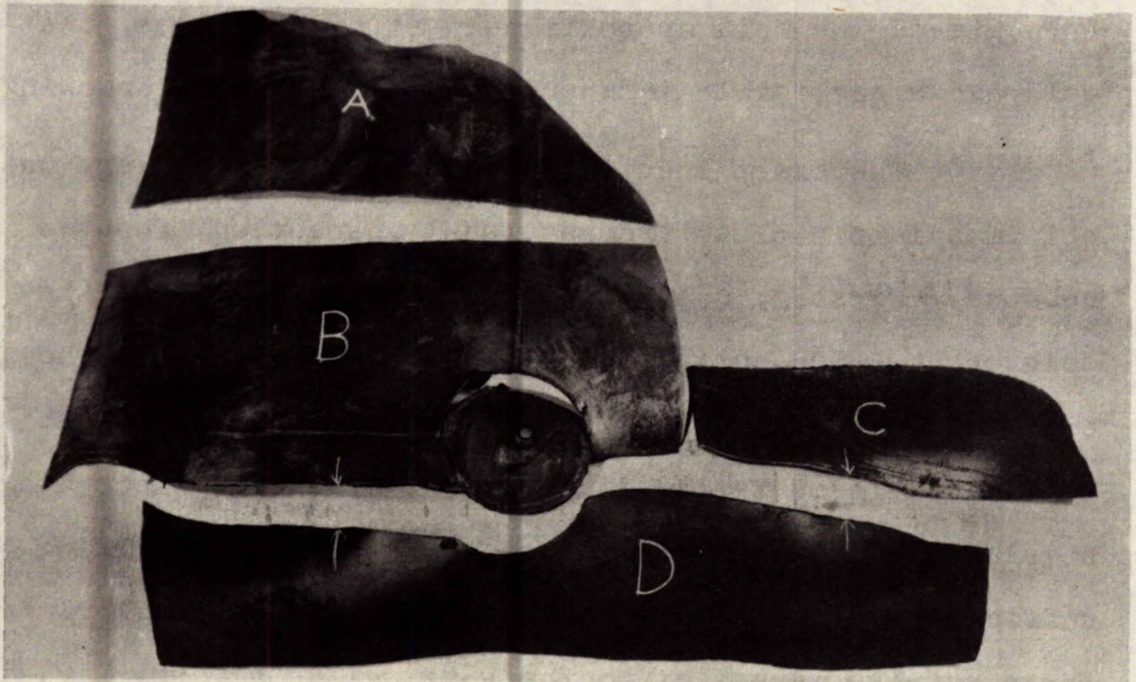

Figure 2 - Samples of pipe near the fracture origin.

A fair idea of the size of the samples in Figure 2 is provided by the circular patch, just below centre, which has a diameter of 12 in.

One large fragment of the pipe, roughly shaped like a half-disc, originally incorporating samples A and B, had been almost flattened, and blown clear of the fire area by the explosion.

Samples C and D had been cut from larger fragments of distorted pipe, and these had apparently remained near the heart of the fire which followed the gas explosion. The metal surfaces were scaled with oxide, unlike those of Samples A and B.

The approximately straight border between samples B and C on the one hand and D on the other shows the main path of fracture. On the left-hand side, may be seen the beginning of the development of the sine-wave mode of fracture.

Two separate pipes are involved in these samples and for convenience of reference, that on the left in Figure 2 will be called Pipe I, and that on the right Pipe II. They are separated by the girth weld running vertically, underneath the circular patch.

A subsidiary crack apparently had started from a point about 12 in. to the right of the patch, thus providing a natural separation between Samples B and C. This crack is represented further by the right-hand edge of Sample B and the top edge of Sample A. It was roughly semi-circular in form and intersected the main crack at a point, not shown in the photograph, about 12 ft to the left of the patch. It is the combination of the subsidiary crack and part of the main crack that provided the outline of the half-disc that was blown clear of the fire area.

At the two positions marked by the small arrows, the fracture showed chevron markings typical of brittle fracture in which cleavage is predominant. At these positions, it is known that the main fracture was proceeding in opposite directions away from the patch. The origin may be sought between these two points. No unusual damage or defects could be seen in this region except at the patch itself, and it was concluded that the fracture originated at some point on the periphery of the patch.

The direction of fracturing could not be established on the subsidiary break. However, there are two reasons for supposing that the break did not originate along this path. Firstly, there is no evidence of damage or defects along the length of the subsidiary crack which could have originated failure. Secondly, the fracture surface consisted entirely of the shear mode, showing evidence of some ductility, and this would be uncharacteristic of the origin of a break of this kind. It may further be noted that the subsidiary fracture meets the main fracture almost at right angles, making it appear that it had occurred separately and subsequently to the main break. It appears most probable that the subsidiary fracture and the expulsion of the half disc from the fire area resulted from the explosive force of the sudden escape of gas followed by the gas explosion.

Figure 3 shows a close-up view of the patch. The

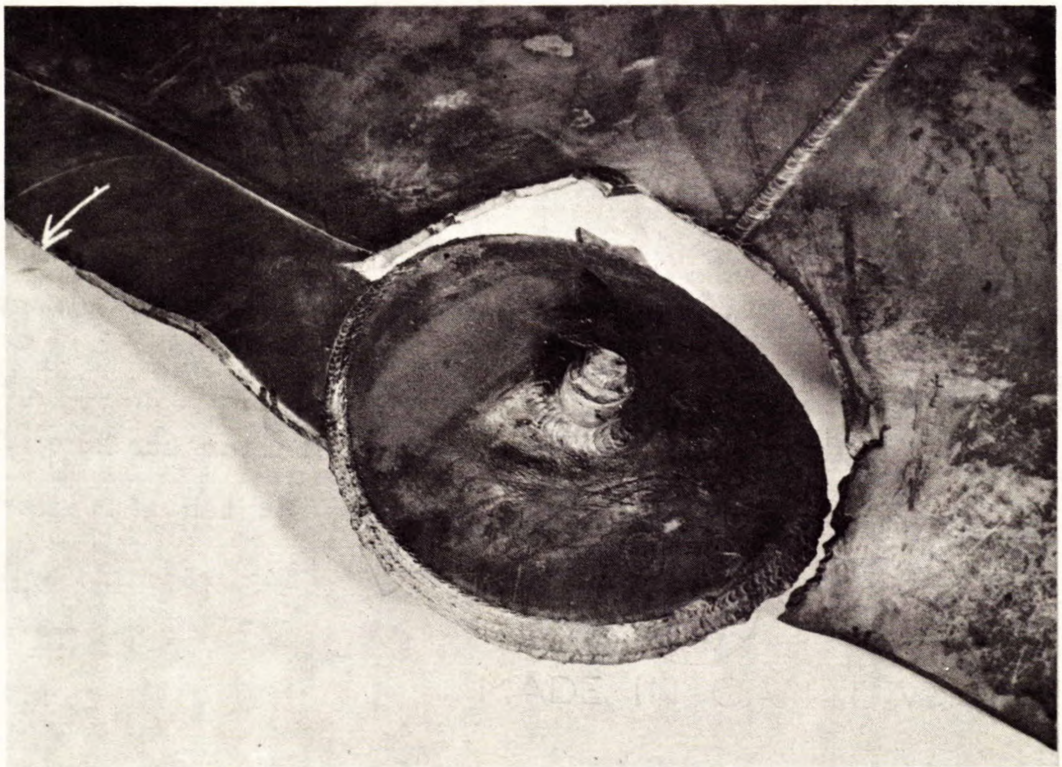

Figure 3 - Circular patch used for pipeline repair.

patch has retained its original curvature, in contrast to the flattened pipe metal surrounding it. This emphasizes in a graphic way the stress field that is introduced at the periphery of such a patch. The appearance of the fillet weld around the patch was consistent with the reported "cold" welding technique, that is the stringer beads had a convex contour. In other respects, the fillet weld appeared externally to be of reasonable quality.

On the assumption that the main crack initiated on the periphery of the patch, it is clear that the fracture is forked, a minor branch following up and around the circumference of the patch, almost completely separating it from the original pipe metal. This illustrates the fact that the fracture has occurred at tremendous speeds, so that the patch was almost completely removed before there was time for relief of the stresses by escape of gas. It is also worth noting that at several points there is a tendency for the fracture to deviate tangentially from the circular path, but was held to its course by the stress field introduced by the patch.

Figure 4 shows a view of the interior surface of the pipe underneath the patch. It was stated that the

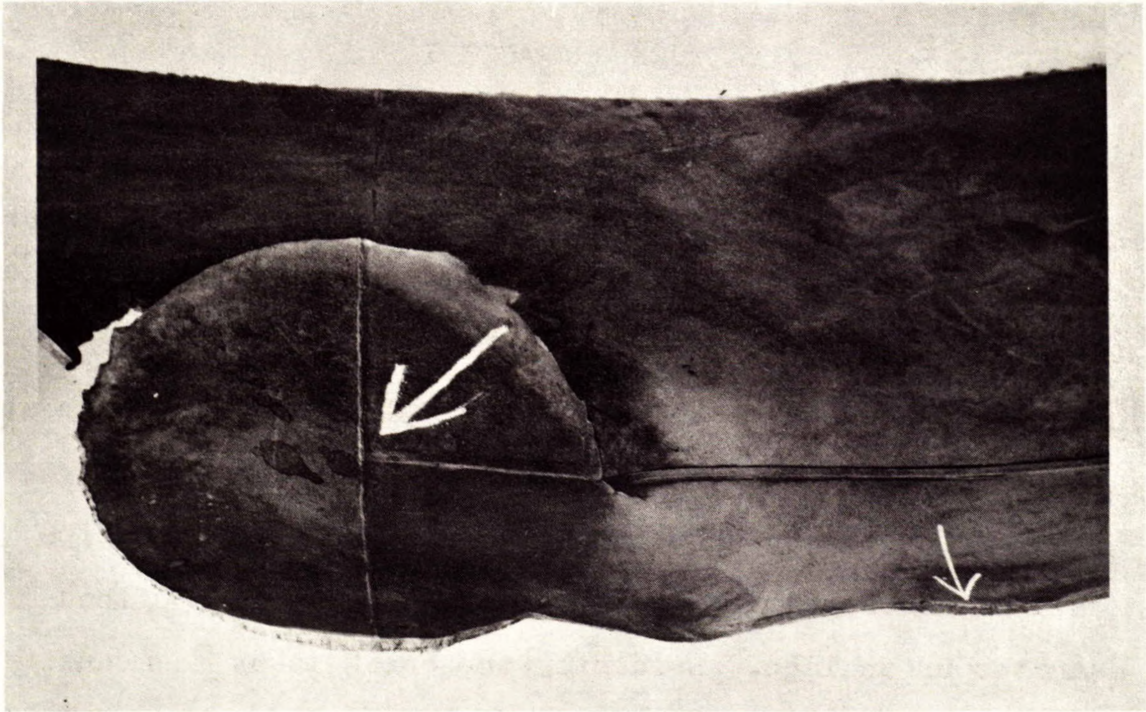

Figure 4 - Interior surface of pipe underneath patch showing location of original leak (large arrow).

patch was applied to repair a leak occurring at the junction of a longitudinal seam and a girth weld. Close inspection showed a short crack or line of separation in the longitudinal seam close to the girth weld, with an apparent extent of about 3/4 in. This was later examined by magnetic-powder and microscopical methods.

FRACTURE CHARACTERISTICS

In the samples chosen for examination, this break was mainly characterized by shear failure, and there was little evidence of cleavage. Some cleavage was evident in the fracture adjacent to the patch weld, and at some other points along the length of the crack. For most of the fracture, where shear failure predominated, micrometer measurements showed that some thinning of the pipe wall had occurred to the extent of about 20 to 30 thousandths of an inch. Evidently the break is by no means entirely brittle. Under these circumstances it is reasonable to look for a rather severe defect to originate failure.

The fracture showed some interesting peculiarities in the neighbourhood of the patch. The plane of the fracture is disrupted by numerous cavities, as shown in Figure 5.

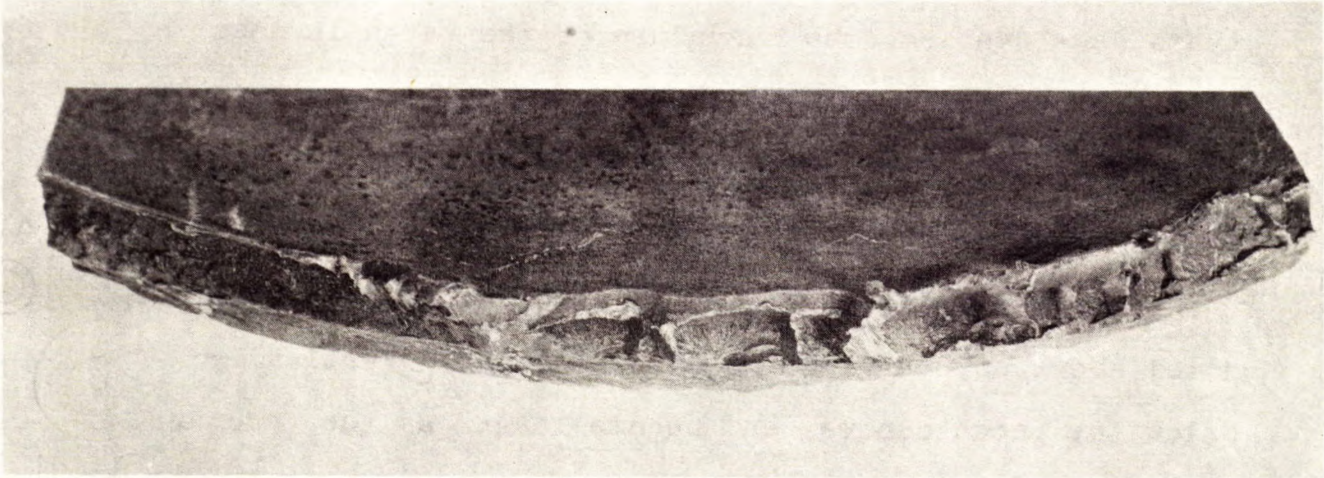

Figure 5 - Large cavities in fracture around circular patch.

The bases of the cavities were flat cleavage surfaces and showed no distortion, in contradistinction to the shear areas of the main fracture surrounding them. This phenomenon is believed to be due to the presence of pre-existing, heat-affected zone cracks from which small cleavages occurred to form the bases of the cavities. Figure 6 shows an adjacent sector of the fracture around the patch.

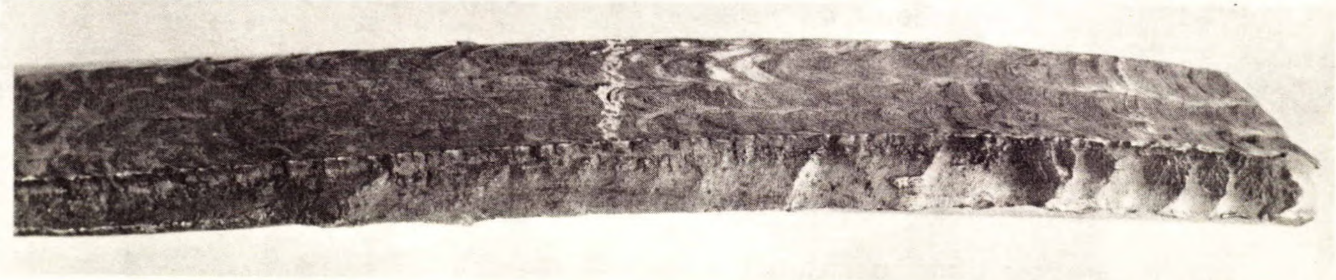

Figure 6 - Small cavities and other markings in fracture around circular patch.

Because of the depth of focus and the use of the side elevation, the curvature of the patch is lost in this photograph. The cavities become smaller and finally disappear. However, at the top edge, adjacent to the weld, smaller disturbances are present.

Referring to Figure 3, the flat cleavage surfaces noted above appear first at a point roughly vertically below the patch centre, and become larger as the fracture is followed in an anti-clockwise direction.

Figure 7 shows a view of a short length of cleavage fracture with chevron markings, to the right of the photograph.

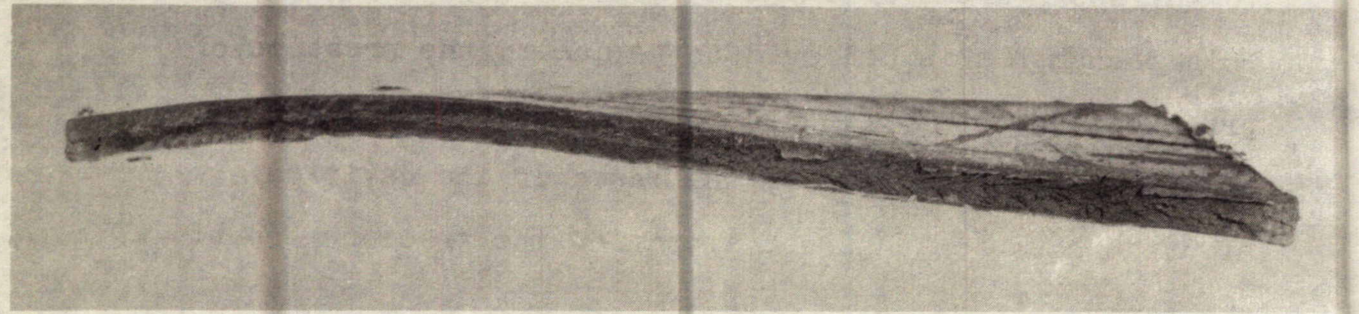

Figure 7 - Cleavage area with chevrons and tapering cleavage area.

The region of the fracture shown in Figure 7 includes the location marked with an arrow to the right of the patch in Figure 2. The cleavage area tapers down to a narrow band on the left-hand side of Figure 7. This is no doubt associated with the presence of a high-carbon band at this location, as noted later on.

MICROSCOPICAL EXAMINATION

To confirm the presence of pre-existent cracking in the neighbourhood of the fillet weld around the patch, several sections were taken through the weld and adjacent pipe steel in the short length which had been undisturbed by the fracture (See Figure 3 - left hand side of patch). At the extremities of this length, brittle cracks were present as shown in Figure 8.

Figure 8 - Extremities of brittle crack in relatively sound section of fillet weld around patch.

Etched nital (2%) Mag. X100

These represent extensions of the main fracture, and were present only in the outer layers of the pipe wall close to the toe of the fillet weld. In Figure 8, the crack runs through weld metal (top), heat-affected zone (centre) into unaffected pipe metal (bottom). At other locations, the nature of the crack was characterized by distortion in the ferrite-pearlite structure of the unaffected pipe metal.

In all of the specimens examined from this region of the fillet weld, there was evidence of heat-affected zone cracking. Most of this was parallel to the weld junction (Figure 9), but some was perpendicular to it (Figure 10).

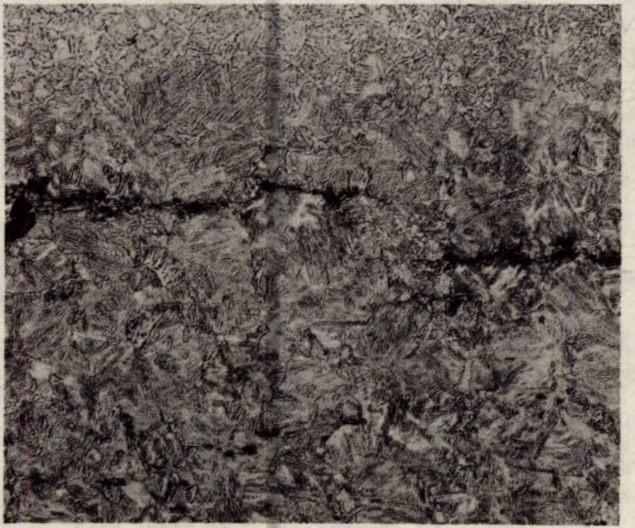

Figure 9 - Heat-affected zone parallel to the weld junction of the fillet weld around the patch.
Etched nital (2%) Mag. X250.

Figure 10 - Heat-affected zone cracking perpendicular to the weld junction of the fillet weld around the patch.
Etched nital (2%) Mag. X100

These two illustrations (Figures 9 and 10) were taken from the central region of the undisturbed weld of the patch, as remote as possible from the main fracture. These cracks were rather fine, typical of heat-affected zone cracking, and quite distinct from the various brittle cracks associated with the main fracture (Compare for example Figure 8).

Figure 11 shows some cross-sections through the fillet weld around the patch, prepared for macroscopical examination.

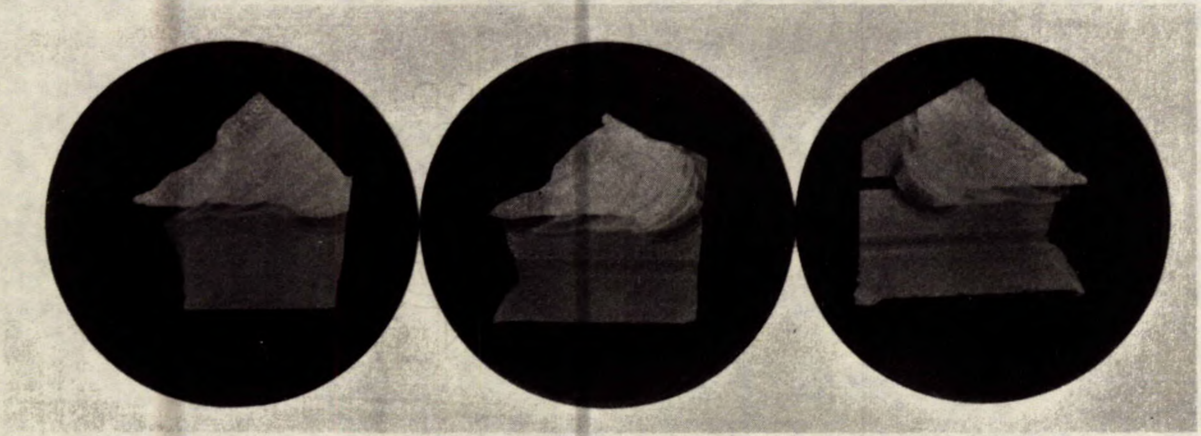

Figure 11 - Cross-sections through the fillet weld around the patch.
Etched nital (2%) Mag. $1\frac{1}{2}$

In all cases, the fracture lies just underneath the toe of the weld, and there is a suggestion from the changes in direction of the fracture of pre-existent horizontal and vertical cracking. The specimens in the centre and on the right were taken through fracture cavities such as those shown in Figures 5 and 6, and it seems most likely that the bases of these cavities are small cleavages separately initiated from pre-existent cracks. In the same specimens (Pipe II) may be seen a dark band about 1/32 in. in thickness at the centre of the wall. By microscopical examination, this was found to be a high-carbon band. The specimen on the left (Pipe I) in Figure 11 does not show this feature.

It was thought that there might be a possibility of heat-affected zone cracking in the girth welds and, to check this, several sections were taken from the samples available. The most satisfactory sections were taken from Samples A and B (Figure 2), since the structure in this case had not been affected by the annealing effect of the fire that followed the explosion. In general, the structure of the heat-affected zones adjacent to the girth welds appeared to be satisfactory. Figure 12 shows the structure of a typical untempered heat-affected zone (that is, adjacent to the last bead deposited) and the structure consists of ferrite and pearlite with some bainite.

Figure 12 - Structure of typical untempered heat-affected zone adjacent to a girth weld.
Etched nital (2%) Mag. X600.

Cracking would not be expected with this type of structure (Figure 12). However, the presence of the high-carbon band, previously noted in Figure 11, was associated with an anomalous structure as shown in Figure 13.

Figure 13 - Normal structure and high-carbon structure in Pipe II.
Etched nital (2%) Mag. X100.

The normal low-carbon, ferrite-and-pearlite structure is at the top in Figure 13, and may be compared with the almost-entirely pearlitic structure of the high-carbon band at the bottom of the photograph. Some minor cracking occurred in the high-carbon band adjacent to the girth weld, as shown at high magnification in Figure 14.

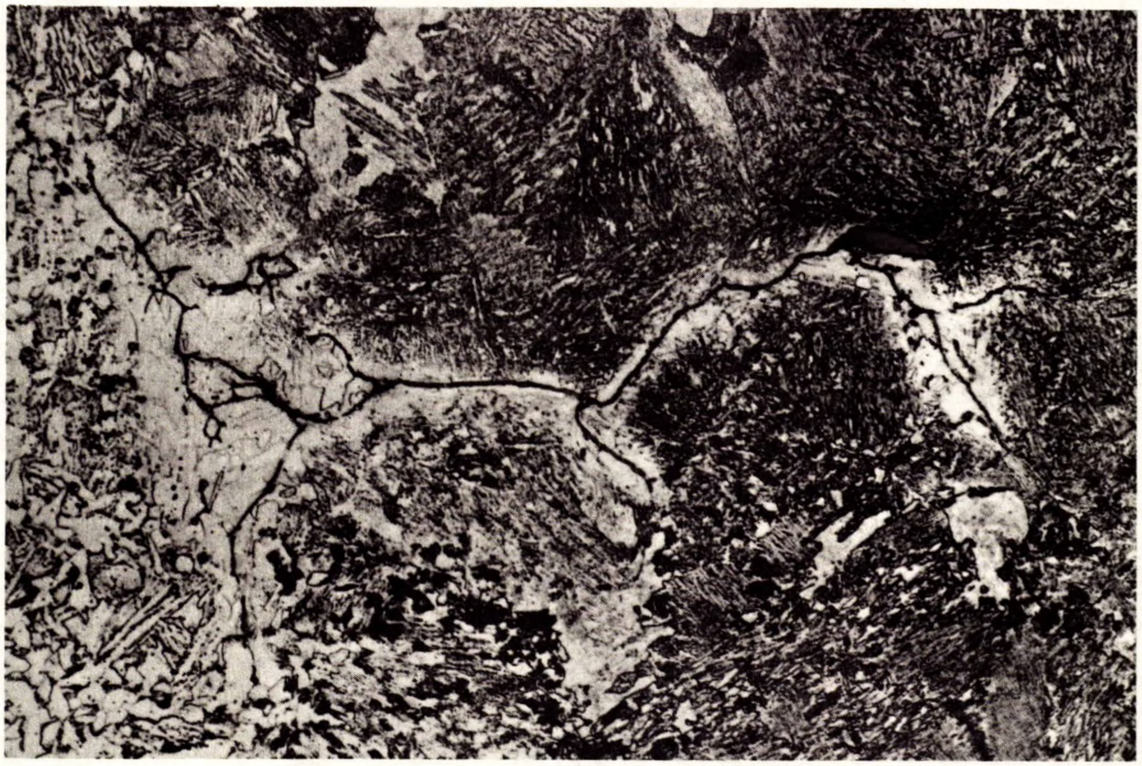

Figure 14 - Fine cracking in high-carbon band adjacent to girth weld.
Etched nital (2%) Mag. X600.

As might be expected, a martensitic structure was produced in the high-carbon band by the weld thermal cycle in the heat-affected zone.

Some attention was also given to the fault in the longitudinal seam which had been responsible for the original leak (See Figure 4 - large arrow). A section was cut through the seam weld at a point about 3/4 in. from the edge of the girth weld. However, this fell into two parts and the seam weld had evidently failed to join at this point. Successive transverse specimens were taken at greater distances from the girth weld, and established that the lack of join extended for a distance of between 1 and 1¼ in. from the end of the pipe. The microscopical study was facilitated by a preliminary examination by means of magnetic powder.

Figure 15 shows the mid-section of the seam weld at a location about 1 in. from the end of the pipe.

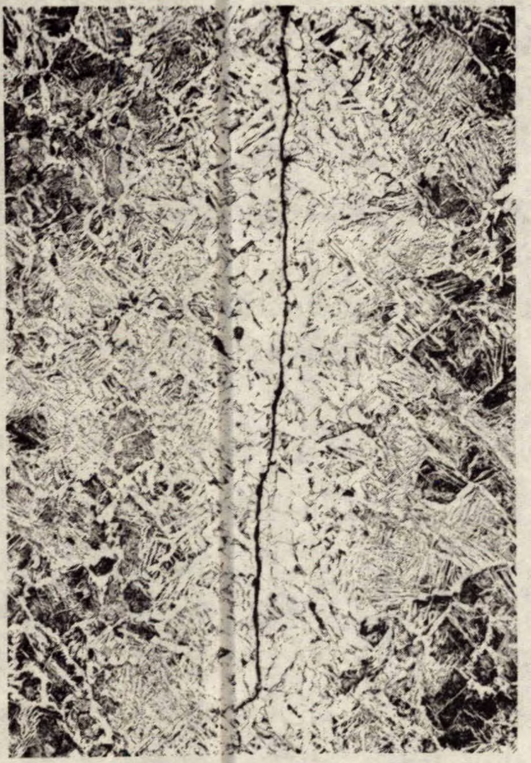

Figure 15 - Mid-section of longitudinal seam at a point near the end of the pipe.
Etched nital (2%) Mag. X100

It may be seen that some decarburization had occurred at the butting surfaces. Cracking has presumably extended from a lack of join in the seam-weld.

CHEMICAL ANALYSIS

Samples were taken for analysis from the metal of both pipes involved (Sample B, Figure 2), and the results are shown in Table 1 below.

TABLE 1

Analysis of Pipe Metals

Pipe	Carbon	Manganese	Silicon	Sulphur	Phosphorus
I	0.28	1.15	0.02	0.020	0.019
II	0.30	1.23	0.03	0.020	0.016

IMPACT TESTING

Pieces were cut from Sample A, Figure 2, from which sub-standard (2/3 size) specimens were machined for Charpy testing. Longitudinal specimens were used, that is with the long axis of the specimen parallel to the rolling direction of the pipe steel. The notch was cut perpendicular to the rolling direction and perpendicular to the plate surface. Sample A was selected for these tests because it was known to have been thrown clear of the fire area, so that the metal was free from the annealing effect to which the bulk of the pipe was exposed. The pipe-metal of Sample A, Figure 2, was flattened, and this might have the effect of raising slightly the temperature for the ductile-brittle transition. Specimens from both pipe metals were tested in triplicate at each of six temperatures, and the results are given in Table 2.

TABLE 2

Results of Charpy Impact Tests on Pipe Metals

Pipe	Sample No.	Temp.	Impact Energy ft lb Individual	Impact Energy ft lb Average	Per Cent Crystallinity Individual	Per Cent Crystallinity Average
I	1	212°F	44	45	0	0
	2	"	46		0	
	3	"	46		0	
	4	Room	36	36	20	20
	5		37		20	
	6		35		20	
	7	0°F	14	15	98	98
	8	"	16		98	
	9	"	14		98	
	10	-10°F	6	7	99	99
	11	"	7		99	
	12	"	8		99	
	13	-20°F	6	5	99	99
	14	"	4		99	
	15	"	5		99	
	16	-40°F	4	4	100	100
	17	"	4		100	
	18	"	4		100	

TABLE 2 (Cont'd.)

Pipe	Sample No.	Temp.	Impact Energy ft lb Individual	Impact Energy ft lb Average	Per Cent Crystallinity Individual	Per Cent Crystallinity Average
	19	212°F	56		0	
	20	"	50	55	0	0
	21	"	58		0	
	22	Room	52		10	
	23	"	41	46	25	18
	24	"	44		20	
	25	0°F	20		80	
	26	"	25	25	80	79
II	27	"	31		78	
	28	-20°F	14		98	
	29	"	3	10	100	99
	30	"	12		98	
	31	-30°F	17		98	
	32	"	6	13	99	98
	33	"	15		98	
	34	-40°F	3		100	
	35	"	3	3	100	100
	36	"	3		100	

From the results shown in Table 2, the 15 ft lb transition temperature is about 0°F for the metal of Pipe I, and about -10°F for the metal of Pipe II. It may be noted that the 50% crystallinity transition temperatures would be a little higher than the above values, as is normally the case.

DISCUSSION

It is well to remember that in high-pressure pipelines, high stresses are present at all times in the steel, and the pipe is operating under conditions similar to those of other high-pressure vessels. For example, the 18-mile length of line was originally tested at 1030 psi gas pressure, representing a hoop stress in the pipe wall of about 80% of the yield strength. The working pressure, 920 psi, in use at the time of the explosion corresponds to a hoop stress of over 70% of the yield strength.

There is no evidence to suggest that the choice of pipe-line steels has been made with the objective of avoiding brittle failure. High strength and economy appear to have been the ruling requirements. It is unfortunately true that over a range of temperatures that might be encountered in practice, these steels are liable to behave in a brittle manner. This has been made clear by tests done by members of the staff of the A. O. Smith Corporation.(1,2) In fact, it appears that with X52 steel pipe it would be necessary to maintain the temperature at above about 180°F at all times in order to ensure that the steel would always behave in a ductile manner.(1)

As some criterion of the sensitivity to temperature of the two pipe steels concerned in this investigation, it may be recalled that the 15 ft lb Charpy transition temperatures were about 0°F and -10°F for the steel from Pipes I and II respectively. These figures may be compared with a figure of +4.5°F given as an average result for 53 pipes tested using similarly-cut specimens.(2) If anything, the pipe steels in this investigation behaved a little better than might have been expected from the average impact values obtained in the previous investigation.(2)

It may be noted that the break occurred at a temperature (approximately 55°F) above those found for the 15 ft lb Charpy transition temperatures. At the failure temperature, an impact energy of 30-40 ft lb would be expected in these steels with per cent crystallinity perhaps around 20-30%. This is in line with the fact that the break as a whole was by no means completely brittle, showing a high proportion of shear in the fracture.

This failure may be designated a "brittle failure" in the sense that the average hoop stress was less than the yield strength, and that no macroscopic yielding occurred. It may be thought academic to discuss the amount of immediate local ductility associated with the fracture. The important, practical consideration is that catastrophic failure can occur despite the fact that the fracture has a high percentage of shear, thus extending the temperature range in which such failures may be expected.

High-pressure pipelines provide an example of an application in which steels liable to catastrophic failure are exposed to high stresses. To avoid frequent failures, it is necessary therefore to avoid defects, notches, changes in section, and stress-raisers such as might initiate a fracture. Thus the A. O. Smith workers(2) recommend "increased supervision and inspection prior to covering the pipe to prevent sharp, crack-like defects". The American Standards Association Code(3) has the following warning (page 36 para 841.24):- "Gouges, grooves and notches have been found to be a very important cause of pipeline failures and all harmful defects of this nature must be prevented or eliminated. Precautions shall be taken during manufacture, hauling and installation to prevent the gouging or grooving of the pipe."

It is in the light of the above recommendations that pipeline operations must be judged. Using this criterion, it must be said that the repair procedure involving the patch plate was quite unsatisfactory, and this was the immediate cause of failure, since the repair provided faults and stress-concentration sufficient to originate the catastrophic failure.

The use of a welded circular patch to repair a leak in a pipeline must be condemned. This system provides severe stress concentration not only for the longitudinal stress but also for the hoop stress. The use of a patch (1/2 in. thick) of thickness greater than that of the pipe wall (3/8 in. thick) would increase the stress-raising effect. Even if no welding cracks had been present, the presence of the patch alone might well have been sufficient to originate a catastrophic failure. If the fillet welds around the patch had been ground to a smooth contour, the stress-raising effect would have been reduced, though not necessarily to a safe value.

In 1959, an account(4) was given of some tests on pipe lengths containing sleeves, patches, etc. As a result, the author concluded that "hydrostatic tests conducted on chambers proved that fittings constructed to encircle the pipe completely will consistently withstand higher internal pressures than the reinforced saddle type fittings". He also recommends(4) that "repair- - - - by welding patches - - - - -should be restricted to the low and medium carbon grades". For steel X52, he recommends(4) "fittings that completely encircle the pipe - - - -for making repairs - - - - or for installing new connections."

In this instance, the welding procedure adopted for attaching the patch resulted in heat-affected zone cracks near the toe of the weld, just at the location where the stress has been raised due to the geometrical effect. This combination may be expected to be extremely effective for the initiation of fracture.

In recent literature, warnings have appeared about the possibility of encountering heat-affected zone cracking in X52 steel. Two conclusions from work done at the Battelle Memorial Institute(5) were as follows:-

"1. The amount of base-metal cracking in welded girth joints increased as the carbon and manganese contents of the pipe approached the maximum usually specified for Grade X52 pipe. Laboratory tests and field-weld failures in pipes with compositions approaching this maximum indicated that cracking could occur to an extent that might seriously lower the strength of joints welded by customary construction methods.

2. Twelve field-weld failures showed weld-heat-affected-zone failures which were associated with pipe compositions of 0.60 carbon equivalent* or greater."

To overcome the danger of cracking, these authors(5) recommended the use of preheat combined with a special welding sequence, or alternatively the use of low-hydrogen electrodes.

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*Calculated from $C.E. = C\% + \frac{Mn\ \%}{4}$

Another author(4), after an extensive practical investigation into the likelihood of encountering heat-affected zone cracking, recommended for grade X52 the use of "E7016 low-hydrogen non-powder electrodes for all welds which are fused to the wall of the pipe".

From the chemical analyses made on Pipes I and II, it may be noted that the carbon equivalents are 0.57 and 0.61 respectively, for comparison with the critical value(5) of 0.60 associated with previous documented field-weld failures.

With regard to the danger of heat-affected zone cracking in X52 steel, the piping codes(3,6) appear to be insufficiently detailed and somewhat lax.

When welding connections, patches, etc., to the pipe wall the danger of encountering heat-affected zone cracking is much greater than in the normal girth welds(4,5). This arises from the metallurgical effect of the greater cooling rate on the structure of the heat-affected zone. Thus in the present instance, the fillet weld was made around the patch with a total thickness of metal of $1\frac{1}{4}$ in. (1/2 in. + 3/8 in. + 3/8 in.) through which heat could be conducted from the weld. This may be compared with a total thickness of 3/4 in. of metal (3/8 in. + 3/8 in.) through which heat can be conducted from a girth weld. The effect of gas flowing in the pipe while welding is in progress can have an appreciable effect in increasing the rate of cooling(4,5).

In the present instance, the patch weld was stated to have been made with a "cold" welding technique, using a low amperage and stringer beads. Though the welder may have been understandably anxious to avoid burning through the pipe wall, this technique increased the rate of cooling and thus facilitated the occurrence of heat-affected zone cracking. With a more appropriate welding technique, involving the use of preheat or the use of low-hydrogen electrodes, the heat-affected zone cracking could and should have been prevented.

For welds adjacent to pipeline steels, conditions of high cooling rate should be avoided at all times. Even if the conditions are not quite sufficiently severe to result in heat-affected zone cracking, consideration must still be given to the hard, brittle martensitic structures of the heat-affected zones. These may be expected to be poor in impact resistance and therefore liable to crack during handling or in other circumstances where stress is applied.

The welding techniques used for the girth welds were probably satisfactory. Apparently the cooling rate obtained in the normal girth welds was insufficient to produce the martensite that is a prerequisite for heat-affected zone cracking. There is the exception that fine cracks were noted in the high-carbon band of Pipe II.

Under some circumstances, the high-carbon band of Pipe II might have given some trouble. However, it is believed that it contributed little to fracture initiation in the present case. The heat-affected zones from the fillet weld were narrow and did not extend to the high-carbon band. The high-carbon band may have assisted slightly the ease of propagation in Pipe II, and the fracture illustrated in Figure 7 is of interest in this respect.

It is of interest to note that the defect which caused the original leak requiring repair was a short lack-of-join in the longitudinal seam at the end of a pipe length. It appears quite possible that such a defect might be covered by the end caps used in expansion and pressure testing during manufacture. If so, it would be desirable either to test separately the ends of the seams or to crop off an adequate slice from the pipe ends. Since it is clear that the repair of leaks does offer some difficulties, it would be desirable to be sure of eliminating all manufacturing defects.

CONCLUSIONS

1. An average hoop stress of about 36,400 psi, 70% of the specified yield strength of the steel, would result from the working pressure (920 psi) of the gas at the time the explosion occurred.

2. The steels used for the two pipes nearest the origin of the failure showed Charpy 15 ft lb transition temperatures of 0°F and -10°F, only a little better than the average value of 4.5°F reported for a number of X52 pipe metals.

3. Appreciable ductility was associated with the failure as evidenced by the large proportion of shear in the fracture. This is in line with the fact that the failure temperature, 55°F, was well above the 15 ft lb transition temperatures of the pipe metals.

4. The use of a circular patch to effect a pipeline repair is to be condemned because of the stress-raising effect caused by the change in geometry.

5. The welding technique used to make the fillet weld around the patch was incorrect in that it resulted in a hardened, brittle heat-affected zone and in heat-affected zone cracking.

6. The immediate cause of failure was the welded patch which was used to make the welding repair, and from which fracture originated, because of the combined influence of the effects noted in conclusions 4 and 5.

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