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PIPE FAILURES AND ANALYSIS - ERW SEAMS

by

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INTRODUCTION

This document describes the principal types of problems that pipeline operators can expect to have with pipelines comprised of older pipe materials with electric resistance welded (ERW) seams. It also provides some suggestions for continuing to operate such pipelines with a minimum of risk to the public. The document is based on the premises that it is neither desirable nor practical to abandon such facilities and that operators can maintain and used them with an acceptable degree of safety.

The format of this document is as follows. It begins with a brief review of what constitutes ERW pipe. Next, the types of weaknesses and deficiencies that can occur in ERW materials are reviewed along with their possible impacts on pipeline safety. Then, the recommended strategies for dealing with the possible problems are discussed. It is recognized that most if not all of these facts are known or can be found in the literature. However, it is the intent of this document to refocus attention on these issues because of the thousands of miles of pipelines that are known to be comprised of older ERW pipe materials. As an adjunct to this review of the issues pipeline operators can, if they have not already, sharpen the key requirements of their specifications for ordering new ERW materials.

THE MANUFACTURE OF ERW LINE PIPE

What is and is Not ERW Pipe

The 38th edition of the API Specification 5L for line pipe[(1)*] classifies the ERW process under Paragraph 2.1.b.1 as a material made by "Electric Welding". The API's definition of electric welding is "A process of forming a seam by electric-resistance or electric-induction welding wherein the edges to be welded are mechanically pressed together and the heat for welding is generated by the resistance to flow of electric current". Within this broad definition, it is possible to manufacture line pipe by a number of processes. In the past, this would have included not only high-frequency (HF) ERW pipe and high-frequency induction welded (HFI) pipe which constitute the primary electric-welded pipe materials today but also such materials as low-frequency (LF) ERW pipe (probably still used to make some types of tubing), direct-current welded (DC) ERW pipe, and flash-welded (FW) pipe. The latter three processes as far as the author knows, are no longer used to manufacturer line pipe. It is important to note that flash-welded pipe, although similar in some respects to ERW pipe, should not be classified as ERW pipe because of its being distinctly different from ERW pipe in certain important respects which will be addressed subsequently.

The other line-pipe products which are mentioned in the 38th Edition of API Specification 5L also are obviously not ERW pipe. These are seamless pipe, continuously welded pipe (formerly furnace butt-weld or lap-welded pipe), submerged-arc welded pipe, and gas metal-arc welded pipe. Of these seamless and submerged-arc-welded pipe along with ERW pipe constitute by far the majority of the line-pipe materials in existence.

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[*]Numbers in parenthesis are References on Page 18.

ERW Processes

Several good summaries of the manufacturing of ERW pipe are available[2-8], any one of which pipeliners can use to inform themselves on the nature of the material not only as it is currently made but as it was made in the past as well. In these articles, one can ascertain that ERW pipe is and has been made by a variety of means and manufacturers. Regardless of the details, however, the basic process starts with coiled hot-rolled strip steel or skelp. The skelp is uncoiled, flattened, and progressively formed (in a smooth transition over several tens of feet) into a circular tube all of which, prior to the actual seam- welding process, are done without heating the material (i.e., it is plastically deformed in the direction of rolling of the coil to get it uncoiled and flattened, and then, it is progressively plastically deformed in the direction transverse to the rolling direction to get it into the shape of a tube). At this stage, the edges of the tube are forced together as the tube is pulled or pushed continuously between a pair of massive c-shaped rolls (see Figure 1) at the instant electric current is applied to heat the edges (and only the edges). The results are the squeezing out of excess material by upsetting of the edges both toward the O.D. and I.D. of the tube and, because of the heat generated by resistance to the electric current, a bonding together of the edges. The excess material squeezed out to the O.D. and I.D. is trimmed flush leaving relatively smooth surfaces. It is neither necessary nor desirable that the heat be sufficient to actually melt the metal although some melting may take place without degradation of the product. The idea is to forge the edges together in a manner which will create as nearly as possible a bond which is virtually indistinguishable in microstructural appearance and mechanical properties from the parent skelp material. A vital additional step which always takes place within seconds of the "welding" of all materials of grades above X42 (and which is usually done for all ERW materials regardless of grade) is the post-weld heat treatment in which the bondline region is reheated to a minimum temperature of 1,000 F (usually to a much higher level) by induction heating to assure that no untempered martensite (a hard, brittle material) remains.

The key difference between the several ERW processes (HF, HFI, LF, and DC) consists of the manner in which the electric current for welding is introduced. Heald[2] states that the earliest "electric" process dates from the 1910-1920 era and was known as the Parpart technique. In 1924 the Johnson technique was introduced[2]. The latter became the "work-horse" technique for LF ERW pipe manufacturing and survived as a means of making line pipe well into the 1960s. In the Johnson technique, an alternating current of 60 cycles frequency (later as high as 360 cycles) was applied through a stationary vertical pair of massive copper wheels beneath which the separate edges rolled immediately prior to being forced together by the horizontal c-shaped pressure rolls. A variation of this arrangement was also used with direct current to make DC ERW pipe.

Osborn[3] indicates that attempts were made as early as 1928 to make electric-welded pipe by means of inducing a high-frequency current (10,000 cycles) onto the edges of the skelp by a noncontacting inductor in much the same way that induction is used for post-weld heat treatment following most ERW processes. By the 1960s, this method had come into widespread use and it survives today as the HFI ERW method. The only difference is that modern HFI manufactures often utilize higher frequencies of 250,000 cycles or "medium" frequencies of 50,000 to 60,000 cycles.

Probably the most common method of making ERW pipe in the U.S. today, the HF technique involving radio frequency (450,000 cycles) alternating current applied through sliding contacts, was introduced in 1955[2]. This method is depicted conceptually in Figure 1.

Although it has not been produced since 1968, flash-welded (FW) pipe should be mentioned briefly. Unlike ERW pipe which is made continuously from long strips of skelp, FW pipe was made from individual rolled plates which were formed into cans prior to being welded. To this point, the FW cans were no different (except possibly by the method of forming) from the cans used to produce submerged-arc welded pipe. The FW seam was effected by electric-resistance heating of the edges of the cans as the entire lengths of both edges were brought together simultaneously. Mechanical pressure was used to forge and upset the material so that a flash weld looks similar to an ERW weld. In fact, the desired objective, a virtually indistinguishable bond, is the same in either case. There are important differences, however. In the first place, it is possible (though it was not always the case) for pipe made from plate materials to have mechanical properties more uniform than and superior to those of pipe made from coiled strip (plates can be cross-rolled, for example). Second, it was possible (and indeed it was common) for FW pipe to be of larger diameter than ERW pipe because of the inherent size limitations of ERW equipment and skelp-making facilities. Third and most importantly, most FW pipe was mechanically cold expanded after being welded. This was a step only rarely taken with ERW pipe, but it is believed to have resulted in an extra form of quality assurance compared to most ERW pipe because of the stress placed on the weld during the expansion process. For these reasons, FW pipe must be regarded as a separate and distinct type of pipe not to be confused with or lumped together with ERW pipe.

PROBLEMS PECULIAR TO ERW PIPE

First and foremost, it must be made clear that when the objective of ERW pipe manufacturing is met, namely, when the microstructural appearance and the mechanical properties of the bondline region are, in fact, virtually indistinguishable from or superior to those of the parent skelp, the quality of the product is at least equal to and can be superior to pipe made by any other method. Because of characteristics inherent in its manufacture, however, ERW pipe is susceptible to a unique set of problems. And, while it is readily possible today with adequate specifications and quality monitoring to obtain high-quality ERW line pipe, it is also readily evident that significant quantities of ERW pipe of less-than-optimum quality were manufactured, purchased, and installed in the past. The evidence for this appears not only in the pipeline accident statistics[9,10] but in the investigations of individual pipeline failures which seldom appear in the open literature.

ERW Seam Characteristics

Shown in Figure 2 is a 6.5 magnification photo of a polished and etched section across a typical HF ERW seam. The first things to note are that the top surface represents the inside surface of the pipe and that the bottom surface represents the outside surface of the pipe. The skelp material in this case is a conventional carbon-manganese X60 steel with a banded pearlite-ferrite microstructure. Characteristic of HF welding, the weld heat-affected zone (HAZ) is hour-glass shaped. This shape arises because of the manner in which the radio-frequency current tends to concentrate near the surfaces. The bondline is highlighted as a white line because just prior to bonding the edges were hot enough to have undergone some decarburization. There is nothing unusual or degrading about this bondline. As shown in Figure 3 at 250 magnification, this bondline (which is oriented horizontally in this figure) is much like the surrounding microstructure. Returning to Figure 2, one can see that the post-weld heat treatment has transformed the microstructure on both sides of the bondline over a width equal to about two wall thicknesses and that it has penetrated the entire wall thickness rather uniformly. That this heat treatment was successful is further evidenced by Figure 3 where it is seen that the HAZ is comprised of fine equiaxed ferrite grains

The remaining features to note with respect to a typical HF ERW seam are the degree of upset at the inside surface, the flash trim at both surfaces, the contact marks, and the upturned fiber pattern of the microstructure. First, a thickening of the material in two locations just beyond the edges of the heat-affected zone is noticeable. Actually, before the flash was trimmed, the entire weld zone was thicker as the intentional result of upsetting. The extra upsetting is done intentionally for several possible reasons. One reason can be to compensate for a possible loss of strength from post-weld heat treating. Another is to assure that all oxides and scale on the edges of the skelp are forced out of the bondline region. In any case, the extra upsetting is always toward the I.D. surface, and the I.D. surface trim is usually arc shaped as shown in Figure 2. At the O.D. surface, however, the trim is flush so that there is nothing to interfere with the inspection of the weld.

The dark areas of the microstructure at the intersection of the edges of the HAZ and the O.D. surface are contact marks. These correspond to the path of the sliding contacts and are points of very high current. Often these zones are transformed to austenite and may upon cooling have a somewhat different microstructure from that of the original skelp. In some cases, these zones may exhibit excessive hardness not unlike arc burns. Usually, however, they are left in an acceptable state of hardness following post-weld heat treatment.

The final feature of note in Figure 2 is the upturning of the ferrite-pearlite banded structure of the skelp. Whereas in the skelp the banding is parallel to the surfaces of the skelp, it ends up being parallel to the bondline adjacent to it.

What is shown in Figure 2 is a typical ERW seam for a conventional line-pipe material The features noted above for this seam are all within acceptable limits with respect to the soundness of the weld. It is possible to obtain even more uniform ERW welds than the one shown in Figure 2. One such weld which one might say is an "ideal" ERW weld, is shown in the top portion of Figure 4. In this case, the evidence of the bondline is obliterated by the heat treatment and only a faint image of the hour-glass-shaped region remains.

In the bottom half of Figure 4, a typical LF ERW weld is shown. This photograph illustrates the relatively deeper penetration of the low-frequency current. This particular weld while sound in terms of the absence of defects exhibits some of the undesirable features of many LF ERW seams. The bondline itself is rather wide and is surrounded by grain-coarsened base metal, a sign of excessive heat. Also, the contact marks are more like contact burns. Like many older LF ERW seams, the I.D. flash has been trimmed but not to the extent that one finds in HF ERW seams. For comparison, a DC ERW seam is shown in Figure 5. It has many similarities to the LF ERW seam shown in the bottom half of Figure 4.

A typical FW seam is shown in Figure 6. Like the LF ERW weld, it exhibits a distinct bondline and a wide HAZ. One of the characteristic features of an FW seam is the flash trim. The characteristic wide, square flash at both the I.D. and O.D. surfaces is unique to an FW seam. Some ERW processes are known to have left a significant O.D. flash as well as an I.D. flash but none is as wide as that of a true FW seam.

ERW Seam Defects

Terminology

Because a number of confusing terms have arisen in regard to imperfections in ERW welds, the author prefers to defer to the "Definitions of Imperfections and Defects Occurring in Electric Resistance Welds" given in API Bulletin 5T1 (Ninth Edition)[11]. The following defects will be discussed using those terms.

For example, Figure 7 illustrates a hydrostatic test break which originated at a series of defects in an LF ERW seam. The tell-tale black-oxide patches visible on the fracture surface indicate one of the typical defects in ERW seams, namely, "cold-weld" zones. According to Reference 11, a cold weld is "a lack of adequate bonding". It is caused by the application of "insufficient heat and/or pressure". It "may or may not have separation in the weld line" according to Bulletin 5T1, but it is certain that a separation existed at the surfaces coated with black oxide in the patches of Figure 7. More examples of cold welds will be presented later.

Misalignment

Misalignment is not, in and of itself, a defect; it may, however, result in defects or conditions which will later produce defects. Many types of misalignment arise in the making of ERW welds. The edges of the skelp may be misaligned vertically creating a kind of high/low condition not actually defined in Reference 11 or in the API Specification 5L. More common, however, is the misalignment of various steps in the process resulting from the tendency of the skelp to twist as it moves through the forming and welding stands. One possible result is the misalignment of the post-weld heat treatment as illustrated in Figure 8. In this case, the heat treatment was offset from the bondline probably because the skelp was twisting through the mill. One way to minimize these kinds of problems is to institute automatic feedback controls. As described in Reference 12, this involves transducers and limit switches monitored by a computer which senses irregularities as the skelp moves through the mill and makes appropriate corrections. Unfortunately, all too many mills are still run with only manual control relying on a human observer or subsequent nondestructive inspection to indicate the presence of a problem.

Cold Welds

Colds welds have already been mentioned, but they can be a significant problem in older ERW materials. Fortunately, the incidences of cold welds have diminished significantly in materials manufactured in the last 20 years especially since the advent of HF and HFI welding. Nevertheless, it still may occur even in an HF or HFI material. Examples of cold welds are shown in Figures 9-12. Figure 9 and 10 are metallographic sections through cold welds in an HF seam and an LF seam, respectively.

The typical appearances of fracture surfaces involving cold welds are shown in Figures 11 and 12. Figure 11 shows a series of black-oxide patches where no bond existed. The repetitive pattern accompanying these patches is "stitching". Stitching is a phenomenon unique to LF welded seams. It is a "variation in properties of the weld occurring at short, regular intervals". Stitching arises from the pipe being welded too rapidly such that 60-cycle power fluctuations were being translated into nonuniform heating of the seam. A stitched region may be interspersed with cold welds or it may not be, but it certainly results in less-than-optimum bondline toughness. Note the absence of stitching on the continuous disbonded region of the DC-welded seam shown in Figure 12.

Cold welds are an indication that either the welding heat or the pressure or both were not conducive to proper welding. The problem was much more likely to occur with LF welding than with HF welding because the former was much more sensitive to contact resistance. In fact, when HF welding was introduced, it was found to be unnecessary to pickle or sandblast the edges of the skelp to achieve good contact[2]. Furthermore, in the period prior to widespread use of HF welding, the ability of mill-inspection techniques to detect cold welds was much poorer than it is today. In particular, neither the ring flattening nor the weld tensile tests were reliable means of detecting poorly bonded seams.

Cold welds are in the author's opinion the worst kind of defect associated with ERW seams. When a poorly bonded seam exists, it is virtually certain that what material remains intact is of very low toughness. In a series of full-scale tests of one particular lot of LF ERW pipe[13], it was shown that the fracture toughness of the bondline region was the equivalent of 2 ft-lb of absorbed energy in a Charpy V-notch impact specimen (full size). In comparison, one could expect the skelp of an X52 line-pipe material to exhibit a toughness equivalent to at least 25 ft-lb. As will be shown subsequently, this results in poorly bonded ERW materials not being able to tolerate very large defects. Fortunately, as documented in Reference 8, the improvements in recent years in the manufacturing of ERW pipe have led to seams having toughnesses more like that of the parent skelp.

Martensitic Microstructure

A rare condition associated with some older ERW materials is the existence of untempered martensite in the weld zone as the result of inadequate post-weld heat treatment. The problem this may cause is that even if the material contains no defects initially it is susceptible to developing hydrogen cracking in service if, for example, it is exposed to hydrogen charging in the soil environment from cathodic protection. An example of hydrogen cracking in a martensitic weld zone is shown in Figure 13.

Hook Cracks

According to API Bulletin 5T1, hook cracks are "metal separations resulting from imperfections at the edge of the plate or skelp, parallel to the surface which turn toward the I.D. or O.D. pipe surface when the edges are upset during welding" Examples of hook cracks are shown in Figures 14-17. Figure 14 shows the presence of a small hook crack near the O.D. surface of an LF-welded pipe material. Note the the crack is not in the bondline but curves outward from the plane of the plate in the upset material near the bondline. In Figure 15, the horizontal lines on the fracture surfaces correspond to hook cracks. Note the contrast between this "woody" appearance and the vertical orientation of stitches and bondline imperfections in the lower photograph of Figure 15.

Hook cracks associated with an HF-welded seam are shown in Figure 16. These are similar to those shown near the LF seam in Figure 14 as are the woody appearances of the HF seam hook cracks on the fracture surfaces in Figure 17. Whether hook cracks occur in association with LF or HF seams, they are the same because their source is the skelp not the welding process. They arise from "dirty" (high-sulfur) steels because of the tendency of such materials to contain elongated nonmetallic inclusions. The inclusions are formed when the ingot is cast and are elongated parallel to the surfaces of the skelp during hot rolling of the strip. As long as they remain in that orientation, they have little effect on the integrity of the skelp (although they tend to have an adverse effect on the ductile fracture resistance of the material). When the edges of the skelp are upset during welding, however, these nonmetallic layers become oriented perpendicular to the maximum principal stress direction. In this orientation, they have a detrimental effect on the pressure-carrying capacity of the pipe.

Hooks cracks can be a severe problem in the retesting of pipelines comprised of older ERW materials. They are often the cause of hydrostatic test failures. And while it is desirable to remove them in this manner, it is frequently the case that the test itself enlarges those which do not fail. More will be said about this later.

Hook cracks can be practically eliminated from any new pipe materials by using ultra low-sulfur steels or sulfide-shape control practices wherein those sulfides which do form are not rolled out into elongated layers.

Selective Corrosion

Selective corrosion can occur in service in some ERW seam materials. In particular, the high-sulfur materials seem to be more of a problem[14]. Selective corrosion of an ERW seam may occur in conjunction with corrosion of the body of the pipe. The difference is that because certain ERW weld zones are more susceptible to corrosion than the surrounding skelp, the bondline of weld and some of the HAZ is preferentially corroded at a higher rate than the surrounding material. The result is often the formation of a v-shaped groove centered on the bondline as shown in Figure 18. At the O.D. surface, the corrosion appears as a linear slot as shown in Figure 19.

Selective corrosion represents a potentially severe defect. It tends to form a relatively sharp notch in a material which is usually a lot less tough than the parent skelp. Pipe with such defects should be removed if the grooving is anything but superficial. In particular, no attempt should be made to evaluate the remaining strength of the pipe utilizing the ASME B31G criterion.

EFFECTS OF ERW SEAM PROBLEMS ON PIPELINE INTEGRITY

Critical Flaw Size

The effect of low toughness in the bondline region of older ERW materials can be seen by comparing critical flaw sizes in Figures 20 and 21. The curves in these figures are based upon the well-known surface flaw equation developed through research by the Pipeline Research Committee of the American Gas Association[15]. Both figures are failure-pressure-versus-flaw-size relationships for 16-inch O.D. by 0.250-inch wall thickness X52 pipe. The difference is that Figure 20 is based on a full-size Charpy V-notch specimen equivalent toughness of 25 ft-lb representing the typical level of toughness which one may expect for the skelp while Figure 21 is based on a full-size Charpy equivalent toughness of 2 ft-lb as was found for the LF seam examined in Reference (13). Compare the critical flaw lengths at the maximum operating pressure (MOP). A longitudinally oriented flaw in the skelp which is 50 percent through the wall thickness would have to be nearly 6-inches long to cause a failure. In contrast, a 50-percent-through flaw in the bondline which was only 2-inches long would be expected to cause a failure. Also, note the location of the leak/rupture dividing line. Based on Figure 20, a flaw longer than 3 inches is necessary for a failure to occur as a rupture at the MOP. In contrast, a flaw in the bondline (based on Figure 21) needs to be only about 1-1/2 inches in length to cause a rupture at the MOP.

The combination of an abundance of small bondline flaws in older ERW materials (particularly LF and DC welded materials) and the effect of the low toughness as demonstrated by Figures 20 and 21 tends to explain why older ERW materials have a rather dismal track record[9,10] compared to ERW materials of more recent vintage and to line-pipe materials made by other processes.

Pressure Reversals

A phenomenon regularly associated with the retesting of pipelines containing older ERW materials is that of a "pressure reversal". The concept of a pressure reversal can result following the raising of the pressure level of a defective segment of pipe to a level high enough to cause the flaw to fail but the pressure is not held long enough for all of the necessary time-dependent growth to take place. Instead, before the flaw has time to grow to failure, the pressure is removed. The phenomenon is illustrated in Figure 22. Upon repressurization, the flaw begins to grow at a lower pressure level because it has been enlarged by the previous loading. It can grow to failure at a pressure level below that reached on the previous pressurization, and if it does, a pressure reversal is said to occur. In the testing of older ERW pipelines, pressure reversals are common, although reversals larger than 10 percent of the initial test pressure are rare. As a result, once a hydrostatic test has been successfully completed, one can have a reasonable degree of confidence that no remaining flaw will be large enough to fail at the MOP.

Flaw Growth in Service

If a pipeline contains numerous flaws as may be the case in an older pipeline comprised of an ERW seam material having one or more of the problems described above, it is possible that those flaws may grow in service if the service consists of many large pressure fluctuations. The potential for this kind of flaw growth, if it exists, can be dealt with by periodic retesting of the pipeline. The interval for such retesting can be predicted on the basis of an existing model[16].

RECOMMENDATIONS

For the pipeline operator who must deal with keeping a pipeline comprised of a problematic ERW material operating safely, some guidance is available as follows.

First, hydrostatic retesting is a prudent and reliable means of establishing the integrity of such a pipeline. As has often been discussed[17], the higher the margin between test pressure and operating pressure, the more effective the test in establishing serviceability. It is the author's opinion that the conventional ratio of test pressure to operating pressure of 1.25 may not be sufficient if the pipeline has a demonstrated track record of service failures or a high rate of seam splits during testing. As a rule of thumb, when the hydrostatic test failure rate exceeds one per mile, it is a sign that the margin of test pressure to operating pressure needs to be more like 1.35 to 1.4 to assure an adequate level of safety.

Second, when an older ERW pipeline is retested, one need not hold the test pressure for long periods of time (more than 1/2 hour, for example). Also, it is a good idea to avoid cycles of test pressure because experience shows that large pressure reversals are more apt to occur as cycles of test pressure become more numerous. Therefore, if possible, it is desirable to raise the test pressure to the target level and hold it briefly. If it is necessary to conduct a leak test, do it after lowering the pressure to no more than 90 percent of the maximum test pressure. Now, it is obvious that such a scenario is not feasible if test failures begin to occur before the target test pressure is reached. If they do, it becomes necessary to continue testing and breaking flaws until the target level is reached. Otherwise, the desired test-pressure to operating-pressure margin will not have been demonstrated. It is also obvious that repeated test failures introduce numerous cycles of test pressure. This is unfortunate because the cycles undoubtedly induce more flaws to grow. But it is never a good idea to sacrifice the margin between test pressure and operating pressure. If the pipeline operator feels that the target test pressure must be abandoned in favor of a lower test pressure to reduce the number of failures, he should be prepared to lower the subsequent MOP as well to maintain an adequate margin of safety.

Finally, in a program of retesting of older ERW pipe, it is a good idea to keep a record of all leaks and ruptures especially if related to seam flaws. At least, it is useful to document such items as failure pressures (referenced to a common elevation for a given test section), numbers of failures per test section, size and location (on the pipe) of the splits or seepers, and to visually ascertain, if possible, whether the failure is the result of a cold weld, a hook crack, selective corrosion, or some cause not readily identifiable. When one knows the failure rates and causes that are typical for a given pipeline segment, it is possible to obtain an improved assessment of the serviceability of the segment and to forecast when, if ever, the segment should be considered for future rehabilitation.

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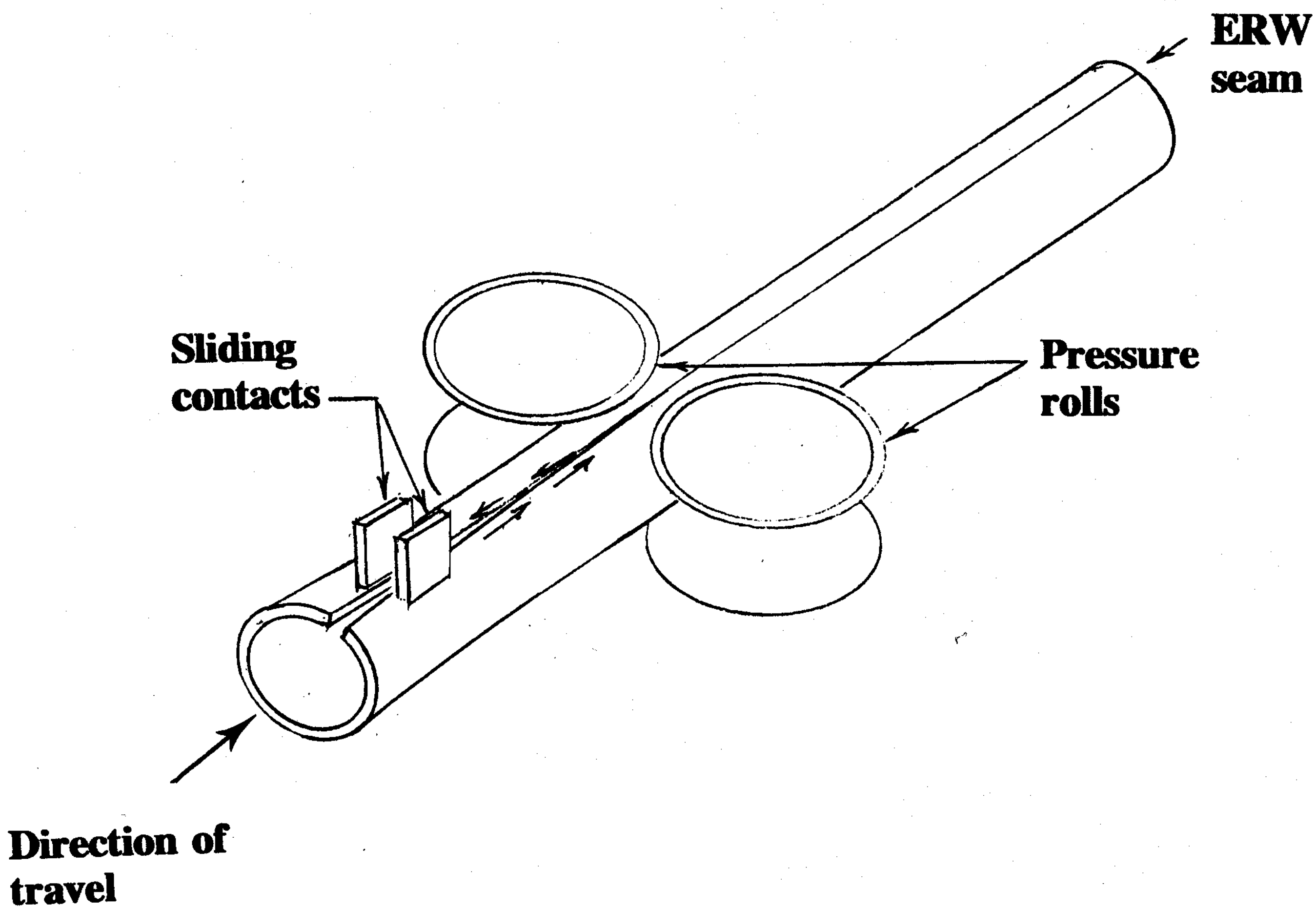

FIGURE 1. KEY ELEMENTS OF A HIGH-FREQUENCY ERW PIPE WELDER

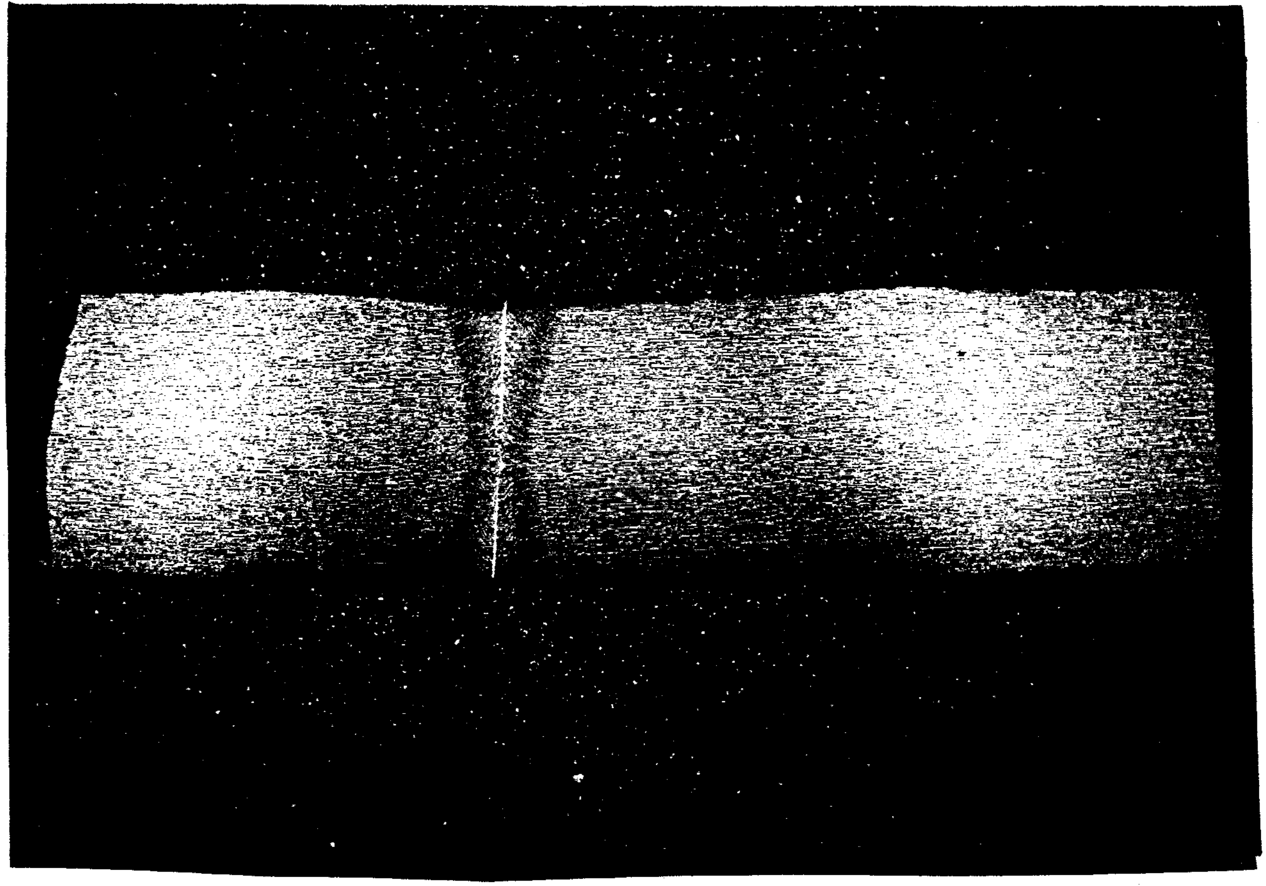

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FIGURE 2. TYPICAL HF ERW SEAM

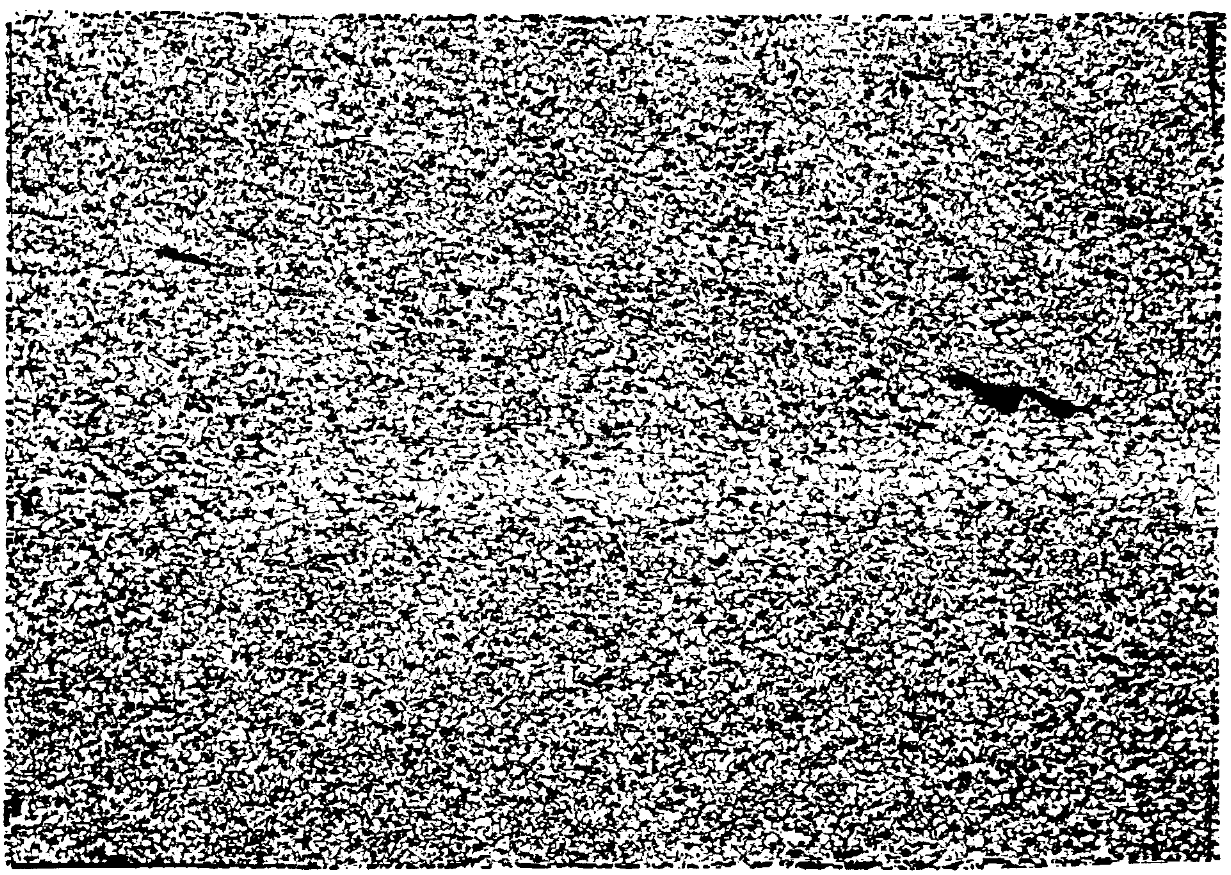

FIGURE 3. MICROSTRUCTURE OF THE BOND LINE

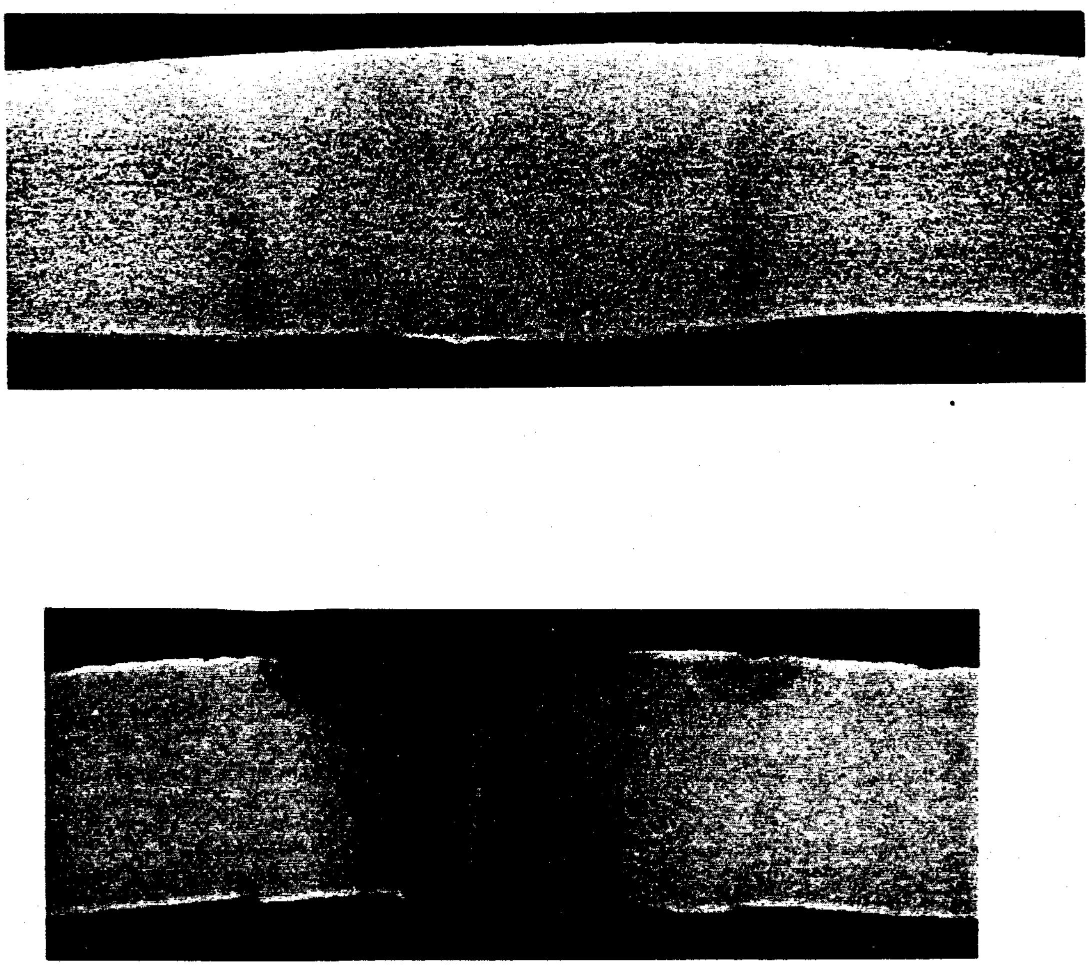

FIGURE 4. AN IDEAL HF ERW WELD AND A TYPICAL LF WELD COMPARED

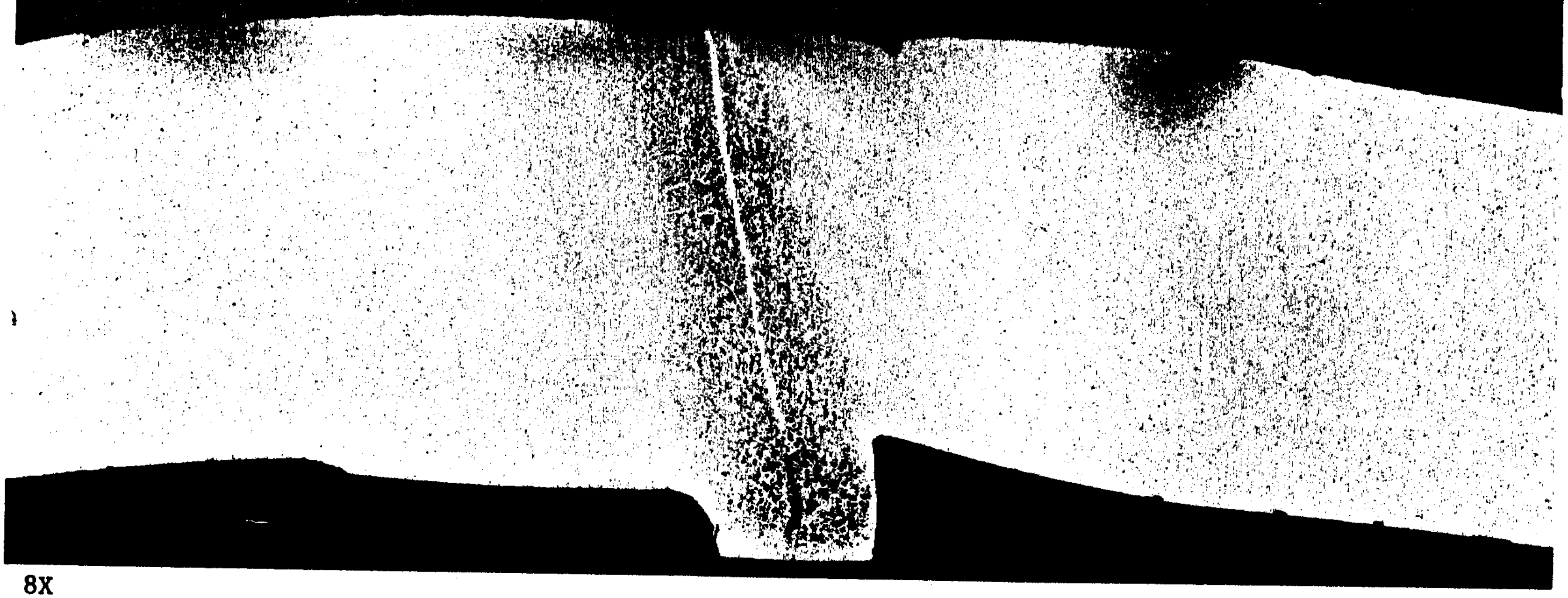

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FIGURE 5. A DC ERW WELD

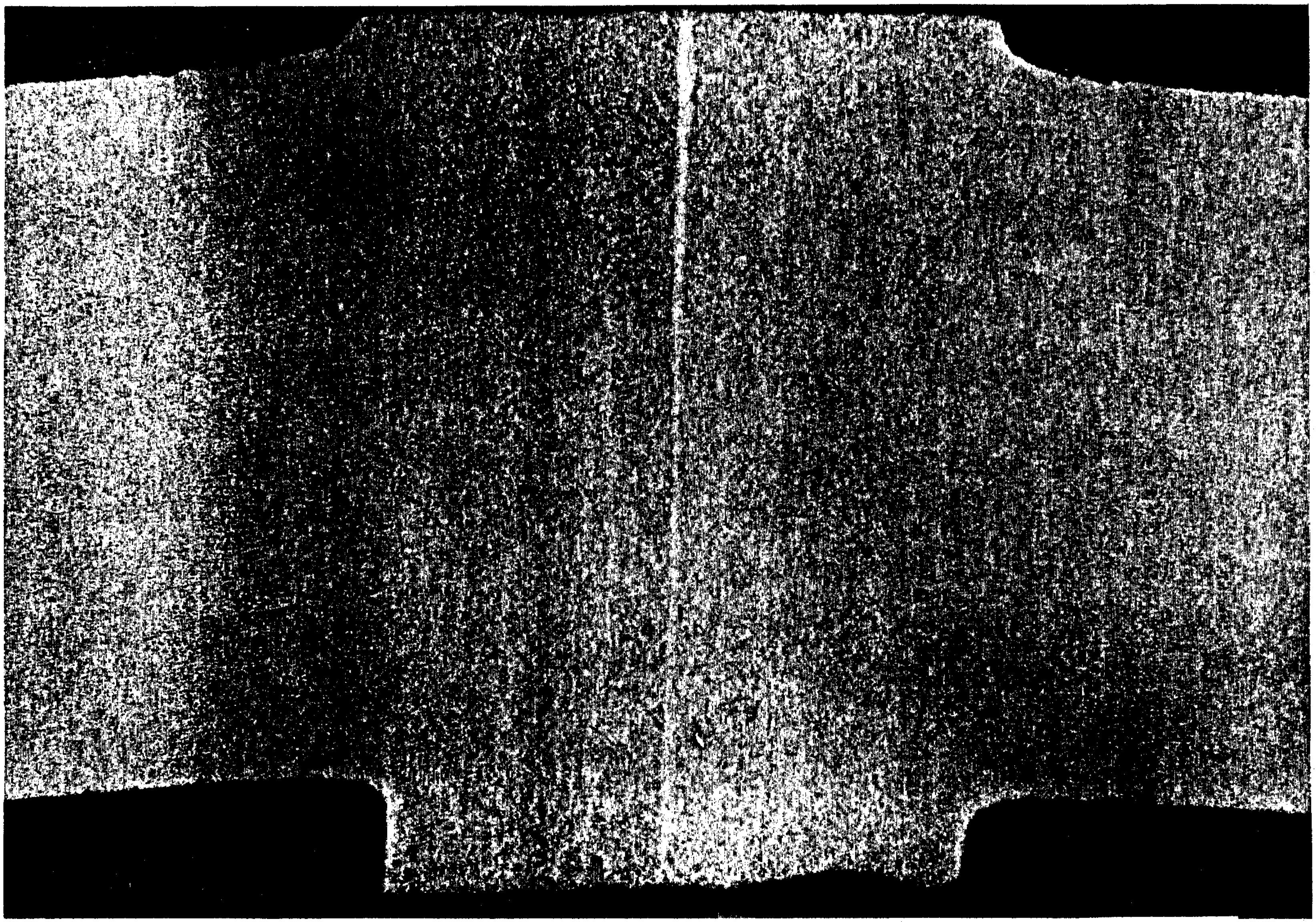


FIGURE 6. A FLASH-WELDED SEAM

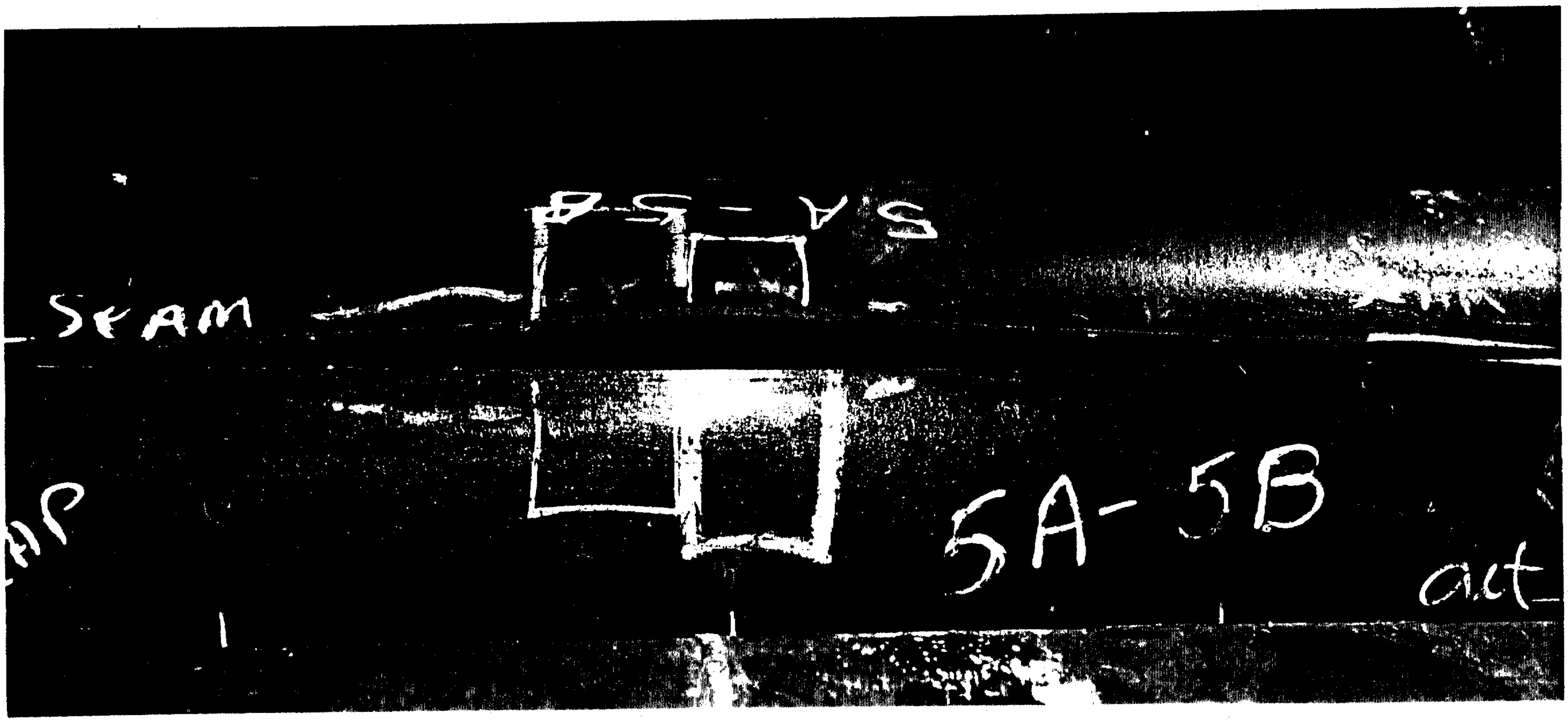


FIGURE 7. HYDROSTATIC TEST BREAK

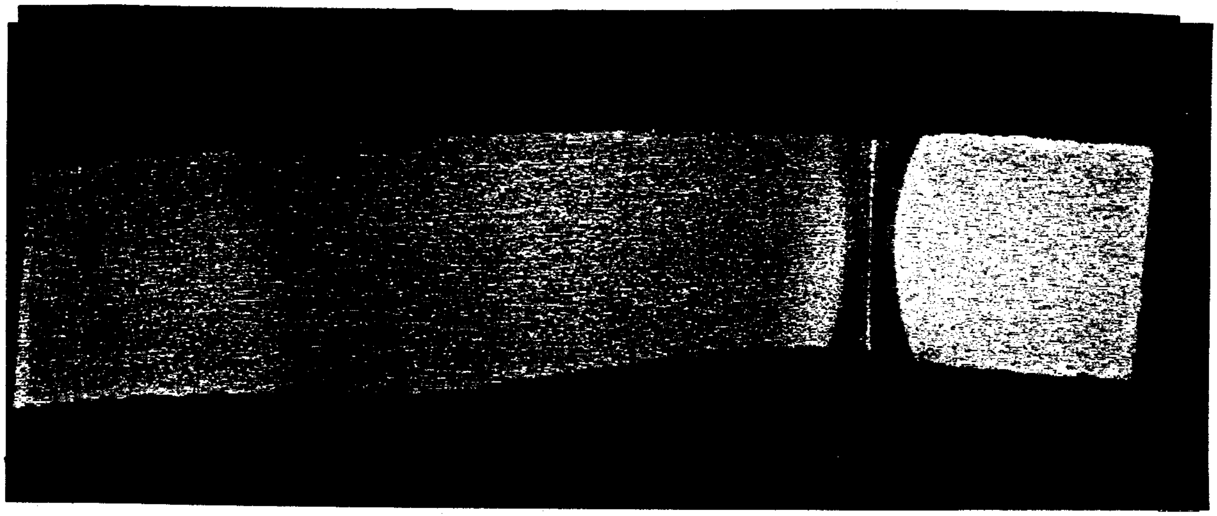


FIGURE 8. MISALIGNMENT

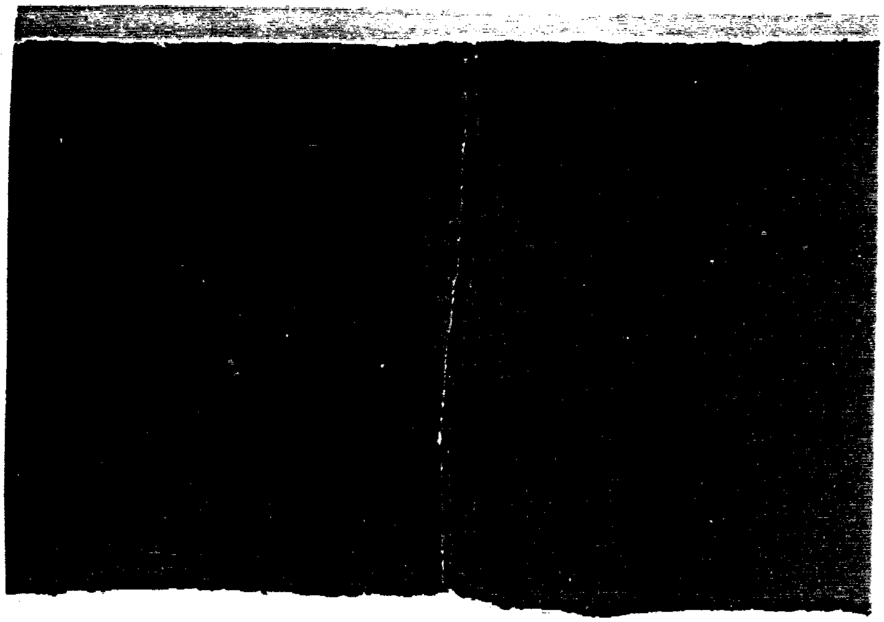


FIGURE 9. A COLD WELD IN HF ERW PIPE

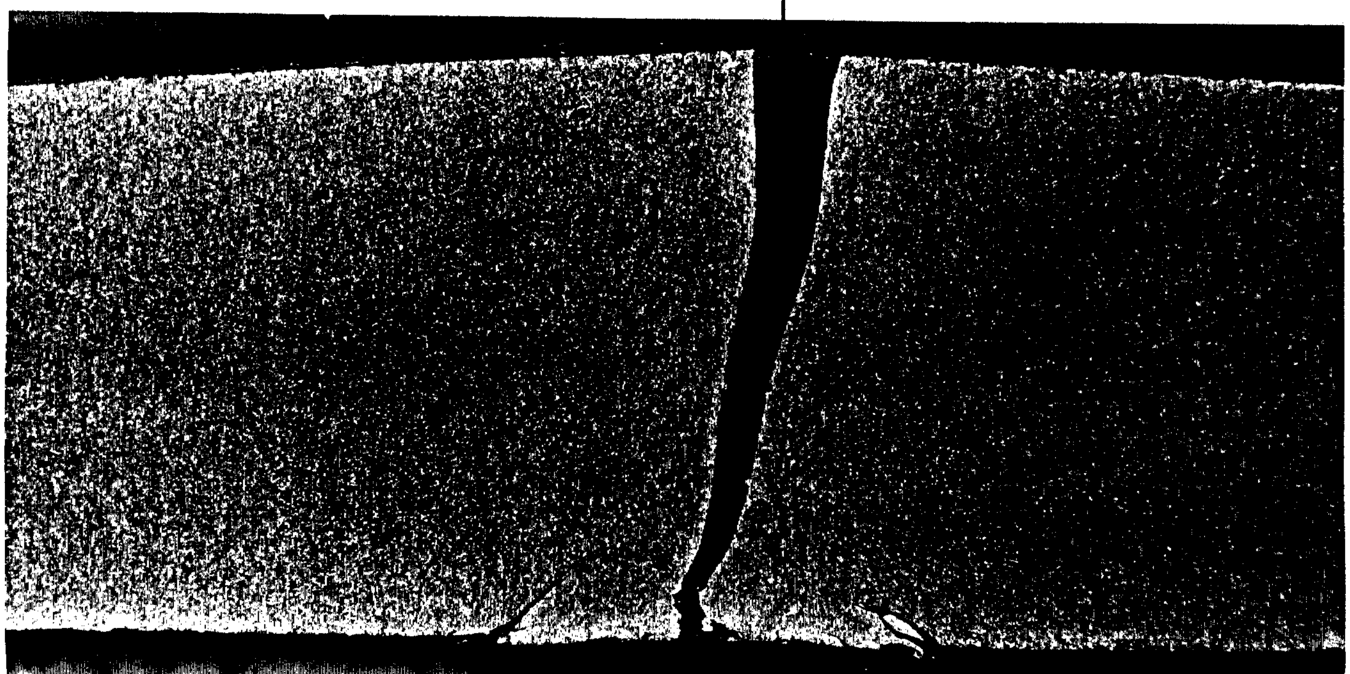
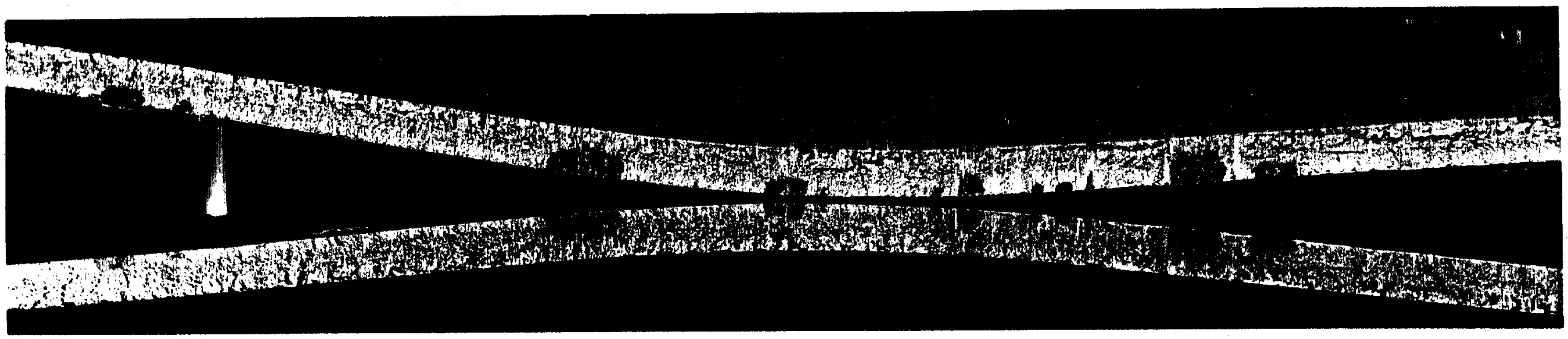
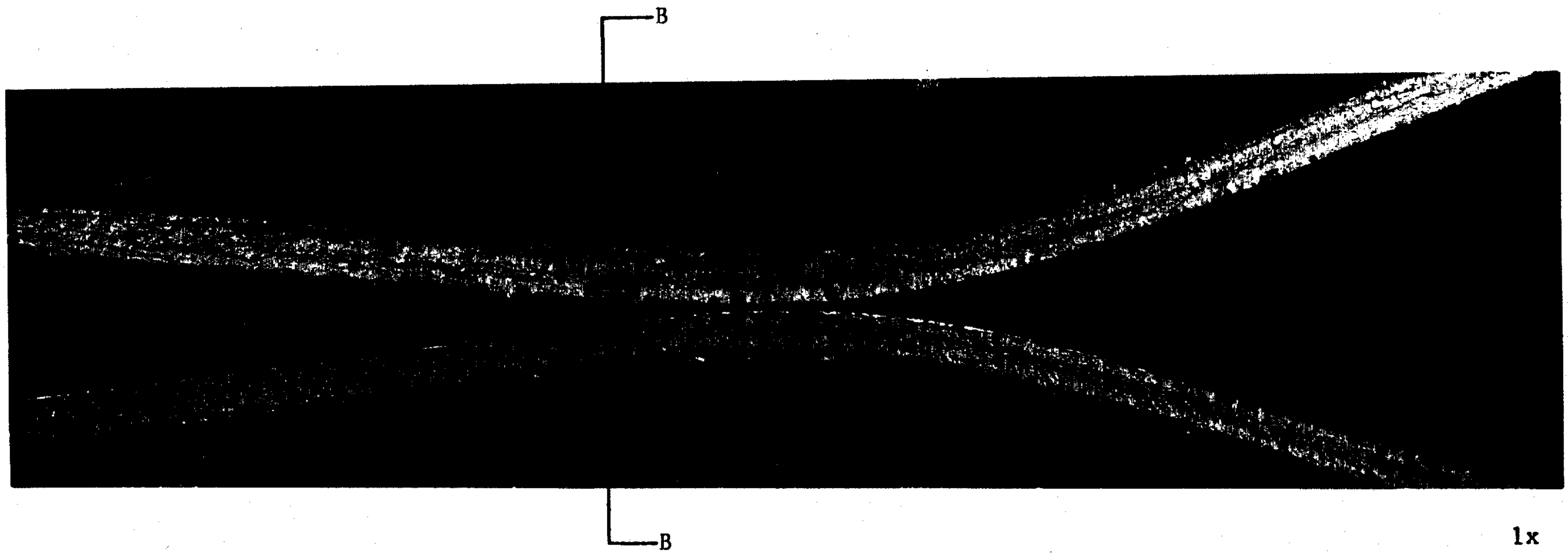


FIGURE 10. A COLD WELD IN LF ERW PIPE



Specimen 3, Defect 8

1x



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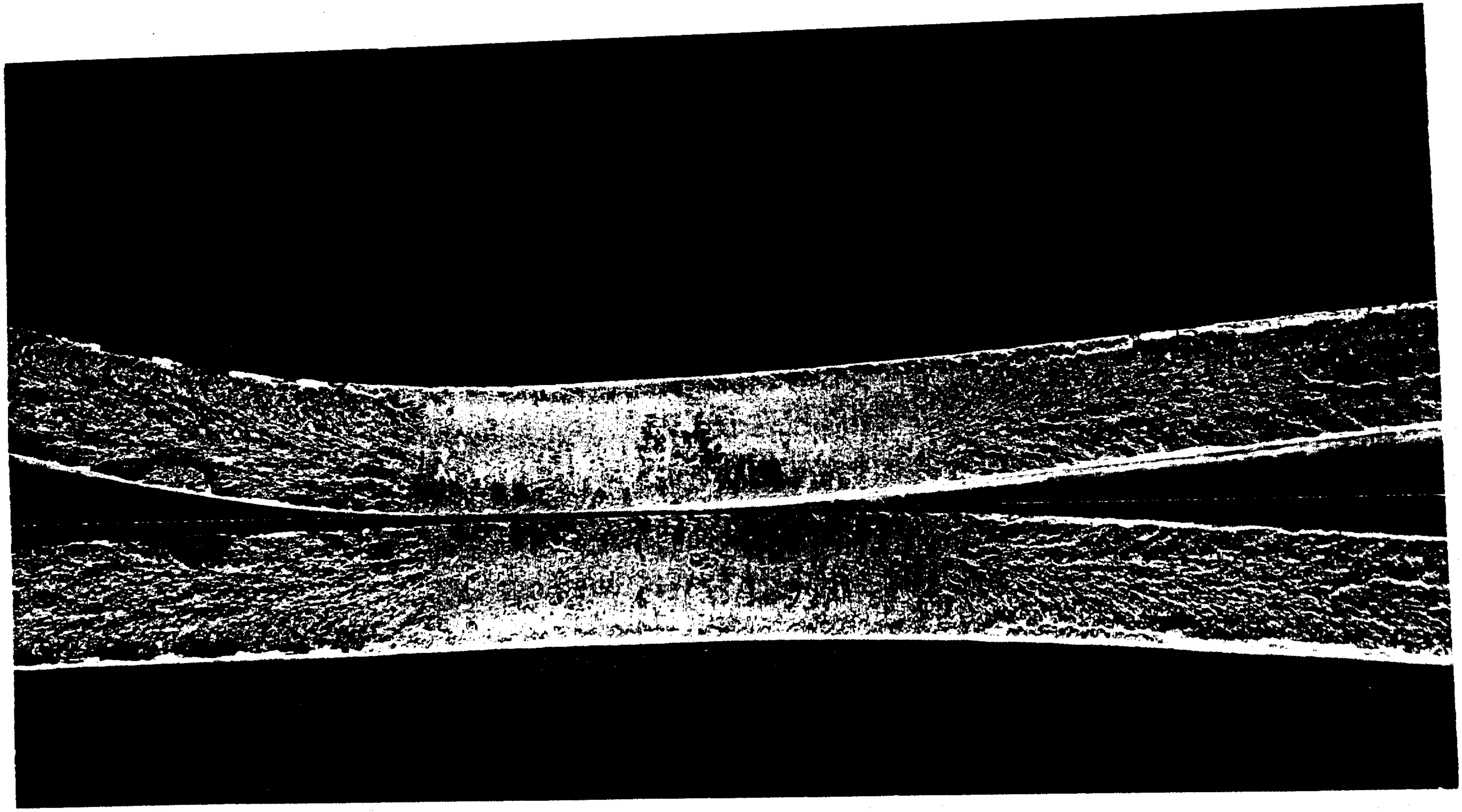
Specimen 4, Defect 11

FIGURE 11. THE FRACTURE SURFACE OF A POORLY BONDED LF ERW PIPE



~ 2X

FIGURE 12. THE FRACTURE SURFACE OF A DC WELDED ERW PIPE

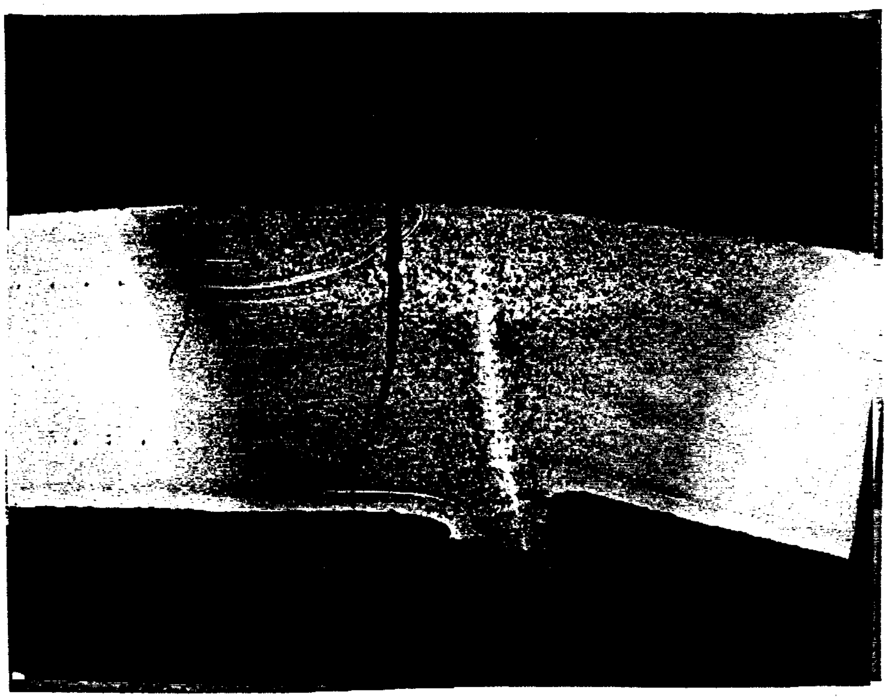


FIGURE 13. A HARD HAZ IN DC WELDED ERW PIPE

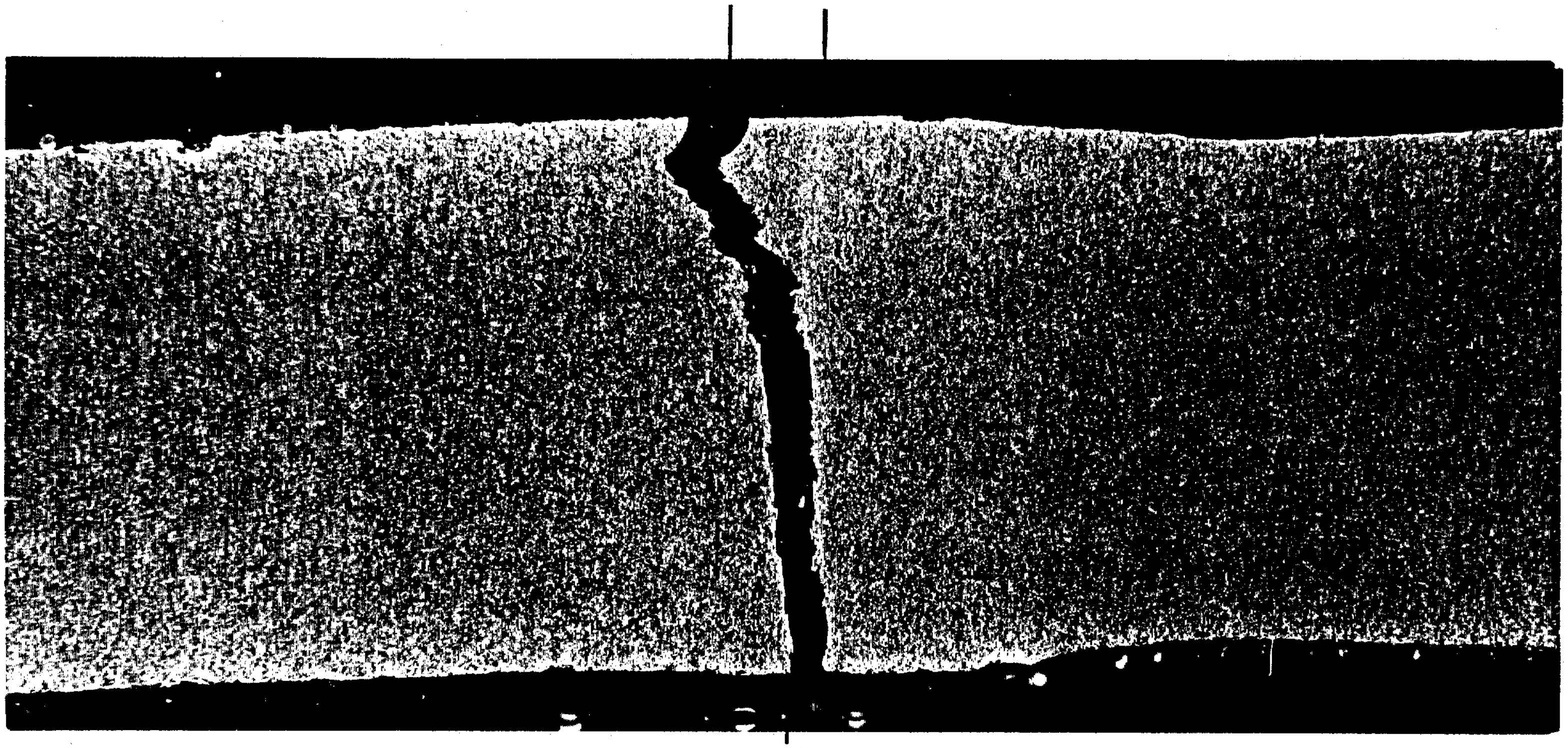


FIGURE 14. HOOK CRACKS, LF ERW SEAM

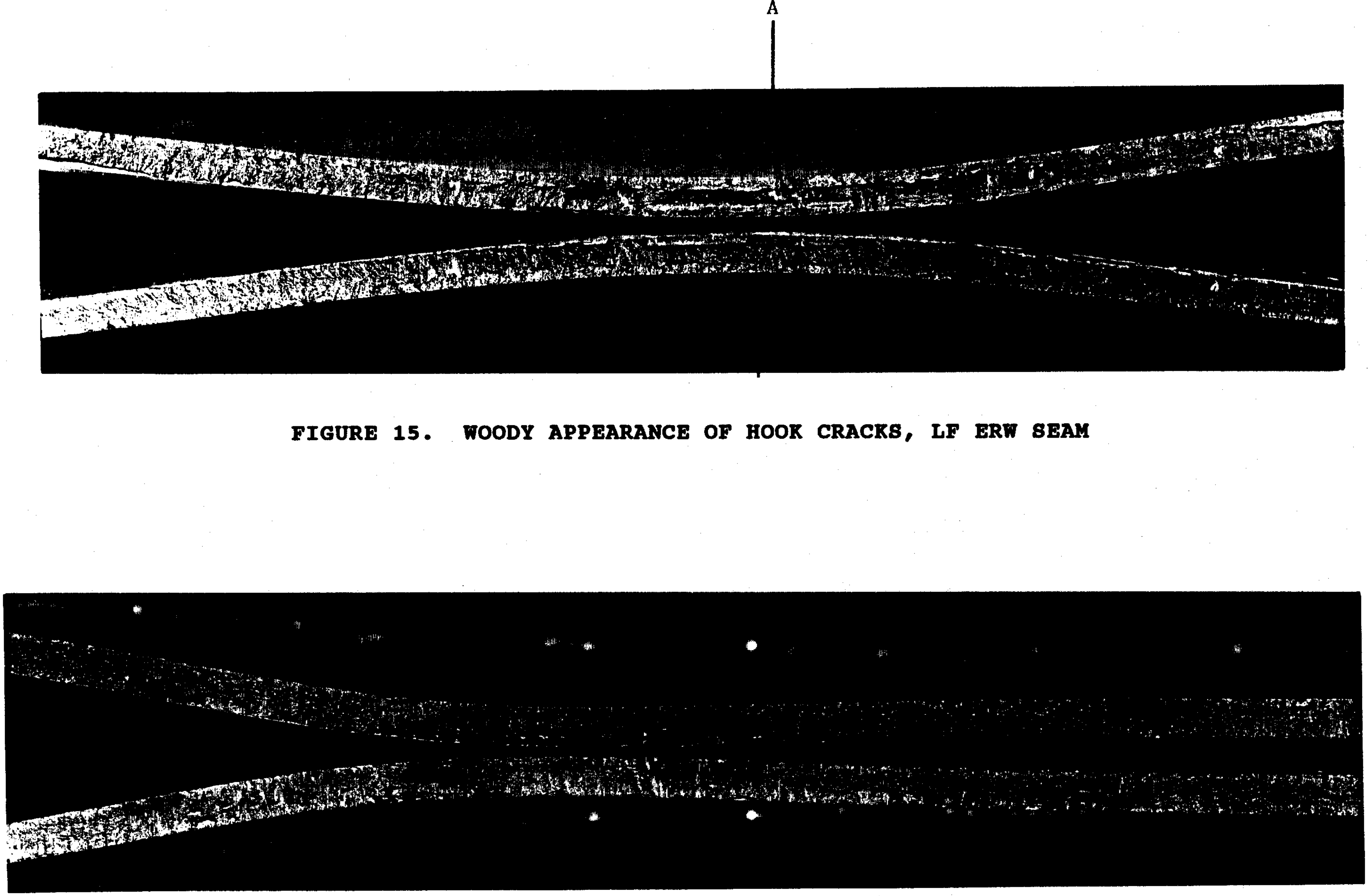


FIGURE 15. WOODY APPEARANCE OF HOOK CRACKS, LF ERW SEAM

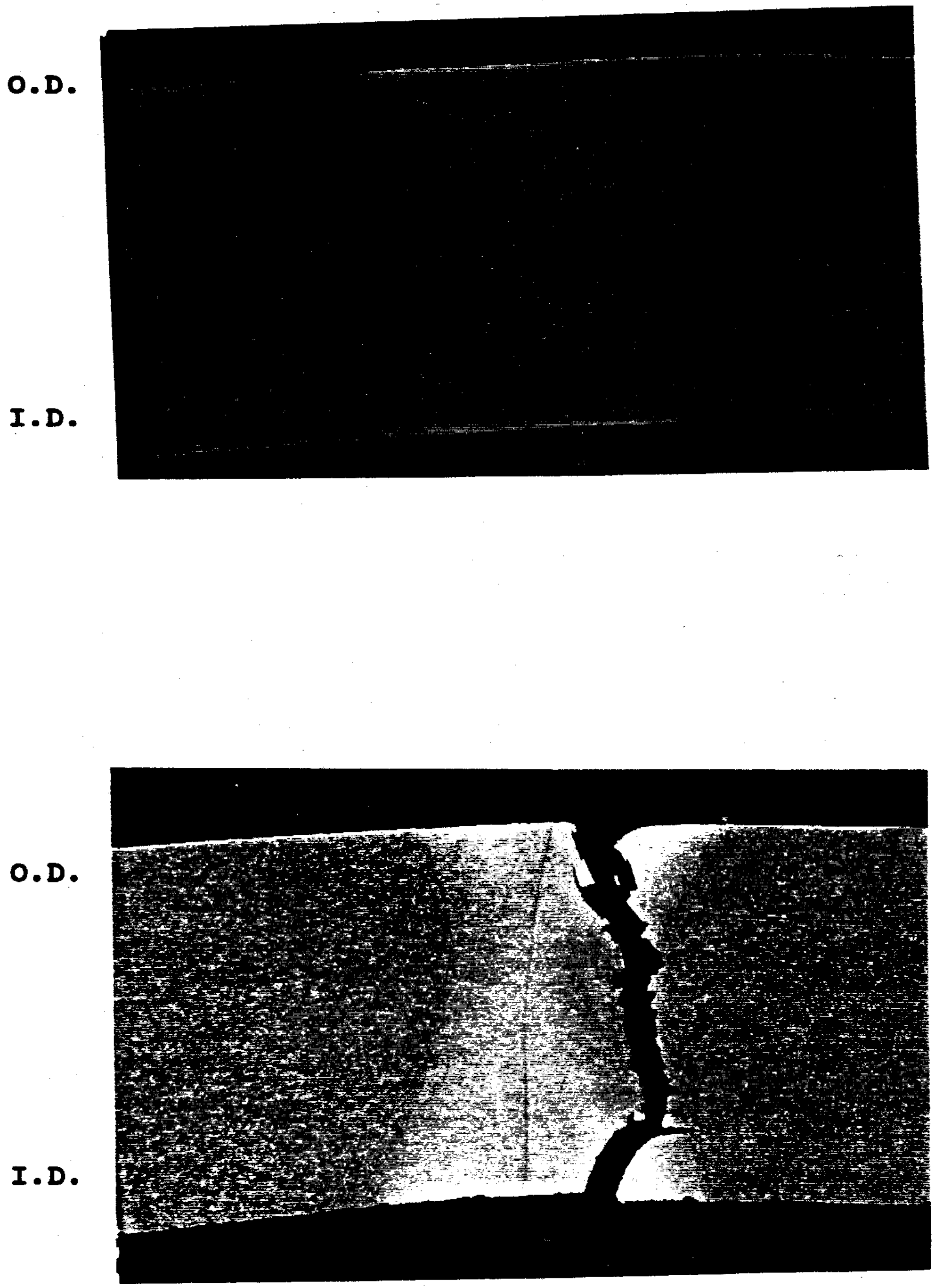


FIGURE 16. HOOK CRACKS, HF ERW SEAM

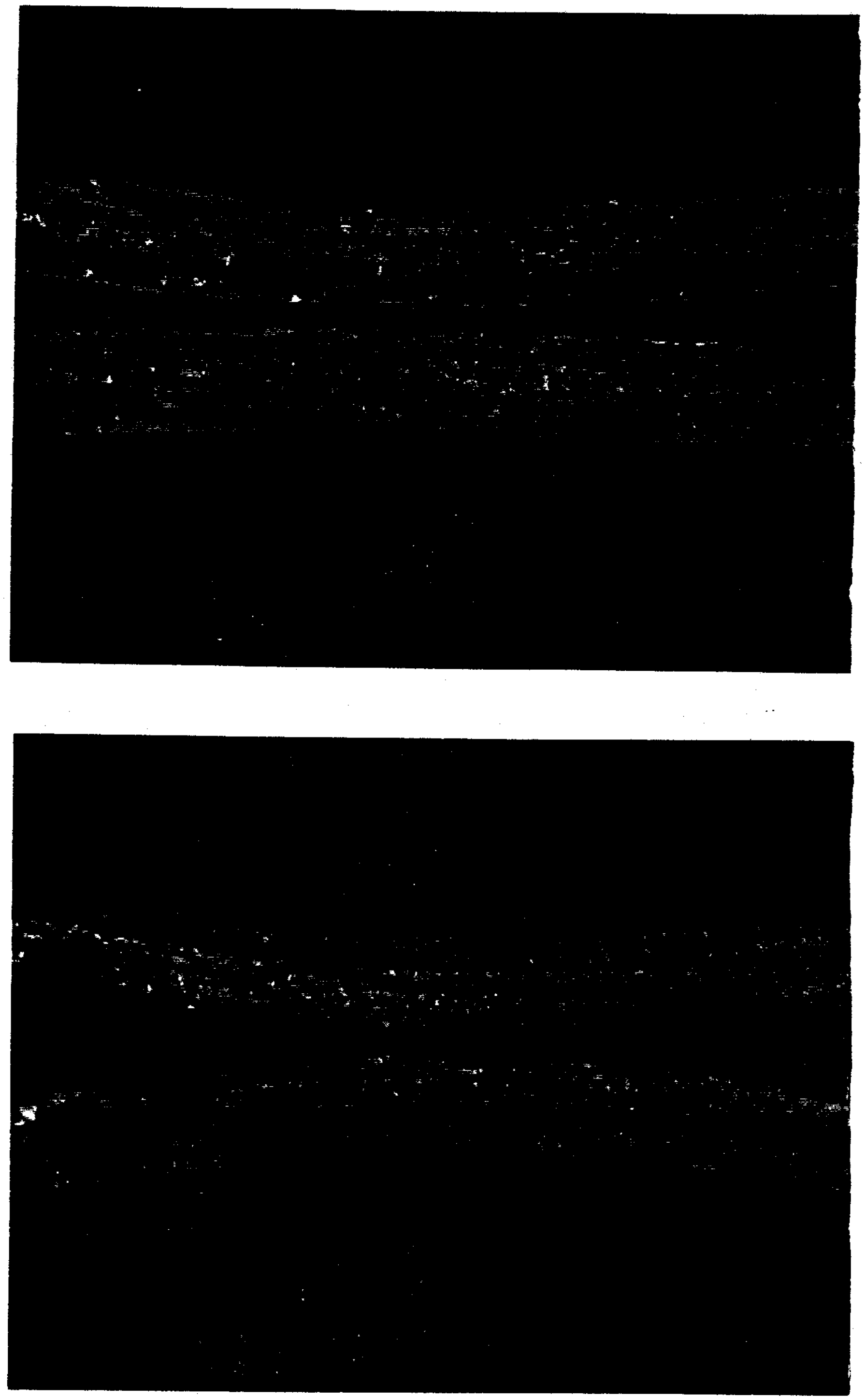


FIGURE 17. WOODY APPEARANCE OF HOOK CRACKS, HF ERW SEAM

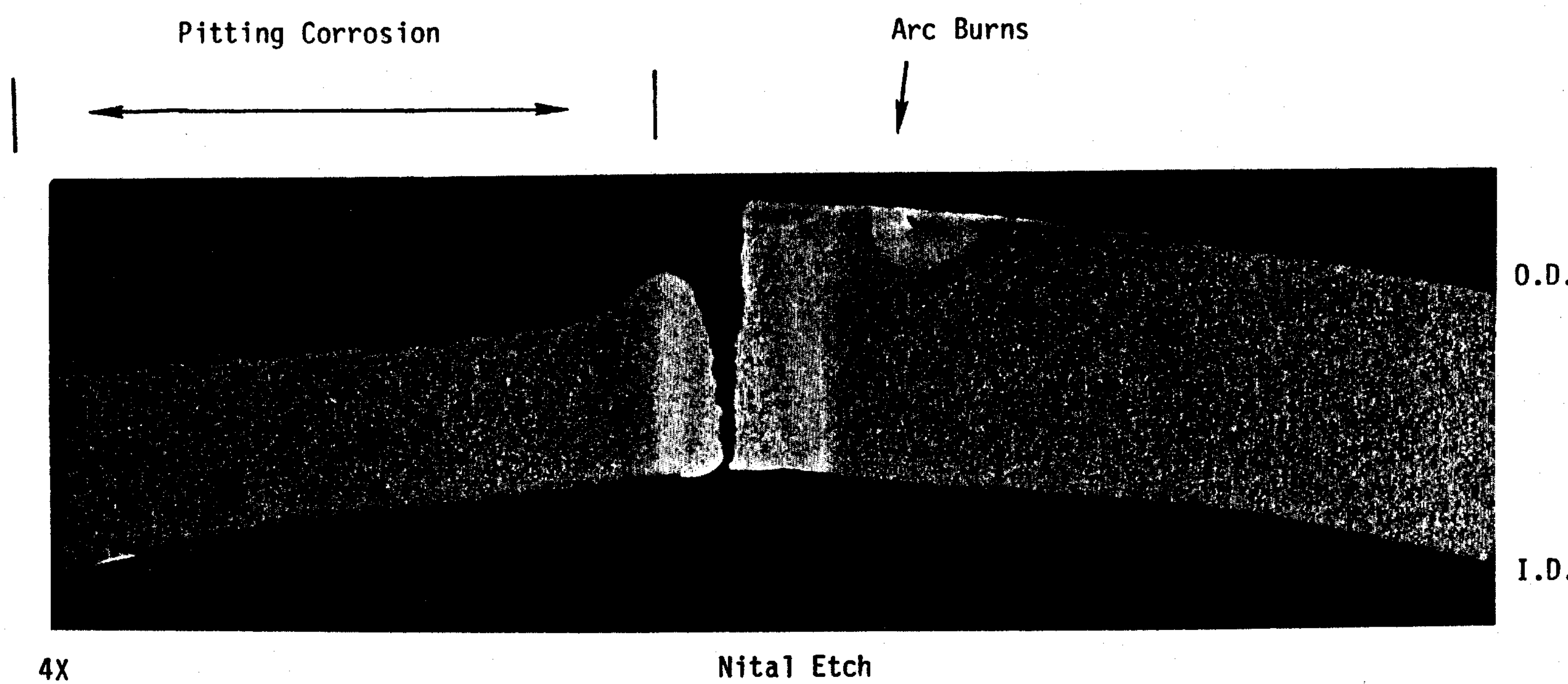


FIGURE 18. SELECTIVE CORROSION OF ERW SEAM

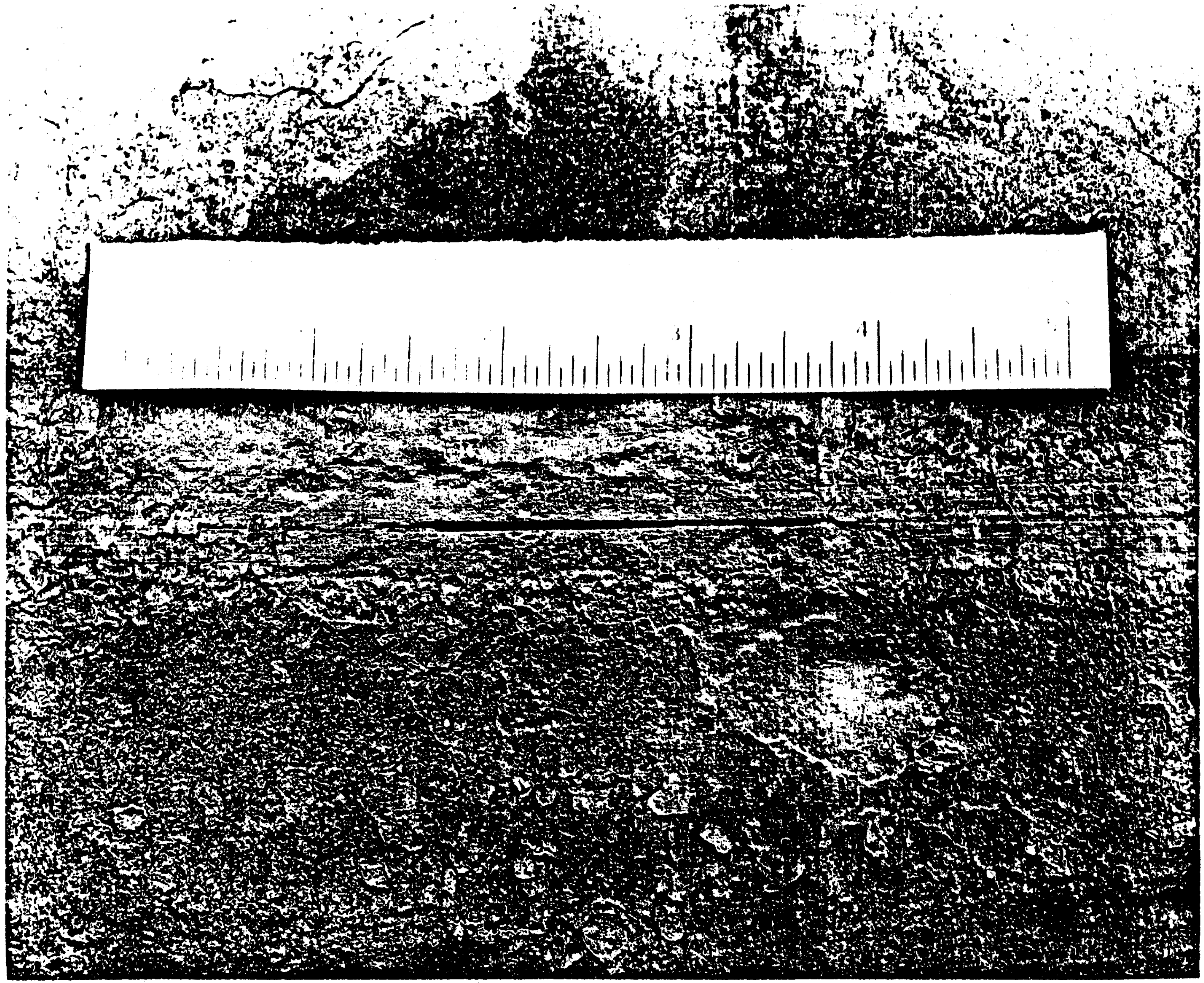


FIGURE 19. APPEARANCE OF SELECTIVE CORROSION AT O.D. SURFACE OF PIPE

16-inch O.D. x 0.250-inch wall thickness X52

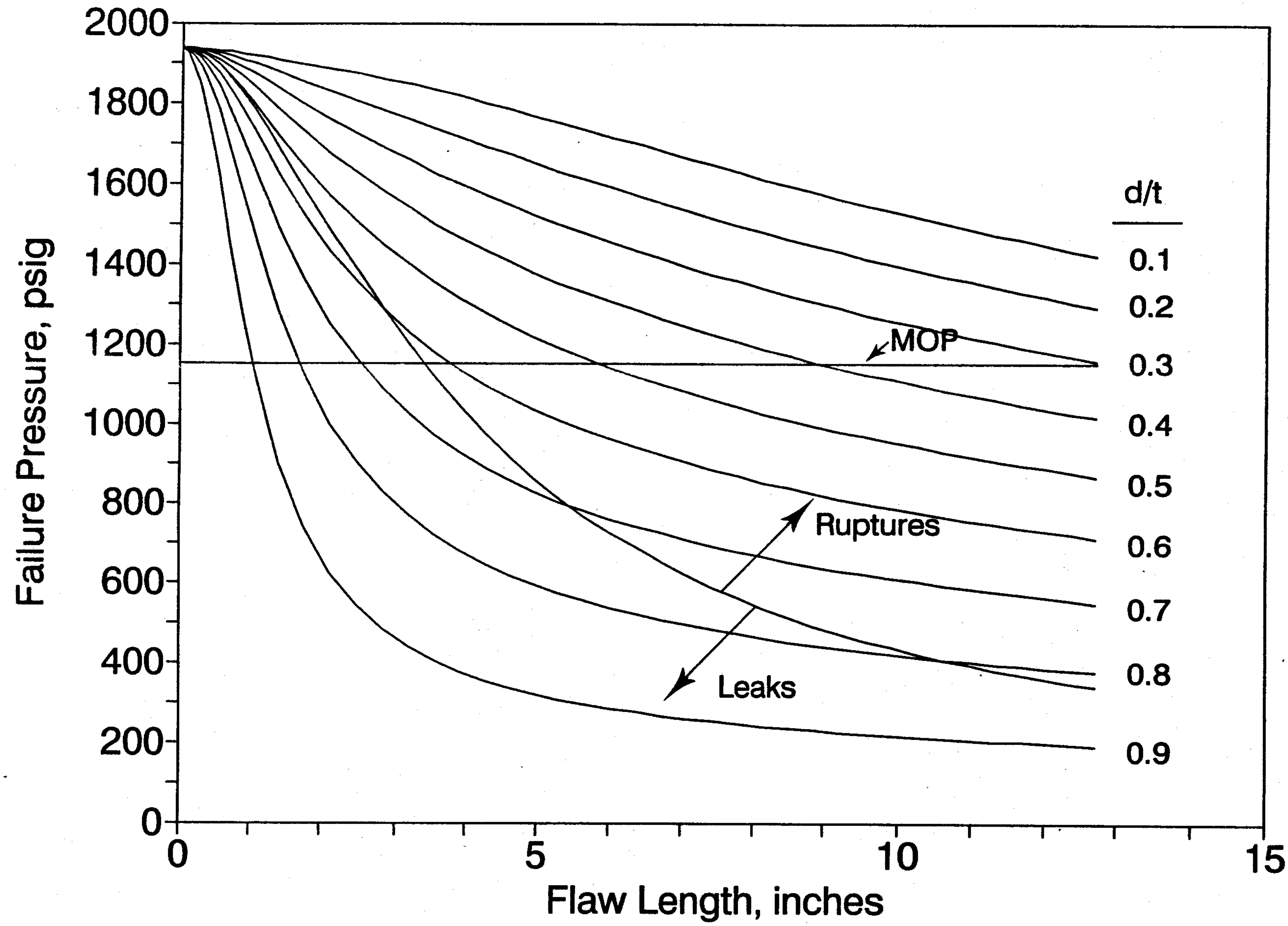


FIGURE 20. FAILURE PRESSURE VERSUS DEFECT SIZE, TYPICAL X52 PIPE

16-inch O.D. x 0.250-inch wall thickness X52

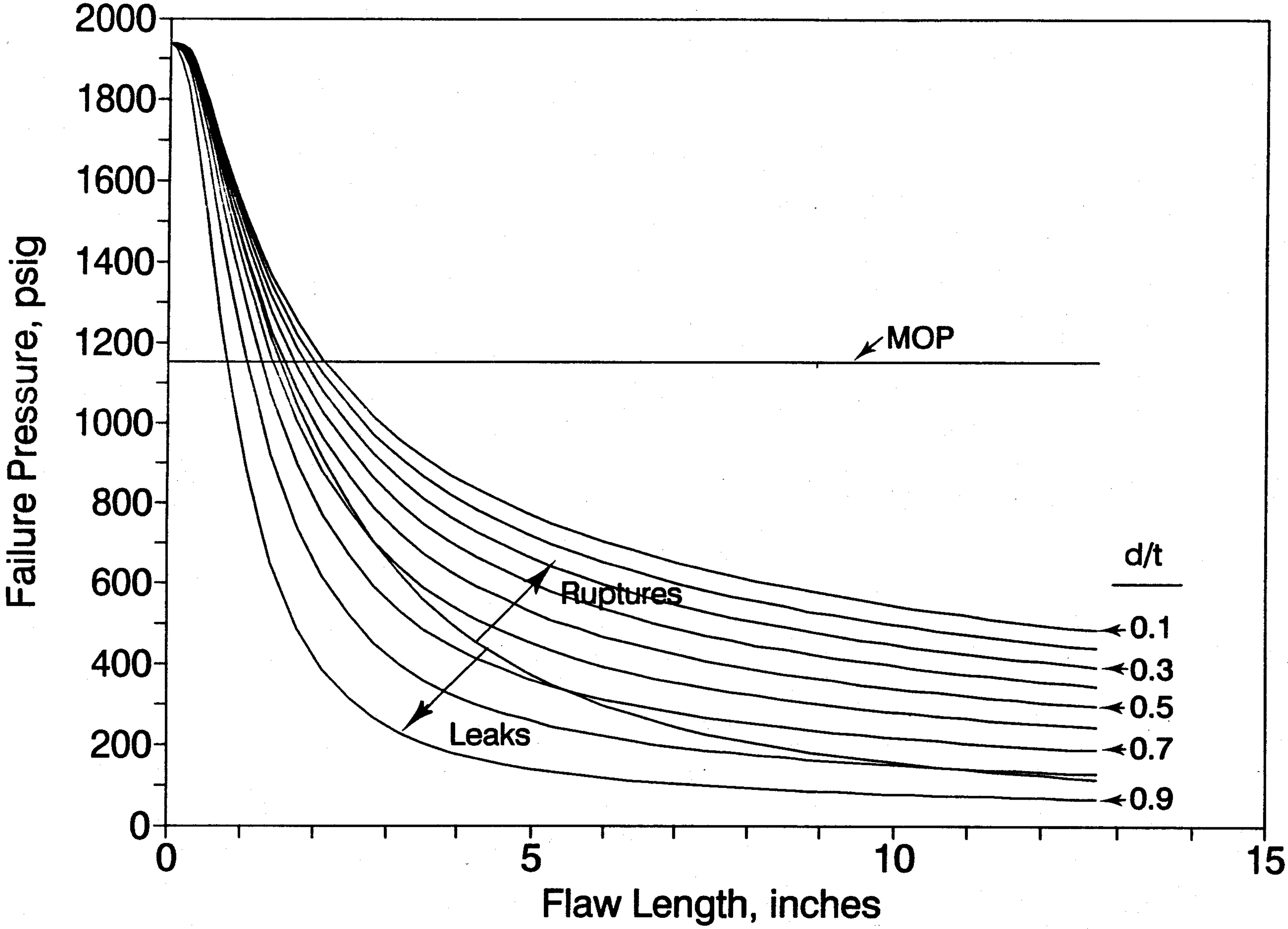


FIGURE 21. EFFECT OF LOW TOUGHNESS IN A LF ERW SEAM ON FAILURE PRESSURE VERSUS DEFECT SIZE RELATIONSHIP

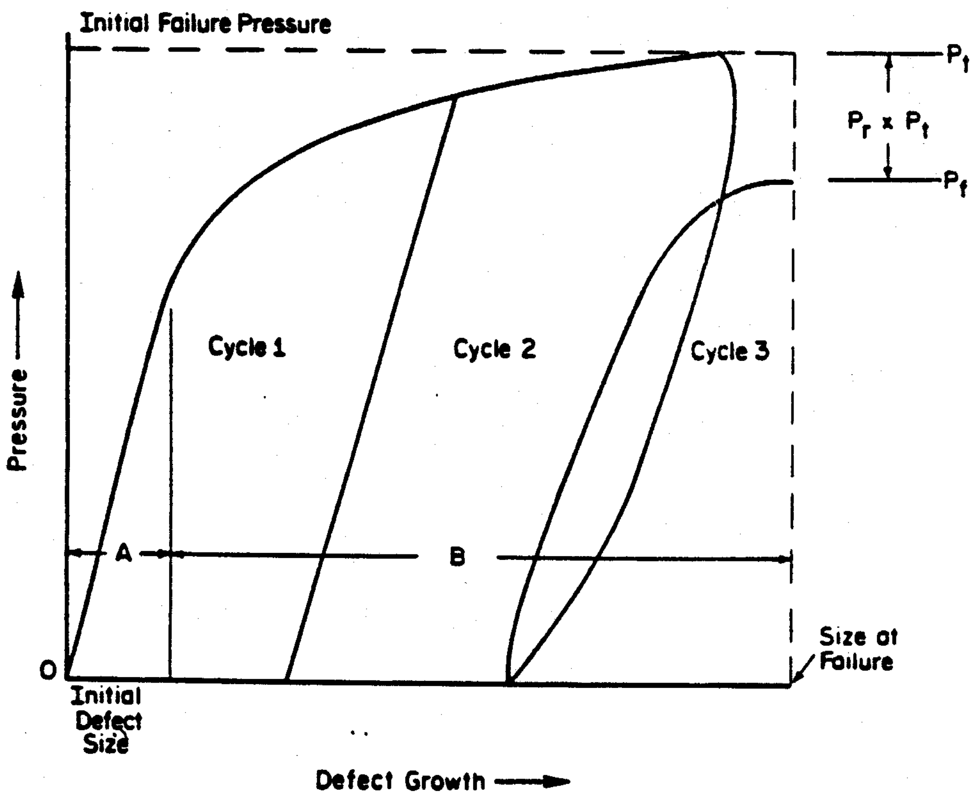


FIGURE 22. THE CONCEPT OF A PRESSURE REVERSAL

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NEW POSSIBILITIES OFFERED BY USING FLEXIBLE PIPE FOR PRODUCTION APPLICATION IN THE GULF OF MEXICO

by
Bernard C. Dubois

Abstract

Flexible pipe made of steel and thermoplastic has been available to the oil industry for 8 years. This new technique has been quite successful all over the world and is now used in the Gulf of Mexico to replace conventional rigid pipe solutions for difficult environments. The domestic use of flexible pipe for short flowlines, vent lines, mud-slide areas, jumper lines and underwater tie-ins are some of the previous experiences which are being developed in this paper.

I. BACKGROUND

The flexible pipe concept was developed 21 years ago by the Institut Français du Petrole, a non-profit organization. In 1971, Coflexip S.A., a company specializing in the manufacture of flexible pipe on an industrial basis was formed.

The first flexible pipe made was for flexo-drilling research and development. The idea to use the same advantages of the flexibility for production lines came later with the deep sea oil challenge.

The first industrial application of flexible pipe for flowlines was the installation, in 1973, of 22 miles of 3", 6" and 8" gathering systems in the Emeraude field offshore Congo by the company Elf-Aquitaine.

II. CONSTRUCTION OF FLEXIBLE PIPE

A flexible pipe is a highly technical product. It can be presently manufactured with an internal diameter from ½" to 22", in long unit lengths exceeding one mile, and with working pressures to 15 000 psi. Furthermore, it is designed to last 25 years. The engineering and manufacturing of this product is then quite sophisticated.

A. Flexible pipeline

Flexible pipeline is made of steel and plastic. Steel components ensure the mechanical performances and plastic components render the flexible pipe leakproof. The lines are built with negative buoyancy in water even when full of gas.

The classic structure (figure 1) includes four principal and one optional layers, the characteristics and dimensions of which are ascertained according to the requirements of the service involved.

1. An interlocked spiraled steel carcass provides resistance to crushing and conserves pipe roundness, even when the pipe is wound on a short bending radius, or subjected to various inside or outside pressure and tensile stresses. This component is generally made of low carbon steel. Its thickness varies according to the working pressure required.

2. Two steel wire crossed armored layers reinforce the interlocked spiraled steel carcass for axial pulling and provide resistance to longitudinal stresses induced by internal pressure. For very high axial strength performance two more layers of wire can be added.

3. The inner thermoplastic tube and outside thermoplastic sheath made of nylon 11 make the flexible pipe leakproof, internally and externally, and provide corrosion resistance. The thickness of the nylon varies with the diameter and the working pressure of the line. The nylon can handle a constant temperature from -40° F to +200° F.

4. An internal or external stainless steel interlocked carcass can be added for extra protection or support of the internal or external nylon sheath.

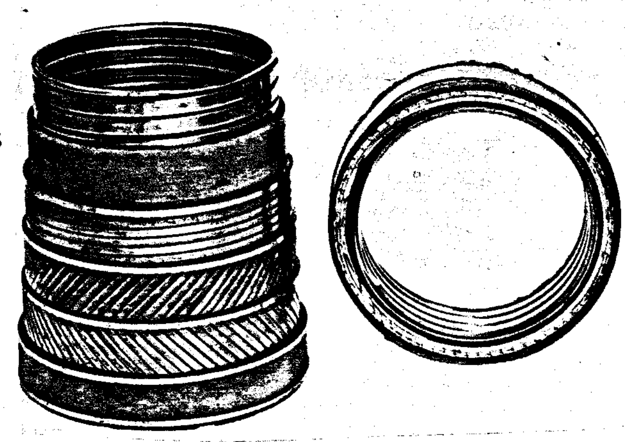


Fig. 1- The component layers of flexible pipe.

Figure 1 shows the pipe with an inside stainless steel carcass to provide extra protection for the internal nylon seal. The oil and gas production lines are generally designed with this protection for extra safety.

B. End Fittings

Couplings are critical points in any piping system and need to be fully reliable. The end couplings are very carefully designed pieces of equipment. They are fitted onto the flexible pipe by specialized technicians and systematically tested. They have reached such a degree of reliability that they retain all the mechanical characteristics of the pipes with a substantial safety margin. Furthermore, the couplings are of the internal flush type, thereby allowing TFL tools and pigs to be passed through. They can be fitted with any type of standard coupling, such as flanges, hubs, etc. (fig. 2) End fittings can also be mounted offshore.

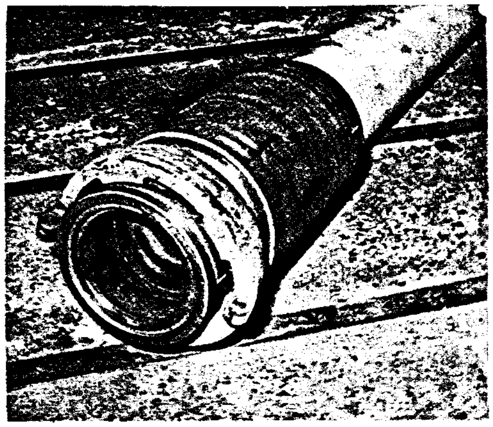


Fig. 2-End Fitting

The parts which are subject to corrosion from sea water undergo a special treatment, called the Ni-Kanigen process, which improves resistance to corrosion. If required it is possible to provide cathodic protection using disposable anodes which are tied onto the couplings.

C. General Characteristics

The maximum working pressure and longitudinal stress resistance are given by the nature and thickness of each steel component. The weight and the minimum bending radius can also be adapted to requirements by using low or high performance steel and a different arrangement of the successive layers.

The maximum unit length of each flexible pipe is only limited by the size of the shipment and the transportation limitations. For example, we limit our unit length at 4000 feet of 8" ID or 1 mile of 6" ID.

Up to certain limits, a flexible pipe can then be designed and built according to the specific requirements of the application.

Rather than giving examples of structures, the manufacturing limitations are specified in figures 3-10. Please refer to the Annex for SI equivalents of the U.S. customary units used.

Figure 3 indicates the theoretical bursting pressure of flexible pipe in relation to internal diameter (with and without presence of H_2S).

Figure 4 shows the ratio between the internal diameter of flexible pipe and the outside diameter for various working pressures.

Figure 5 shows the nominal diameter of curvature of flexible pipe used dynamically, in relation to the axial stress, with no internal or external pressure.

Figure 6 shows the nominal diameter of curvature of flexible pipe used dynamically under maximum working pressure in relation to reeling speed.

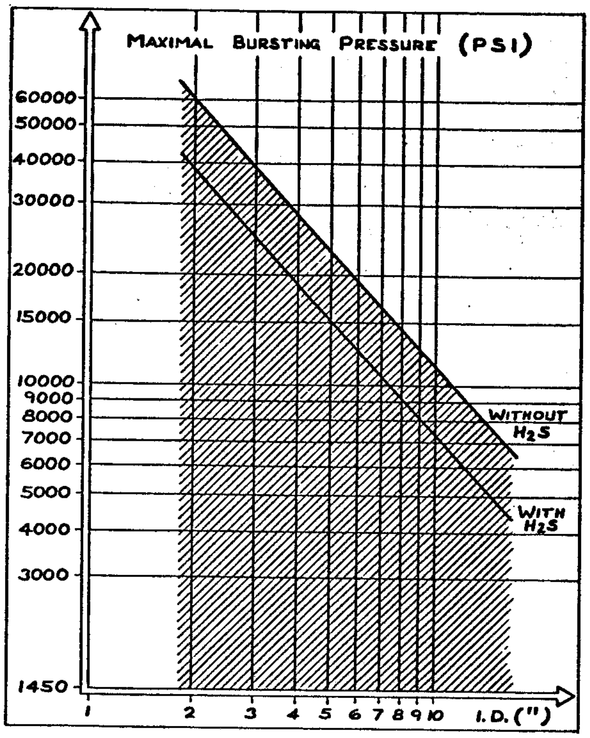


Fig. 3-Theoretical bursting pressure

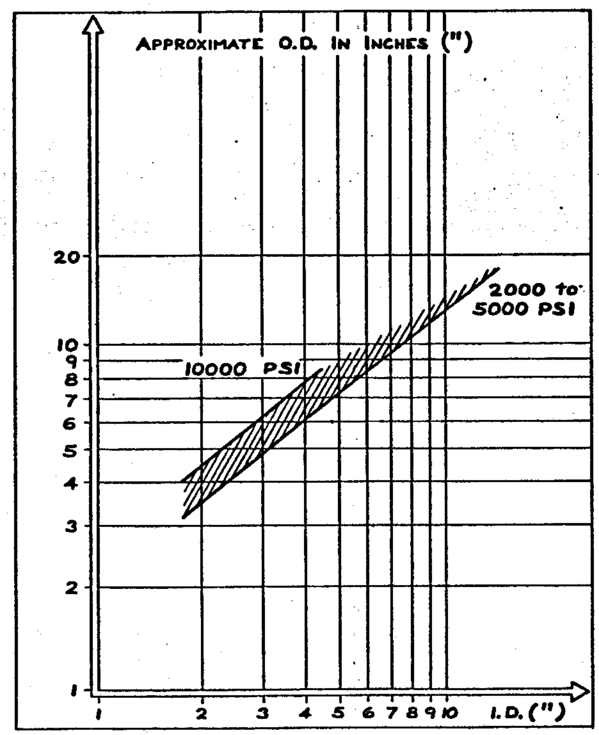


Fig. 4-Internal diameter-Outside diameter ratio

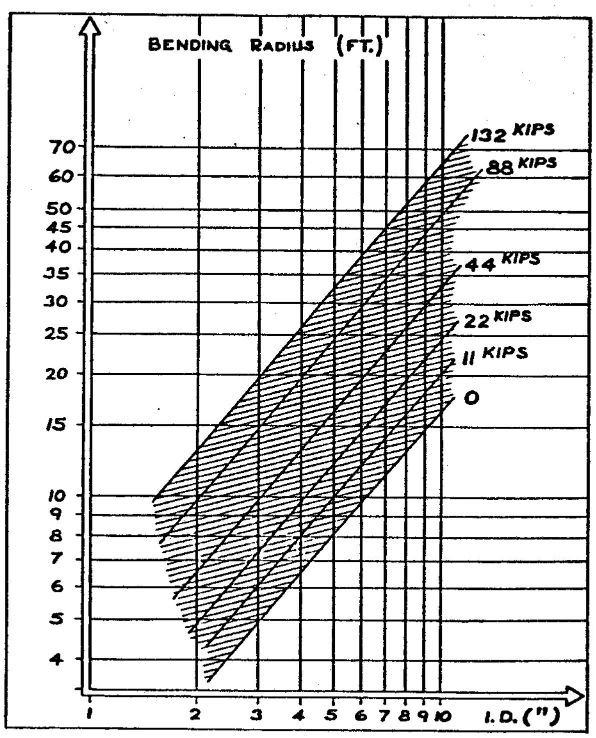


Fig. 5-Nominal diameter of curvature with no pressure

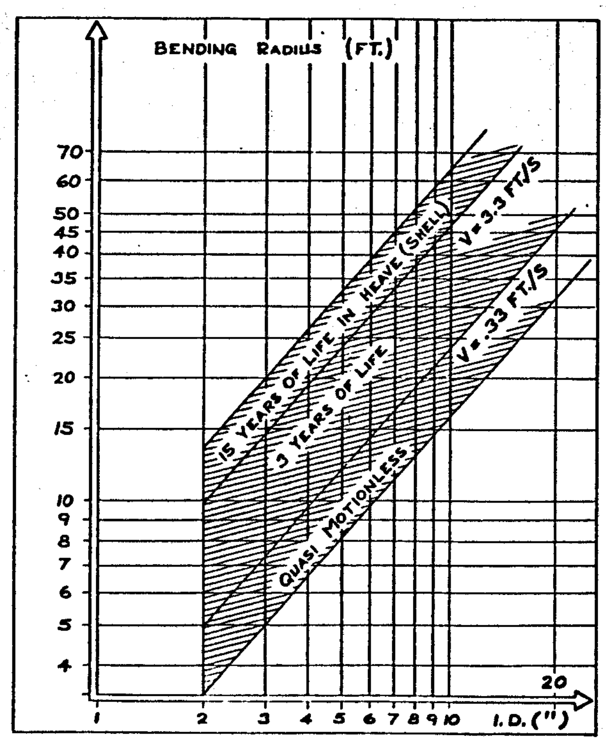


Fig. 6-Nominal diameter of curvature under maximum working pressure

Figure 7 specifies the linear weight of flexible pipe in relation to internal diameter and working pressure. This is for information only as weight could be easily changed by using high or low performance steel.

Figure 8 expresses the nominal pressure of ovalisation with no axial load and no internal pressure, in relation with internal diameter.

Figure 9 outlines the theoretical breaking pull of flexible pipe, without internal pressure in relation to internal diameter and different types of structures.

Figure 10 gives the minimal diameter of curvature of flexible pipe for storage, without axial stress, with no pressure, in relation to the internal diameter.

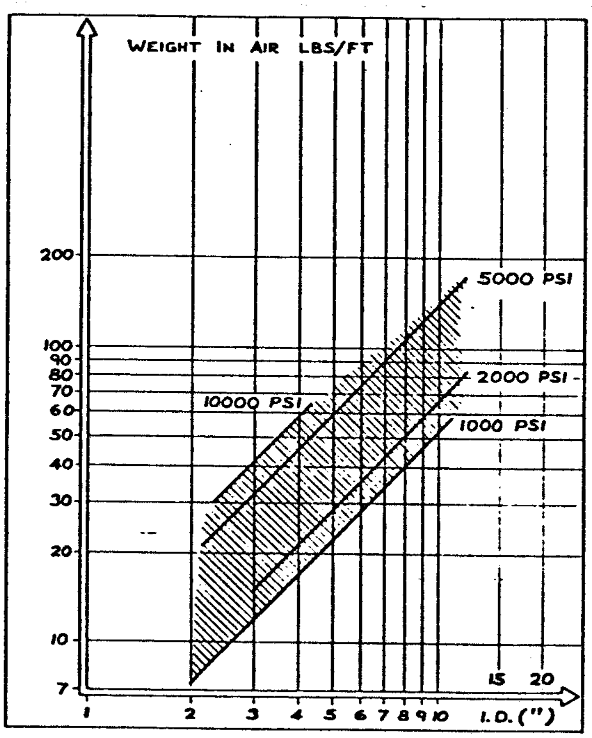


Fig. 7- Linear weight

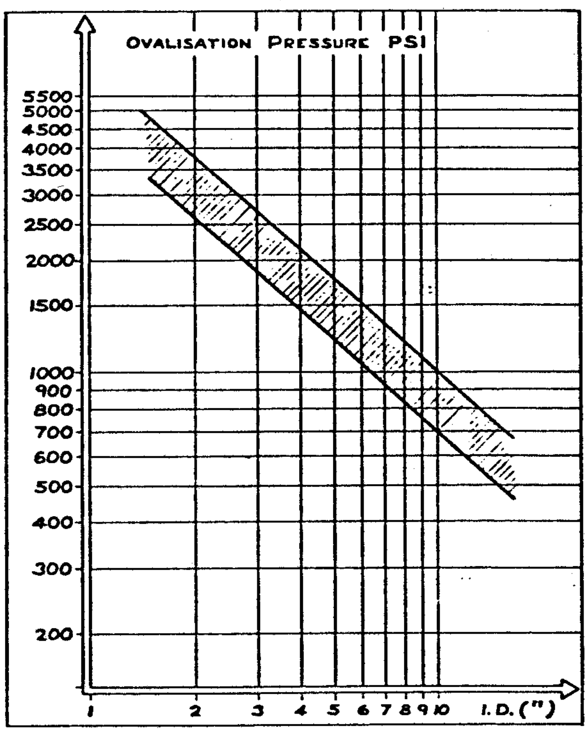


Fig. 8- Nominal pressure of ovalisation

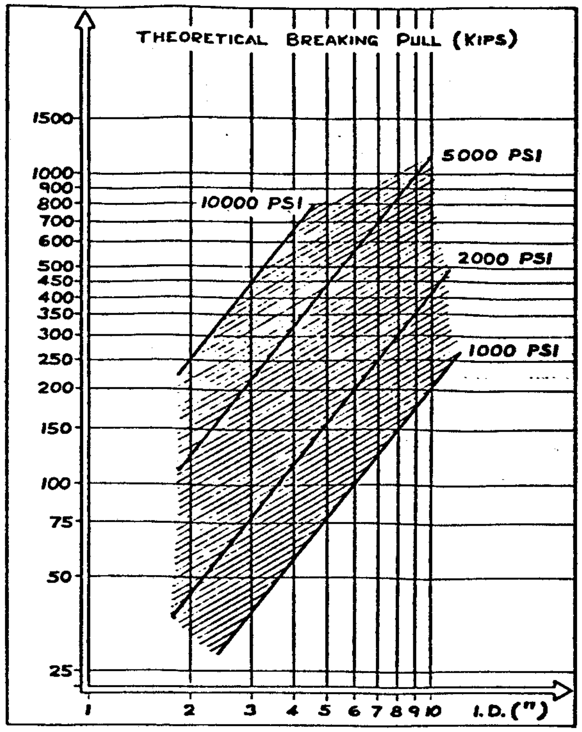


Fig. 9 - Theoretical breaking pull

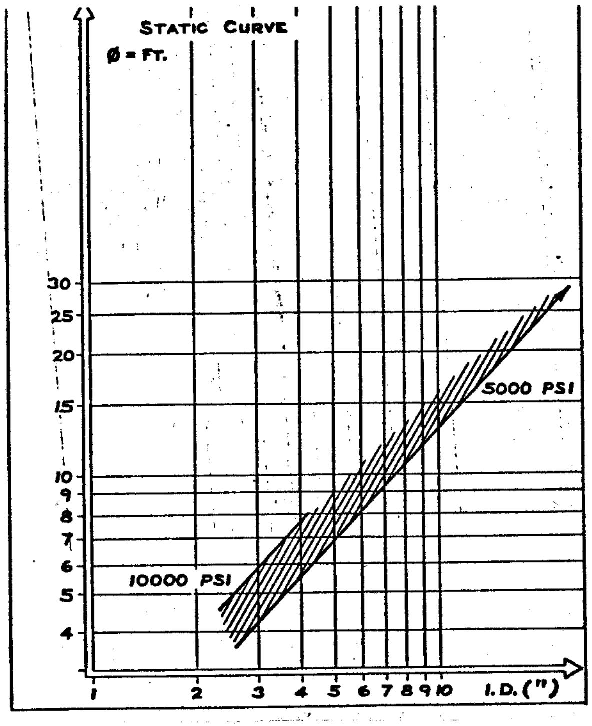


Fig. 10- Minimal diameter of curvature for storage

D. Testing and Official Acceptance

All flexible pipe is designed with a burst pressure equal to a minimum of 3 times the working pressure. All lines for production are tested for 24 hours at 1.5 times the working pressure.

In North America, the United States Geological Survey and the Department of Transportation have always approved the use of flexible pipe on a case-by-case basis, just as they do for rigid pipe.

III. ADVANTAGES OF FLEXIBLE PIPE SOLUTIONS

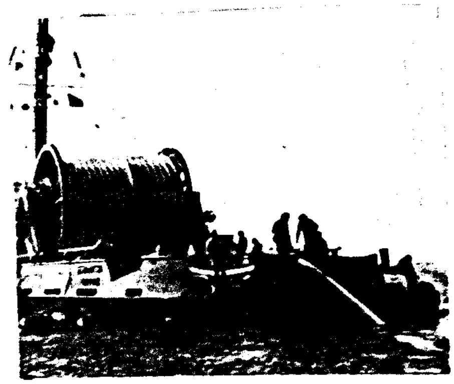
A. Technical Advantages

1. Ease of installation

In the Gulf of Mexico most of the installation can be done with a standard work boat, 100' to 260' long (fig. 11). A laying winch carrying the flexible pipe reel must be installed on the deck of the work boat. A gutter is placed on the aft part of the boat to avoid over-bending during the installation.

The laying is accomplished without constant tension, at a speed of 1 to 2 knots. A line can be as easily recovered as it has been laid.

Fig. 11-Installation of Flexible Pipe



For a conventional flowline to be laid the work boat approaches the first platform and passes one end fitting of the flexible pipe to the platform with the platform crane. While the riser is being clamped on the platform bracings by divers the line is laid off by the work boat until the second platform is reached. At that time, the second end fitting is passed to the second platform. The riser is clamped on the bracings. The entire procedure generally takes less than one day. Three specialists are usually required on board the work boat: a project manager, a flexible pipe technician, and a winch operator.

The flexible pipe can also be pulled inside a pre-installed J-tube without special difficulties.

Any installation of flexible pipe is very quick. This means that flexible pipe can be laid year-round in the Gulf of Mexico; it is always possible even in winter to do a job in a short weather window. Furthermore, the absence of a stinger usually makes the laying of flexible pipe possible in rougher weather than rigid pipe can be laid in.

There is no water depth limitation. The flexible pipe is always self-supporting and with a collapse resistance far above the hydrostatic pressure.

2. Flexibility

The built-in flexibility (fig. 12) of the product gives technical advantages for the following conditions:

- Uneven ocean bottom: the line follows closely the bottom, avoiding risk of vibration.
- Mud-slide: the line easily follows movement of the mud bottom.
- Earthquakes: the line can generally resist such conditions.
- Allows thermal expansion or contraction without inducing stresses at the bottom of risers.
- Facilitates greatly underwater connections (tie-ins). No misalignment problem and buckling risks.
- Location of the line can be changed.

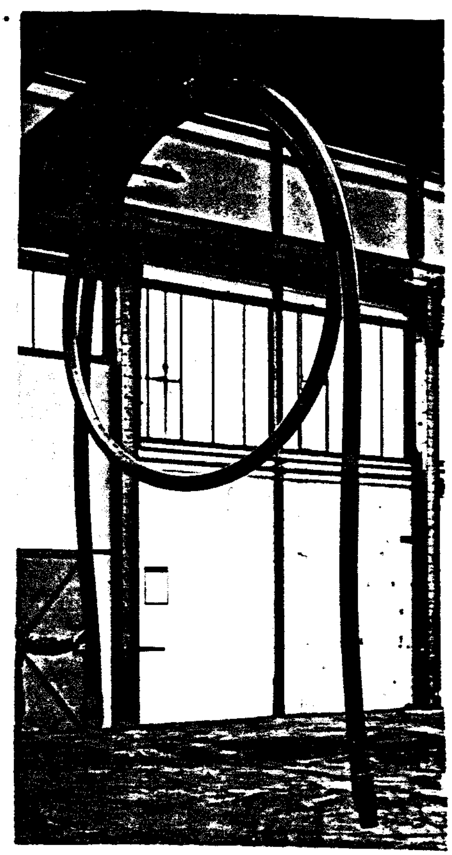


Fig. 12-Flexibility of the Pipe

3. Easy Maintenance or Repair

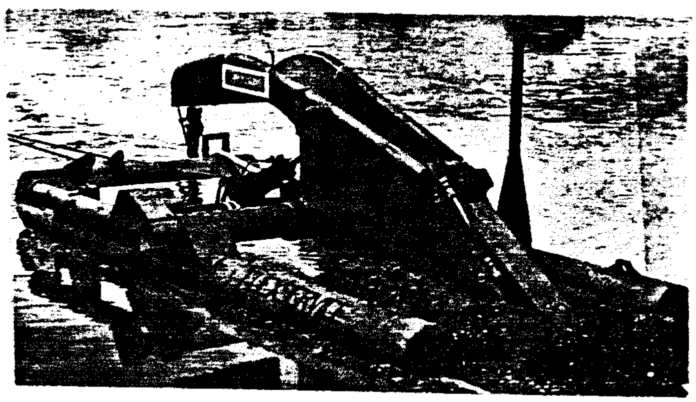
The lines are perfectly protected against corrosion by the outside nylon coating. They do not require any special protection.

If a flexible pipe is accidently damaged by an anchor for example, a work boat has to be mobilized for the repair. Each damaged end is pulled on the work boat and an end fitting is replaced within a few hours on board the vessel. The two sections are reconnected underwater. Generally, the line can be back in service within a few days after the accident.

4. Burying

The flexible pipe can be laid and buried simultaneously. A trench is made with a specially engineered plow which is pulled by the laying ship (fig. 13). The flexible pipe travels through a gutter on the sled and down into the trench.

Fig. 13-Burying sled



B. Financial Advantages

Cost of installation is tremendously reduced because the installation takes much less time and is made with a small naval support vessel. There is no heavy cost of mobilization-demobilization for remote locations. The flexible pipe solution also avoids a lot of costly down-time.

It is important to mention that the amount of savings increases proportionately with the shorter lengths, the smaller diameters and the deeper the water.

For temporary production the flexible pipe is a recoverable investment, which becomes particularly attractive for marginal fields.

In mud-slide or in other difficult environments, the flexible pipe solution is safer and must be considered as a more reliable investment.

For water over 600' deep, the flexible pipe solution is generally always less expensive than a rigid pipe solution.

C. Applications in the Gulf of Mexico

In 1978 an assembly plant was built in New Orleans and stocked with flexible pipe in order to make the product more widely available to the local industry.

During these two years some very interesting applications have been developed by several major companies.

1. Early Production System

Early production systems, as the name indicates, make possible the rapid partial production of a field which otherwise would come on stream at a later date when the permanent construction is finalized. The early cash flow generated by this early production eases the financial burden of the construction period.

A major company applied this concept recently quite successfully in the Gulf of Mexico in 27 feet of water. The configuration of a gas field offshore Texas called for three 6-slot satellite platforms situated 300 feet away from a central production platform which was to process the gas before transporting it to shore through a gas line. (ref. fig. 14)

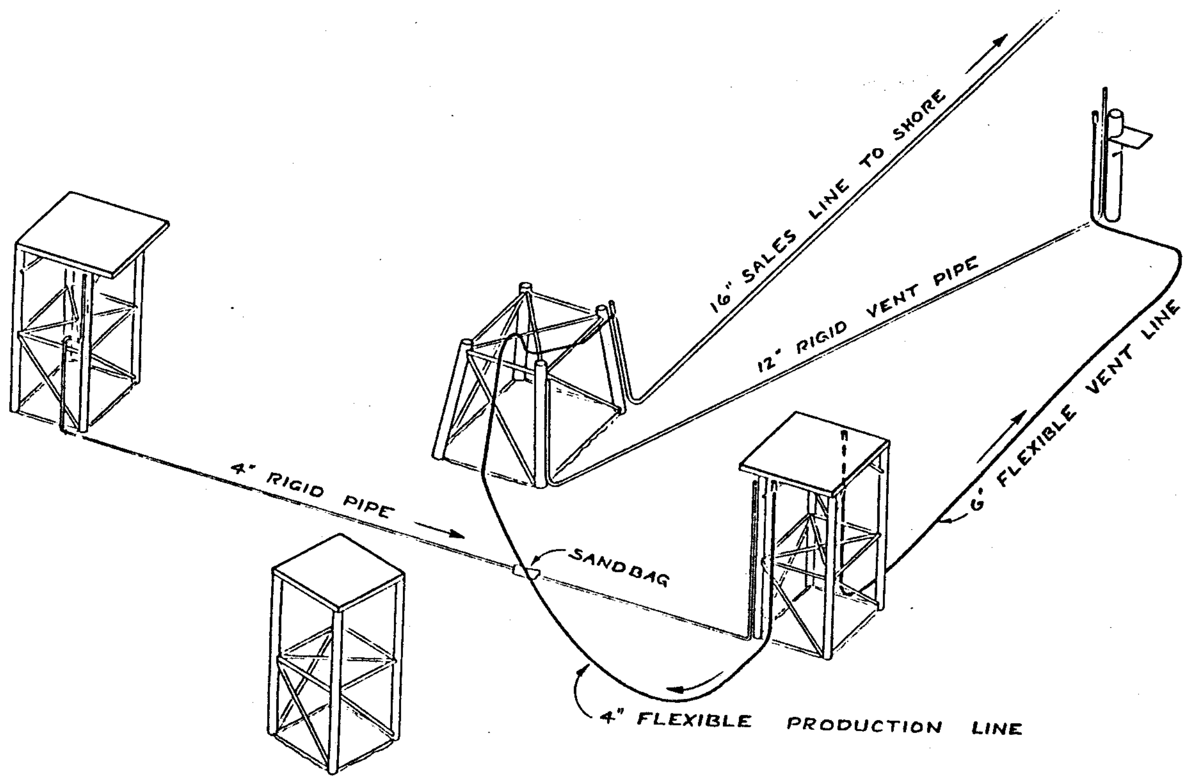


Fig. 14-Early Production System in the Gulf of Mexico-1979

At this time, only the bare jacket of the production platform was protruding from the sea and the production deck was not scheduled for another four months at best. The sale line had already been laid and clamped to a leg of the production jacket. (ref. fig. 15)

The initial request was to install a 4" flexible gas line 450' long from the northern satellite platform to the production jacket. A 4" ID steel pipe was to connect the southern satellite platform to the northern one, passing by the production jacket located between the two satellite platforms. Production from one well was scheduled to flow from the southern satellite platform to the northern platform where is was manifolded with a well of the northern platform. The combined production was to flow through the 4" ID, 1440 psi W.P. gas line and thus to shore.

The 4" ID flexible pipe took 10 hours of actual working time from the initial unspooling of the flexible pipe to the flanging of the flexible pipe end connection to the rigid deck piping. By comparison, the installation of the 4" rigid pipe took about 5 days (without allowing for the weather down-time).

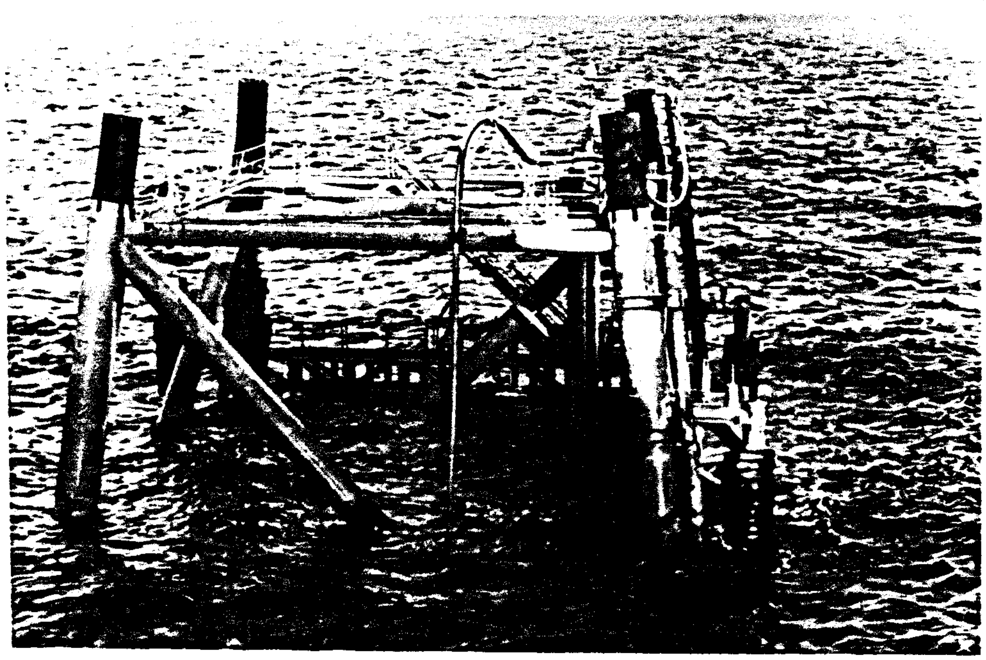


Fig. 15-Flexible pipeline in an early production system in the Gulf of Mexico, 1979.

The installation equipment required for this job was minimal:

-the reel carrying the pipe

-a roller actuator to rotate the reel

-a spout set at the water/vessel interface

-miscellaneous equipment such as ropes and Chinese fingers.

The vessel used to perform this operation was the construction company's barge readily available at the site. However, any other vessel, such as a supply boat, would have been sufficient.

This specific early production application brings to attention the following additional remarks which note the advantages of using flexible pipe rather than other solutions:

-The installation of flexible pipe is fast, reliable and can be performed under a wide span of weather conditions.

-The installation is not tied to a rigid schedule.

-The use of flexible pipe relieves the engineering department of an additional work load in specifically defining the early production scheme.

-The use of flexible pipe permits retrieval at a later date and reuse elsewhere.

2. Vent Line

Vent lines must often be installed in a field in order to bleed the excess gas and pressure that could be encountered during production.

A flexible pipe was recently installed in the Gulf of Mexico for use as a vent line. Due to construction requirements on the production platform and vicinity, it was decided to use a flexible 6" ID vent line 500 feet long going from one of the satellite platforms of this field directly to the vent pile.

The 6" ID vent line was flanged at the deck 50 feet above water and clamped along the bracing of the satellite platform. At the vent pile the flexible pipe was clamped along the vertical rigid riser. (ref. fig. 16)

Again, this flexible pipe was installed in about 10 hours even though the weather deteriorated to a five foot sea.

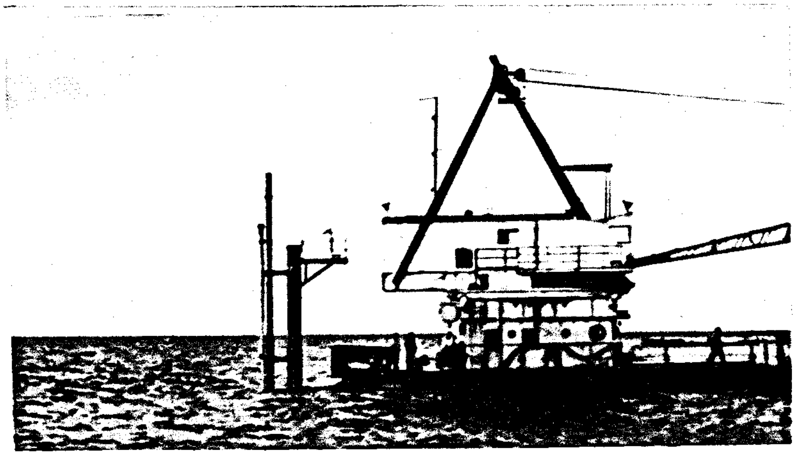


Figure 16-Flexible pipe vent line in the Gulf of Mexico, 1979.

3. Jumper Lines

Short sections of flexible pipe have been installed locally where high pressure lines were needed between two offshore platforms or other structures and where allowances for some relative movement of the two had to be considered. (ref. fig. 17)

The flexible pipe is preferred over swivels because:

One: Flexible pipe is easier to install. You simply flange it up at each end as though it were a plain piece of pipe. (It is a piece of pipe, pipe that bends.) The flanges themselves will support all the weight of the flexible pipe in most applications. There's no need for a support structure.

Two: A swivel is a right angle turn in flow. That means more erosion and greater pressure drop. The flexible pipe hangs in a smooth curve with a constant, circular cross section. Less erosion and less pressure drop. This is especially important on gas wells where high-velocity particles can quickly eat through steel elbows.

Three: Where there's a swivel, there's a seal and that's a potential leak, especially on a gas line. The flexible pipe has no intermediate connections, only the two secure ones at the end. Fewer places for leaks to develop.

Flexible pipe is also preferred over expansion joints. When relative movement of the two end points is small, a large diameter loop of steel pipe is sometimes used to make the connection. The loop has enough "give" to allow the end points to move.

Flexible pipe has advantages over this solution, too.

One: There is greater flexure fatigue resistance with the flexible pipe. These lines have lasted five years in jet service on pipeline burying barges, a job that wears out a rubber hose in six months. The lines have been used in drilling service since 1972 without fatigue failure.

Two: The flexible pipe is easier to handle and store than is the large, unwieldy loop. You handle it as though it were a hose. That's important if the connection must be periodically broken and made up again.

Three: These lines are less vulnerable to damage by wind and waves.

Four: Because they last longer, they will not have to be replaced as often; production can continue without interruption for longer periods of time.

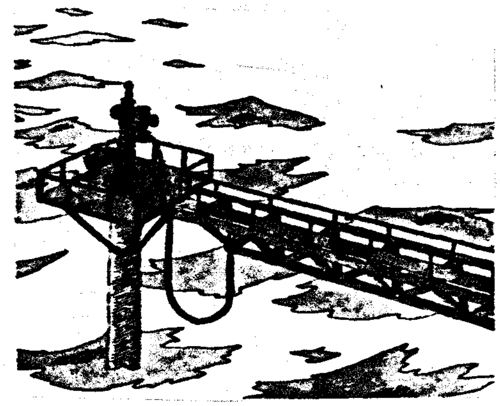


Figure 17-Flexible jumper lines have many advantages as flow connections between offshore structures with relative movement: simple installation; minimum pressure drop; virtually no maintenance; and many more.

4. Tie-Ins.

Flexible pipes are currently used in the Gulf of Mexico for tie-ins. (ref. fig. 18)

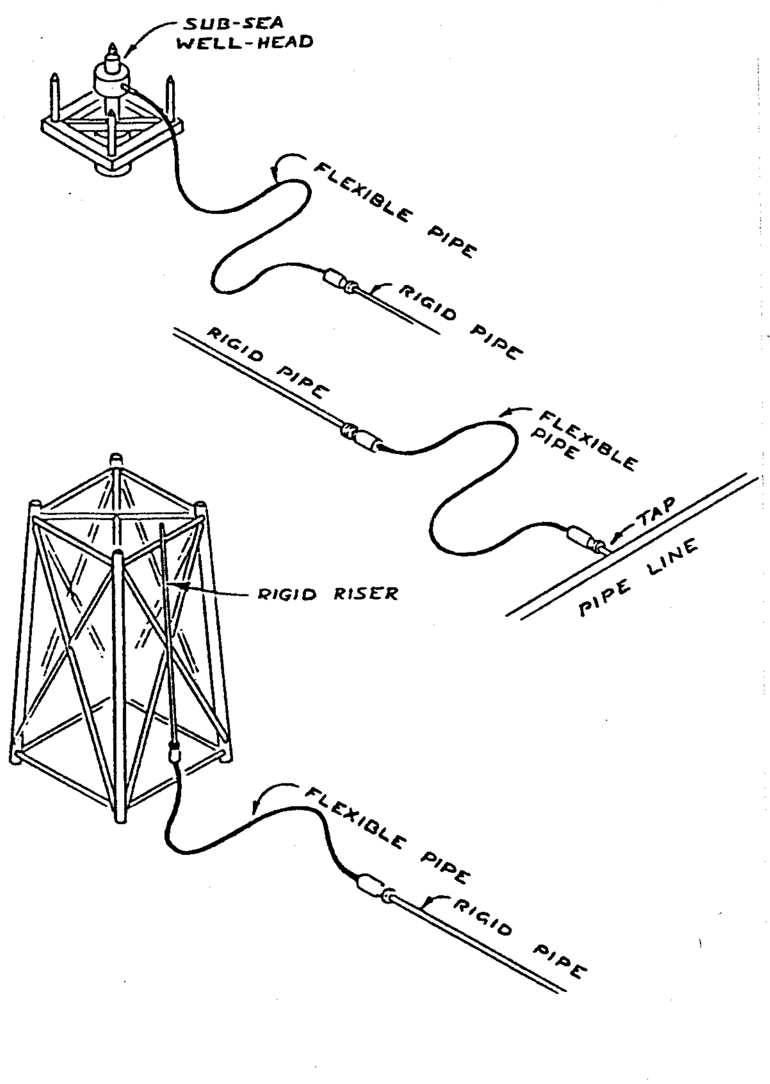
To connect pipelines under water is difficult and very expensive because of the precision necessary in the positioning of each part to be connected. This is a difficult process in any present standard solution. It takes very often several days (sometimes weeks) of barge time to position the extremities of pipe to perform the connection.

The advantage of using flexible pipe comes from the much larger tolerance that is available in the positioning of the rigid extremities. The longer the length of the flexible pipe, the more tolerance there is and the faster the tie-in will be. It is easy to calculate the tolerance available according to the length of flexible pipe used. As a rule of thumb, a minimum length of 20' per inch diameter is required, with a minimum length of 100'.

Other technical advantages of using a flexible pipe for a tie-in system are that in light mud the flexible tie-in will accept settlement and with high temperature production will accept thermal expansion and contraction.

Fig. 18-

Flexible tie-ins



5. Risers in Mud-Slide Areas

Flexible pipe presents great advantages over rigid pipe in mud-slide areas.

The risk of damaging a pipe because of bottom movement is very high close to the mouth of the Mississippi. A flexible pipe with the same axial or collapse resistance as rigid pipe but not the same stiffness has much less chance of being damaged if enough slack is allowed to accommodate the movement of the slide.

Mud-slide areas are not always damaging to pipe because of horizontal movement but also because of vertical movement: the slow settlement of the pipe in the mud induces bending moments and stress corrosion, particularly close to risers.

Some major oil companies have decided to use flexible pipe for risers in mud-slide areas in the Gulf of Mexico.

For one of these applications in a water depth of 450 feet, the operator expects the pipe to settle up to 60 feet below the mud line. (ref. fig. 19)

One thousand feet of 10" ID flexible pipe will be installed to allow for approximately 500 feet of slack to accommodate movement in any direction.

The standard J-tube, because of the circumstance, has been modified into an I-tube, with a bell mouth turned toward the bottom, at the under-water extremity.

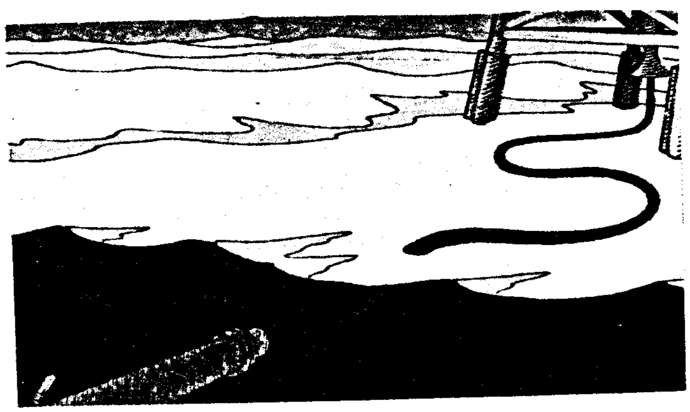


Figure 19-Flexibility and strength of flexible pipe risers prevent damage when steel gathering lines settle into light mud. This platform is equipped with a bell-bottom I-tube to permit the flexible riser to move freely.

V. CONCLUSION

This brief description of this new product and the new solutions opened up by using flexible pipe illustrates only a few of the numerous possible efficient uses. The flexible pipe can also be used to replace conventional corroded risers, for river crossings, to make allowances for thermal expansion and contraction, etc. Its capability of being laid in almost any water, without a stinger or big barges makes flexible pipe an important element in the deep water oil and gas industry challenge.

With the New Orleans facilities, and engineering in Houston, any assistance can be given through Coflexip & Services, Inc., to anyone interested in further information on the use of flexible pipe.

APPENDIX
Factors Used For Conversion to SI Units

Quantity	Conversion	Factor
Plane angle	degree to rad	1.745 329 E−02
Length	in to m	2.54* E−02
	ft to m	3.048* E−01
	mile to m	1.609 344*E+03
Area	in^2 to m^2	6.451 600*E−04
	ft^2 to m^2	9.290 304*E−02
Volume	ft^3 to m^3	2.831 685 E−02
	US gallon to m^3	3.785 412 E−03
	in^3 to m^3	1.638 706 E−05
	oz(fluid, US) to m^3	2.957 353 E−05
	liter to m^3	1.000 000 E−03
Velocity	ft/min to m/s	5.08* E−03
	ft/sec to m/s	3.048* E−01
	km/h to m/s	2.777 778 E−01
	mile/h to m/s	4.470 4* E−01
	mile/h to km/h	1.609 344*E+00
Mass	oz(avoir) to kg	2.834 952 E−02
	lb(avoir) to kg	4.535 924 E−01
	slug to kg	1.459 390 E+01
Acceleration	ft/s^2 to m/s^2	3.048* E−01
	std. grav. m/s^2	9.806 65* E+00
Force	kgf to N	9.806 65* E+00
	lbf to N	4.448 222 E+00
	poundal to N	1.382 550 E−01
Bending, Torque	kgf-m to N·m	9.806 65* E+00
	lbf-in to N·m	1.129 848 E−01
	lbf-ft to N·m	1.355 818 E+00
Pressure, stress	kgf/m^2 to Pa	9.806 65* E+00
	$poundal/ft^2$ to Pa	1.488 164 E+00
	lbf/ft^2 to Pa	4.788 026 E+01
	lbf/in^2 to Pa	6.894 757 E+03
Energy, work	Btu(IT) to J	1.055 056 E+03
	Calorie(IT) to J	4.186 8* E+00
	ft lbf to J	1.355 818 E+00
Power	hp(550 ft lbf/s) to W	7.456 999 E+02
Temperature*	°C to K	$t_K = t_C + 273.15$
	°F to K	$t_K = (t_F + 459.67)/1.8$
	°F to °C	$t_C = (t_F - 32)/1.8$
Temperature interval	°C to K	1.0* E+00
	°F to K or °C	5.555 556 E−01

*°F should be converted to °C. Absolute temperatures should be converted to K.

The factors are written as a number greater than one and less than ten with six or less decimal places. The number is followed by the letter E (for exponent), a plus or minus symbol, and two digits which indicate to power of 10 by which the number must be multiplied to obtain the correct value.

For example

1.745 329 E − 02 is $1.745\ 329 \times 10^{-2}$ or 0.017 453 29

*Relationships that are exact in terms of the base units.