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# Common Causes of Material Degradation inBuried Piping (U)

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## ABSTRACT

Buried pipe may fail for innumerable reasons. Causes can be mechanical damage/breakage, chemically initiated corrosion, or a combination. Failures may originate either internally or externally on the pipe. They may be related to flaws in the design, to excessive or unanticipated internal pressure or ground level loading, and/or to poor or uncertain installation practice. Or the pipe may simply "wear out" in service. Steel is strong and very forgiving in underground applications, especially with regard to backfill. However, soil support developed through densification or compaction is critical for brittle concrete and vitrified clay tile pipe, and is very important for cast iron and plastic pipe. Chemistry of the soil determines whether or not it will enhance corrosion or other types of degradation. Various causes and mechanisms for deterioration of buried pipe are indicated. Some peculiarities of the different materials of construction are characterized. Repair methods and means to circumvent special problems are described.

## BACKGROUND

Piping materials vary considerably in their characteristics. Materials for consideration always include the following

<u>metal</u>: steel, aluminum, copper, stainless steel, cast iron, etc.;
<u>plastics</u>: polyethylene, PVC, ABS, polypropylene, fiberglass, etc.;
<u>other</u>: vitrified clay tile, concrete, orangeburg (cardboard), etc.

The list is by no means complete. Moreover, in selecting pipe for an application, coatings and linings should also be considered. Although economics will ultimately dictate design of a system, all of the properties of the different materials in relation to the process and surrounding environments must be weighed.

It is important to realize that different materials require different installation techniques to provide the performance needed for the process.

For example, soil compaction for flexible plastic pipe is far more important than that for steel pipe, because the soil plays a larger role in support for the less rigid plastic. Similarly, the soil must be compacted beneath the haunches of cast iron, concrete, and clay piping to prevent excess distortion. These pipes cannot tolerate significant wall deformation and can break sharply under relatively low load conditions if the backfill is inadequate. Generally, steel pipe is not subject to these problems to the same degree because of its significant ductility and toughness. Soil compaction is still important for steel pipe, because it affects fatigue and strength of attachments. Moreover, compaction affects corrosion performance, and uncoated, underground steel pipe has poor resistance to corrosive attack. Where corrosion resistance is imperative, polymeric piping materials or organic coatings are usually employed. But where nonmetals are used, operating temperatures must be sufficiently low to avoid softening and otherwise affecting the materials.

Buried steel pipe failures are most often corrosion related. Numerous examples discussed below concern external corrosion or oxidation of steel pipes in service environments. Corrosion resistant coatings and/or cathodic protection are usually employed to curtail external corrosion on buried pipe. Note that coating damage occurring during handling and backfill operations often leads to localized attack and future leaks.

Piping systems containing natural water sometimes fail by internal corrosion. Untreated well water can absorb substantial $CO_2$, which translates to carbonic acid. At SRS, pH as low as 3.9 has been measured. The effect has been corrosive attack of the carbon steel piping. Cement-lined steel pipe or PVC can be used in lieu of steel in most cases.

Though corrosion is much less of a problem with plastic pipe, mechanical properties of plastics introduce constraints different from those of metal pipes. Plastic is less rigid and strong than metal pipe, and much more flexible. As a result, backfill plays a larger role in mechanical capability of the pipe system than it does for most other materials.

Orangeburg pipe frequently fails by root intrusion at joints. The pipe is used only for gravity drain applications. Because of its makeup - in effect, a cardboard/resin mastic sandwich - this pipe will not support internal pigging or scraping.

## Corrosion

Corrosion is an electrochemical process involving oxidation/reduction reactions in a medium capable of supporting that behavior. The chemistry of the soil is important as to whether or not it may be expected to enhance the corrosion. Note that soils may also contain elements detrimental to plastics or concrete. The corrosion phenomenon is one characteristic or feature of a buried system which can not be eliminated and must be addressed to achieve reasonable life of buried pipe.

General experience with underground corrosion indicates that once leaks start to occur, an increase in the rate of development of leaks can be anticipated. The accumulated number of leaks typically follows an exponential curve with time (Fig. 1, after Ref. 1). As suggested in the graph in Fig. 1, a normal leak-free infancy can be expected. However, the natural tendency to corrode or oxidize eventually leads to some leaks.

Corrosion is probably the origin of more problems in underground pipe than any other cause. It is a natural phenomenon and can be viewed from the standpoint of chemistry and physics. Thermodynamically, a metal runs downhill as it corrodes, and the metal tends to return to its natural or stable condition, that of the ore. To protect the metal, assure its structural integrity, and retain the base usefulness for which it was selected, it is necessary to arrest this tendency to react and corrode.

A good coating is the first line of defense against corrosion, especially in a buried system. Coatings provide isolation from the soil, which is the electrolyte or electrolytic medium required for the chemical reactions to proceed. Although protective coatings alleviate much of the corrosion problem, the existence of holidays or faults in coatings is inevitable. To minimize the occurrence, it is necessary that the coatings be properly applied and that the coated equipment be handled carefully to prevent damage. Testing and repair of damage sites is necessary following installation and before backfilling is allowed to begin.

Field applied coatings are more apt to be defective than mill applied protection. Coal tar mastics and coal tar epoxies, with or without paper or fiberglas overwrap, are often applied in the field. Mill-applied products include these, as well as filled epoxies, Kraft paper wraps, polyolefin extrusion coatings, and fiberglas overlays. The mill application is better controlled and usually offers more sure protection than a field application. However, instances of leaks do occur with each application.

Coatings may be marred during installation by rough handling, by walking on the pipe, and by strikes with shovels or other tools. Coatings will inevitably be damaged during excavations. Inspection of coated pipe and repair of coating damage is imperative before proceeding with any backfill operations on pipe, whether it is newly installed, newly repaired, or just secondarily present in an excavation.

An alternative for corrosion protection that is sometimes used is powdered thermal insulation employed as a backfill. The insulation material is hydrophobic, has high electrical resistance, and when properly placed, appears to be completely protective against corrosion as a result of the exclusion of water. However, incidents of corrosion have occurred even with this material. Proper design and installation is required, and disturbance of the fill after initial compaction requires special care on reburial.

Cathodic protection (CP) is a means of corrosion protection which makes use of the electrochemical nature of the corrosion process. CP technology makes use of galvanic principles in establishing an electrical current flow opposite to that naturally required to develop corrosion. In the sacrificial approach to CP, a material with a higher galvanic potential than the piping is incorporated into the system, such that it corrodes in lieu of the pipe (it is more anodic). When an impressed current CP system is used, electrical current is provided to establish the direction of current flow. In the impressed current system, the anodes are less sacrificial and the protection system itself may last longer and be more forgiving. However, monitoring to confirm continuity in operation of the CP system is suggested. With either approach, periodic surveys are needed to assure adequate protection.

Backfill

When external soil and surface loads are applied to buried pipe, the pipe deforms and load transfer to the surrounding soil takes place (Ref. 2). With flexible materials such as polyethylene (PE), the deformation and load transfer leads to a mechanical support of the pipe and its contents by the backfill (Refs. 3-5). It is important that the fill be sufficiently compacted or densified to minimize the flexing required to effect the needed support, and thereby to escape the possible formation of voids along the top and bottom of the pipe (at the 6 and 12 o'clock positions). Such voids introduce the possibility of strain instability and buckling. These tendencies exist for all piping materials, but most have larger moduli or stiffness properties than PE and can better resist excessive distortion. Actually, fracture on the pipe sides (3 o'clock and 9 o'clock positions) would occur with most materials long before the critical buckling strain was reached. The buckling problem may be exaggerated under conditions of external hydrostatic loading, such as in a river crossing or at a location of high water table, where the surrounding soil may be fluid and unable to provide the needed support (Ref. 6). In this case, other means may be required to establish the mechanical support for PE piping.

Where the pipe material is gray cast iron and essentially brittle, excessive flexing and distortion of the pipe wall will result in fracture. This may occur as a result of loads applied at grade or ground level. The flexing can become excessive due to inadequate support beneath the lower haunches, to generally inadequate or improper backfill, or to localized disturbance of the fill without proper recompaction. If support is not adequate beneath the haunches, axially oriented cracks may develop on the sides of the pipe. If the pipe can be deflected in the axial direction, such that a crack initiates in a circumferential orientation, a failure having the appearance of a shear separation often results. Numerous examples of this type of break are related to poor backfill techniques at small excavations, whereby the original compaction anchors the pipe (the pipe is "built-in") but bottom support is lacking at the new earth filled region (the hole is simply filled up and compaction is either inadequate or non-existent). This allows localized deflection, a sharp transition in strain near the excavation wall, and a sharp break in the pipe. Such failures, which are common in municipal water and sewer systems, often occur in the general location of prior leaks, especially at sites subjected to vehicular traffic.

Concrete and vitrified clay tile pipes are also unable to support excessive deflections resulting from insufficient compaction. Clay pipe is often cracked during installation. Because it is so brittle, breakaway often occurs, resulting in creation of a window in the pipe wall. Consequences include loss of containment, soil intrusion, possible pluggage of the pipe, and compromise of the soil support. With weakened support, complete crushing can result from small loads, which otherwise might cause no problem. Concrete is somewhat like clay pipe, in that no deflection is allowed. It can fail mechanically in essentially the same way as the vitrified clay due to the brittle nature of the material. Crack growth is slower and more difficult in concrete, but the material is still brittle. A shear failure phenomenon like that in cast iron is possible with either concrete or clay pipe, but the fracture rarely extends full circle without including some axial component. Moreover, flexure in the side walls could lead to development of an axially oriented crack which grows more rapidly than the circumferential crack.

EXAMPLE FAILURES

The following examples were selected essentially at random and serve to illustrate several types of failures of buried piping.

1. A 2-inch, schedule 40 pipeline, 150 psi steam, buried in a powdered insulation, failed at an elbow. The hole occurred at a weld joint due to erosion from the inside. Significant misalignment and a step in the weld joining the elbow and pipe (Fig. 2) led to the erosion. The outside surface exhibited considerable corrosion, possibly due to entrapment of the escaped steam in the insulation envelope. The line was buried for about 2 1/2 years, but was in steam service only 14 months, indicating that corrosive attack had been very rapid.

2. A buried 1-inch, sch. 40 pipe developed a leak at a sharply defined interface between two types of backfill material (Fig. 3). The pipe was coated with coal tar epoxy, but the coating was thin, incomplete, and generally poorly applied. The fills were a clay soil and an hydrophobic granular insulation. Electrical resistivity for the two fill materials is significantly different. This difference created the driving force for electrochemical action and corrosion.

3. 2-inch, sch. 40 steam piping was buried with no external protection applied. The pipe was used intermittantly. The external surfaces became deteriorated by exposure to the wet soil environment.

4. A 1-inch, sch. 10 stainless steel pipe contained within a 2-inch carbon steel pipe developed a leak. Monitoring of the annular space detected the leak. Investigation revealed chloride stress corrosion cracking (CSCC) in a cold formed, long radius elbow section of the pipe (Figs. 4, 5), and for 3 to 4 feet along the horizontal extension from the long elbow. Although the hydrotest water was drained, the pipe was not put into service for several years and some water remained trapped in small pockets in the section. Moreover, for 6 months during the lay up period, a steam leak from a nearby underground pipe elevated the temperature in the vicinity, thus enhancing the corrosion process. The carbon steel jacket pipe was contained in a powdered thermal insulation backfill. It showed some corrosion but was generally acceptable for continued use.

5. A 2-inch, sch. 40 carbon steel air line failed after 2 years service. The line was coated with a coal tar epoxy. Pitting occurred beneath the coating. This was surely related to poor coating application, with inadequate inspection of the outer coat before burial.

6. A 1/2-inch, sch. 40 galvanized air line failed. The pipe was direct buried, and the zinc coating had virtually disappeared.

7. An 8-inch, cement-lined cast iron water pipe failed. A circumferential crack occurred on the bottom side of the pipe (Fig. 6). The pipe rested directly on a concrete slab. The break was in a high traffic area and nearby soil had been disturbed to repair another leak.

8. Three pipes in a steam system failed.

(a.) 3-inch, 25 psi supply. Corrosion occurred on an elbow where pipe meets riser. A powdered thermal insulation used as backfill. Repair was by weld overlay.

(b.) 2-inch, 25 psi supply. A riser and adjacent horizontal section were heavily corroded within a powdered insulation backfill. The section was replaced.

(c.) 1 1/2-inch drain. Extensive corrosion existed on the pipe, which had no corrosion protection applied.

9. A 1-inch, sch. 40 flush water pipe failed. This pipe appeared to be a dead leg off the main line, and it appeared to serve no purpose. The line was unprotected and heavily corroded.

10. A 2-inch, sch. 40, 150 psi steam pipe failed. Deep pitting and extensive general corrosion existed (Figs. 7, 8). The pipe was not coated and was direct buried.

11. A 3-inch cast iron pipe broke and water washed out a hillside (Fig. 9). A crack occurred in the pipe as a result of heavy traffic on grade and variable soil support. A concrete slab beneath the pipe probably contributed to the break. Pits on the outside surface along the crack (Fig. 10) are associated with seepage at the crack before it encircled the pipe and opened up.

12. A 1-inch Type K copper tubing air line cracked as a result of differential settlement. The tubing was buried in concrete and failed at the exit point. Repair consisted in bypassing the original line in the slab with new tubing outside the concrete.

13. Buried PVC pipe used for a safety shower supply developed leaks after several years. The pipe was 2-inch, sch. 40, with socket joints. The joints were poorly made, but not realized until the failure. The bad joints were

dirty and had insufficient solvent. Water seepage eventually led to slight erosion and development of a hole in the pipe (Fig. 11). Further and increased flow led to substantial eddy formations incorporating soil particles, and to enlargement of the hole. This mode of failure occurred at several locations on the pipe.

14. A buried 6-inch steel pipe with coal tar coating used in inhibited water service developed a leak. The hole was on the side of the pipe in a large pit on the exterior surface. For repair, a seal was clamped over the pipe at the leak site.

15. A 2-inch, sch. 80 steel pipe buried in powdered thermal insulation failed by external corrosion in a vertical leg. A dime-sized hole developed in the pitted surface of the riser (Fig. 12). Pitting extended in the horizontal pipe beyond the elbow located at the bottom of the riser.

16. Five pipelines were exposed during excavation on a pipe relocation project. None of these leaked, but coal tar epoxy coatings, tape wrap, and galvanized surfaces used for corrosion protection all suffered damage and required repair. Only mild corrosion was observed on any of the pipes. Note that excavations in the vicinity of buried lines usually lead to damage such as described here. To avoid subsequent corrosion, repairs of the coating are required before backfilling.

17. An 8-inch cast iron pipe cracked "full circle". Recent new installations and repair on a domestic water line nearby had resulted in soil disturbance and heavy equipment traffic in the area. Failure was attributed to these.

18. 6-inch, sch. 40 steel pipe used for cooling water supply suffered many leaks over a two year period. Some were due to external corrosion. But most were related to internal corrosion by the untreated water (Fig. 13). The water has low pH and is very corrosive. Numerous repairs were made by inserting and welding short sections of new pipe, by welding patches at the leak site, or by using full circle compression clamps. The entire line was eventually replaced with PVC piping.

19. Numerous underground steam lines have failed as a result of external corrosion. In many cases extensive corrosion occurred due to water breaching the insulation envelope surrounding the pipe. In several instances, the pipes were replaced with grade level installations.

20. A 2-inch, sch. 40 steel pipe teed to a 6-inch cooling water supply failed by erosion/corrosion. Leaks occurred at the impact location on the downstream surface at the turn. Severe wall thinning occurred (Fig. 14).

21. An insulated stainless steel pipe failed by CSCC from the exterior (Figs. 15, 16). Although this case did not involve buried pipe, it is included because the problem relates to use of insulation containing leachable chloride ion, and the application could just as well have been underground. Moreover, the same phenomenon has been observed with carbon steel pipe. Water penetrates the insulation, extracts chlorides from the material, and exposes the pipe surfaces to the wet chloride environment. Chloride cracking of the stainless resulted.

22. A 2-inch air line, mastic coated and fiberglass-wrapped, leaked at a hole in a large pit on the external surface. No other corrosion damage was evident, suggesting penetration in the protective coating probably occurred during installation as a result of handling or a tool strike. A short section of pipe was replaced.

23. A 2-inch, sch. 40 steel pipe developed a steam leak in a portion of the line beneath a foundation for an above ground structure. The line was encased in powdered thermal insulation and was probably corroded from the exterior due to water intrusion of the insulation. A bypass was installed to repair the leak and avoid undue disturbance of the backfill.

24. A 3/4-inch air line junction consisting in a threaded connection between steel pipe and copper tubing and fitting was severely corroded. This was a classic case of galvanic corrosion of the buried metals. No protective coating was applied, and the steel was sacrificed (iron is anodic to copper).

25. A 2-inch, sch. 40 steel pipe used for discharge of waste overheads from an evaporation/concentration process leaked. At the site of the original leak, the line together with parallel standby and steam condensate pipes had thin, poorly applied asphalt coatings for corrosion protection (Fig. 17). All three pipes had considerable pitting, and the coatings could be wiped off with a rag. Some of the sections of pipe at other locations along the 3-pipe run appeared to have proper factory applied coatings, though butt weld sites were suspect. The waste line failed hydrotest and was removed from service. The standby line was pressed into service, but it was recommended that all three lines be replaced.

26. A 4-inch CPVC waste line failed by brittle fracture within a few months of exposure to an unusual wetting agent, tributylphosphate (Ref. 7). Normally, the rigid vinyl pipe material would be resistant to the solutions to which it was exposed. However, specific solvents may alter surface characteristics so as to allow the surfaces to be wet by such solutions, and thereby allow absorption into the structure. The material can be plasticized, or suffer a change in glass transition temperature, or experience a decrease in stress level for initiating crazing. Solvent stress cracking may result, a particularly insidious form of attack which is able to cause rapid catastrophic failure. Whenever organic compounds are included in the mix, nonmetallic piping and associated equipment must be studied to assure safety of operations.

## DISCUSSION

A principal observation in this selection of examples of pipe failures is that corrosion plays a key role in many of the failures. 18 of the 26 examples in the above list involve corrosion. General thinning and pitting on pipe walls are common corrosion results, and often lead to penetration and leaks. But corrosion may also contribute to or abet situations leading to mechanical failures. So it is very important to address corrosion protection in the design phase and to carry through in the installation phase, in particular as regards inspection to assure coating integrity before proceeding with burial.

One of the corrosion failures was a galvanic corrosion problem (#24). Copper and steel were joined and directly buried with no protective coating. The soil acts as an electrolyte with the dissimilar metals, resulting in a natural potential difference and driving force for corrosion. Copper is more noble, so that the steel is sacrificed in this couple. Any dissimilar metal pair, which is joined electrically (welded or soldered together) such as this, requires isolation from an aqueous environment to avoid significant corrosion. If this had been a water pipe, corrosion would have proceeded from inside and failure would have occurred much sooner.

Two of the corrosion failures were on stainless steel pipe, and both of these were due to chloride stress corrosion cracking (CSCC). In example 4, source of the chloride was the hydrotest water. CSCC proceeded from highly stressed areas on the inside surface. The second CSCC failure occurred beneath thermal insulation on the outside of the pipe, example 21. The polyisocyanurate foam insulation containing >100,000 ppm chlorine from the blowing agent was the source of the chloride leading to the CSCC. Note that many adhesives contain chlorides, so that labels and tapes applied to a stainless surface may result in a similar cracking phenomenon.

Cracking under insulation is a recognized problem and has been much studied over the last 10+ years (Refs. 8-10). Great efforts are sometimes made to assure that it wont happen, including coating the outer surface of stainless pipe or tanks with a chloride-free paint before applying the insulation. Also, fiberglass insulation is now typically used because it contains no $Cl^-$. The phenomenon results because contact of the insulation with the surface produces crevices, and small amounts of chloride may concentrate at these sites and be very destructive.

One of the two plastic pipe failures in the list was the result of an environmental muddle. Rigid CPVC pipe was used to handle waste discharged from a chemical process. The waste had slight acidity, but was indicated as benign. One constituent which had not been included as part of the mix was tributylphosphate (TBP). The concentration was low and believed by the designer to be not significant. Unfortunately, many organics often are chemically active and important at very low concentrations. TBP is a surfactant or wetting agent for PVC and CPVC. It reduces the surface tension and may allow liquids which would otherwise be unable to wet the surface to intimately coat onto the surface. In addition, TBP is itself a solvent for many plastics, including PVC, and can chemically attack the material. It may cause softening, crazing, and/or cracking. Solvent stress cracking occurred in the pipe of example #26 of the above list. Laboratory tests showed that most plastics and elastomers fared no better than CPVC, but that both high density polyethylene and PVDF pipe materials performed satisfactorily in handling the wastes (Ref. 7).

Four of the examples listed were mechanical failures of the brittle shear type described in the Background section under Backfill. In three of the cases, ground level overloading in the vicinity of prior excavations led to pipe breaks. These three were all cast iron pipelines, and compaction in the reconstituted backfill was questionable. The fourth failure in the list was at a fixed slab, and the break occurred at the point where the pipe exited the slab. This is a high stress location in terms of pipe bending, since it is rigidly fixed by the concrete slab, yet free to deform in the immediately adjacent space. Compaction of the earth in this neighborhood is extremely important. Evidently it was inadequate and allowed either the pipe or the slab to move. Repair was made by bypassing the slab with a new pipe, and simply abandoning the old line.

A peculiar failure occurred with example #13. This was a solvent welded PVC water line. Although it passed hydrotest, a small leak existed at a socket joint. Water seeped through a tortuous path in the fused material over an extended period of time. Over time, the material became somewhat eroded, the path became somewhat less tortuous, and the resulting pressure drop at the leak exit site became somewhat less than at the outset. Eventually the water flow was fast enough to cause roiling at the exit. Particles of sand in the newly established eddy abraded and eroded the pipe on its outer surface until a hole was worn through the pipe wall near the original leak site, just beyond the socket. The new hole provided a much more substantial leak than the original, leading to discovery of the problem. Such a development is not peculiar to plastic pipe, but it more likely to occur with plastic than with metal assemblies.

## SUMMARY

All materials exposed to the elements eventually change to the most stable state for the prevailing conditions. Structural materials originally converted from ore have a tendency to revert. The steel corrosion product and process are probably the most recognized of any, since everyone is familiar with rust. Protection of steel from direct exposure to the elements is usually accomplished by coating or painting the exposed surfaces. Cathodic protection is sometimes employed in addition to coatings.

Specifications applied for burial conditions should be tight and must be followed in order to achieve design life. Special concern must be applied to reburial after any excavations, where tamping and compaction of the backfill has often been ignored. An old saw: "failures beget failures" applies, because original conditions are usually unknown and repair oversight is often absent.

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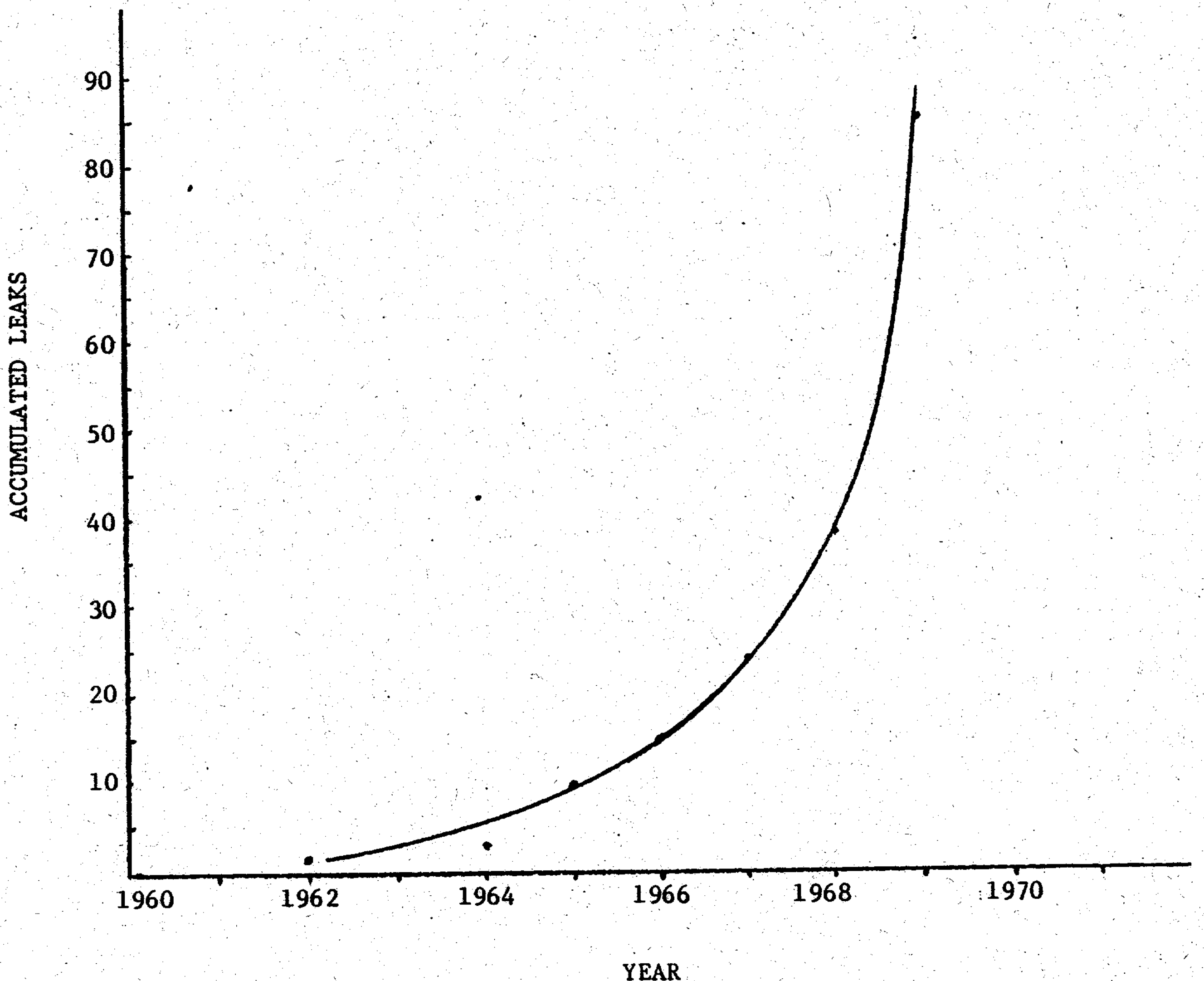



Figure 1. Leak history of an underground pipeline. The curve is prototypical and exponential. Reference 1.

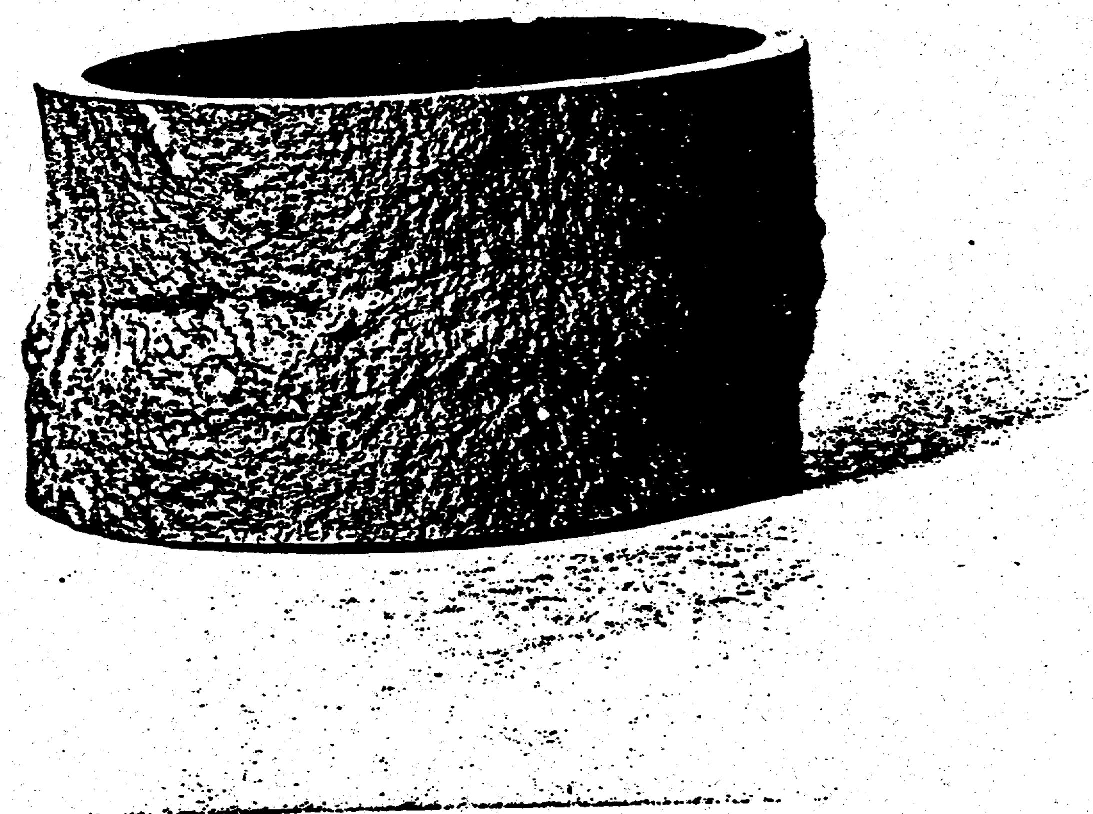


Figure 2. Misalignment of pipe and elbow segments in a failed steam line. Wet steam erosion occurred at the resulting step on the inside. Exterior was blast cleaned to reveal corroded surface.


Figure 3. Large excavation at leak site. Hole C in the leak detection system drain pipe occurred at the interface between two backfill materials having very different electrical properties.

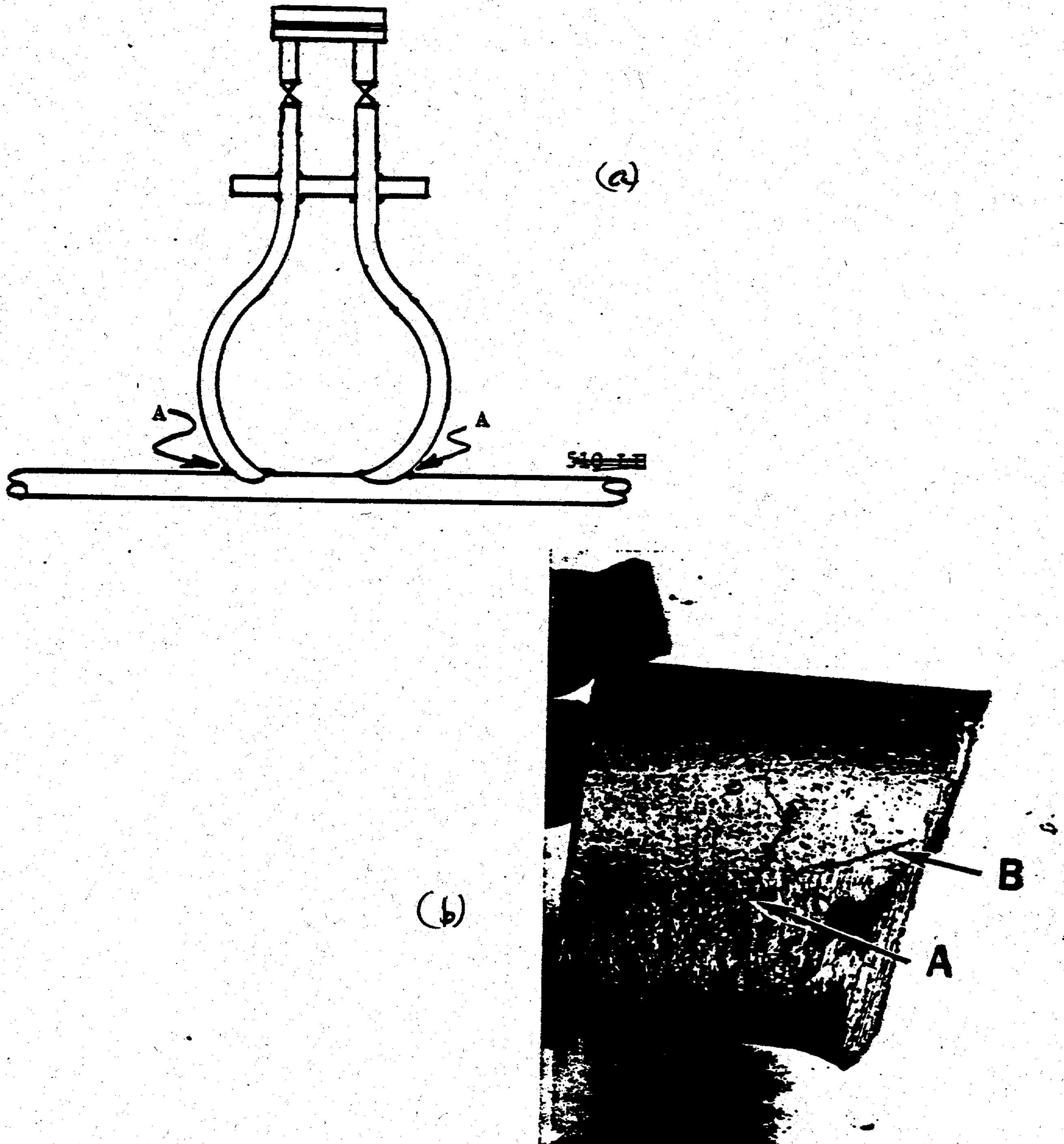



Figure 4. (a) Cleanout port detail, illustrating crack (CSCC) locations in stainless steel catheter pipes.
(b) Outside surface of failed catheter, showing CSCC leak site.


Figure 5. CSCC in second catheter, illustrating origin at inside surface. Magnification: 50X.

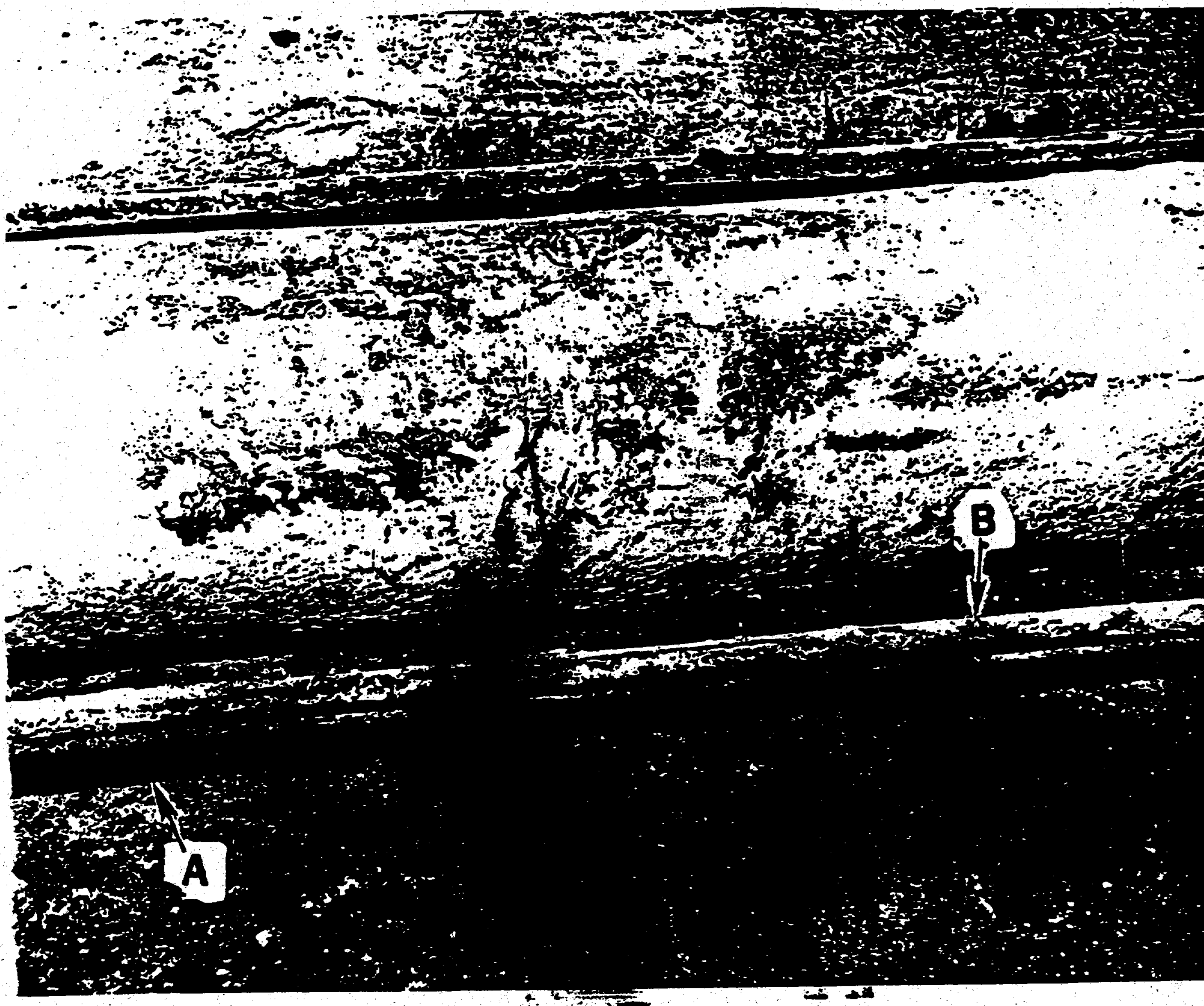



Figure 6. Crack in 8 in. iron pipe extends ~ 1/2 the circumference around the bottom. Note shadow (A) of tie bar (B) on the concrete slab beneath the pipe.

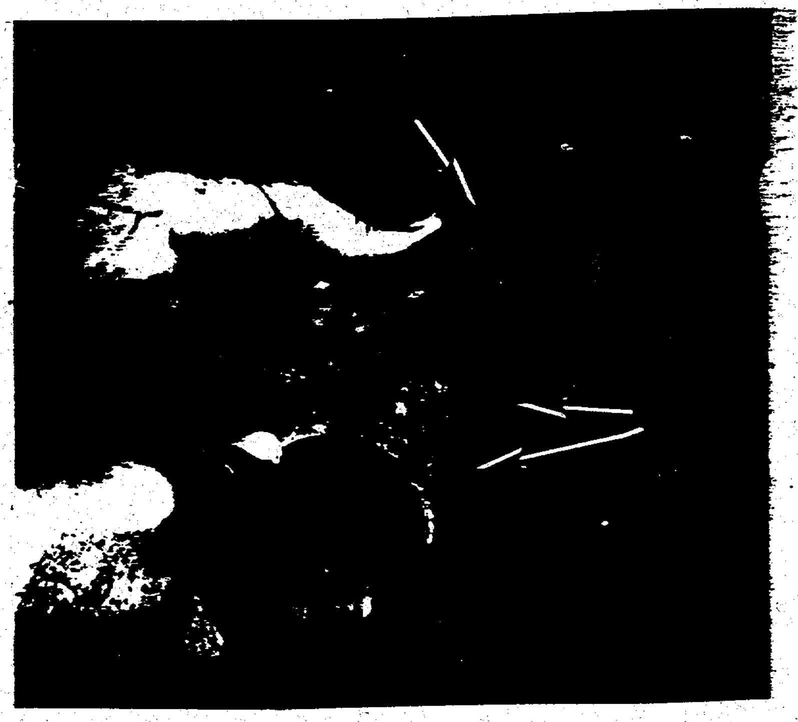


Figure 7. Corroded 2 inch pipe showing hole (A) and additional pits (B).


Figure 8. Cross sectional view of pipe in Figure 7 shows pit depth is approximately equal to full wall thickness.

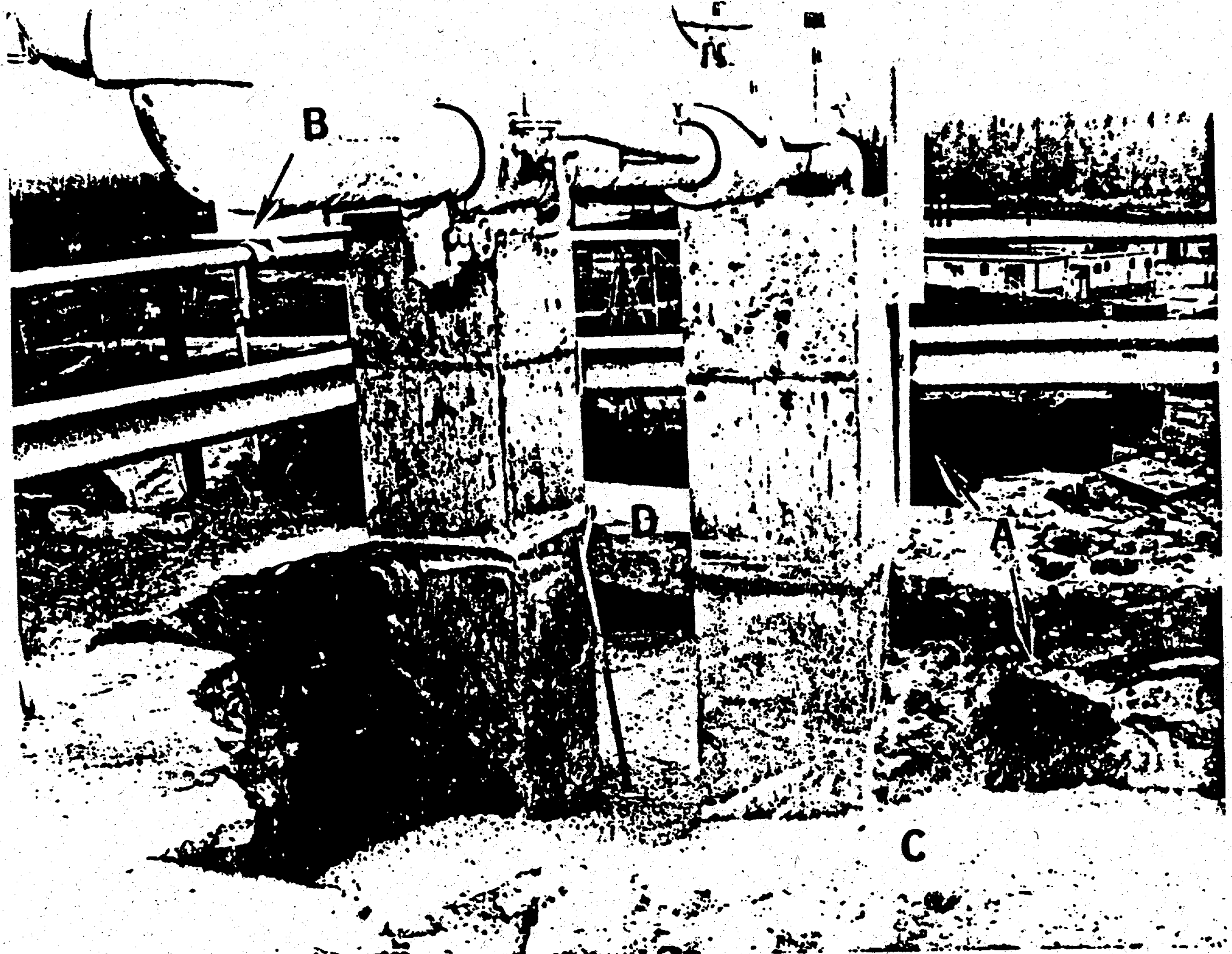



Figure 9. Steam equipment at edge of hill. Large wsahout (A) occurred due to broken underground water pipe 300 ft. away. The pillar supporting the steam pipe at B fell into the hole and is buried in the aggregate C. Slab D bridges a gap created by the washout. Several buried pipes on the hillside were exposed.


Figure 10. Broken section of well water line. Corrosion pits at A are full depth. The crack existed prior to the pitting.

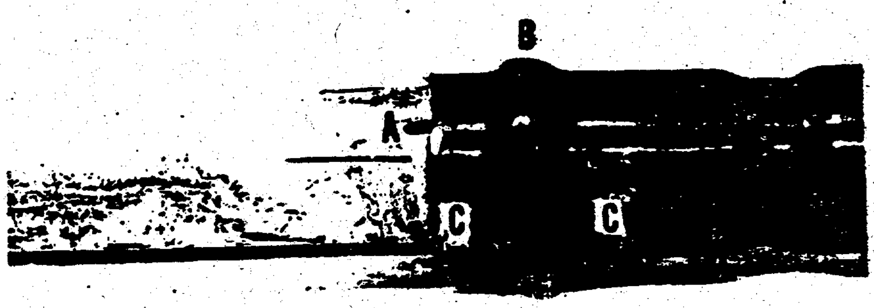
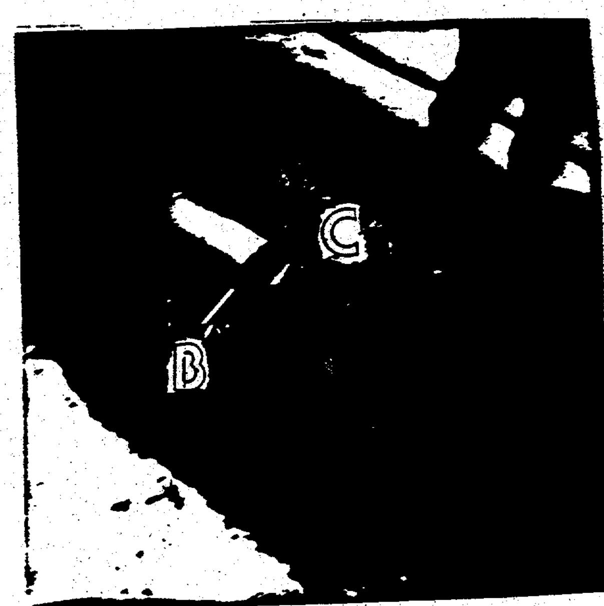



Figure 11. Failed section of PVC piping. Hole A resulted from erosion on the outside. Bump B in the coupling is designed to contain an O-ring, though none was used or should have been necessary in this solvent welded assembly.


Figure 12. Failed steam line. Inordinate corrosion exists between A and B. including elbow C. Remnants of a powdered insulation backfill exist all the way to grade level. Inset shows hole and thin wall: 0.031 in. wall (nominal is 0.218 in.).




A

B

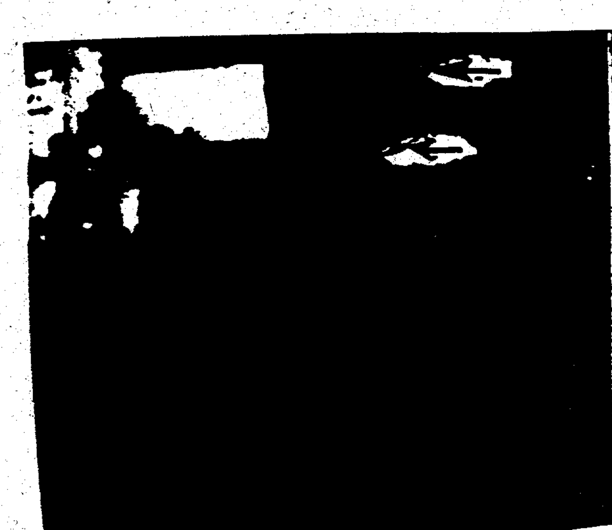


Figure 13. External pitting on process water supply pipe (B). Nearby are two full circle clamps and an abandoned hose clamp (A).

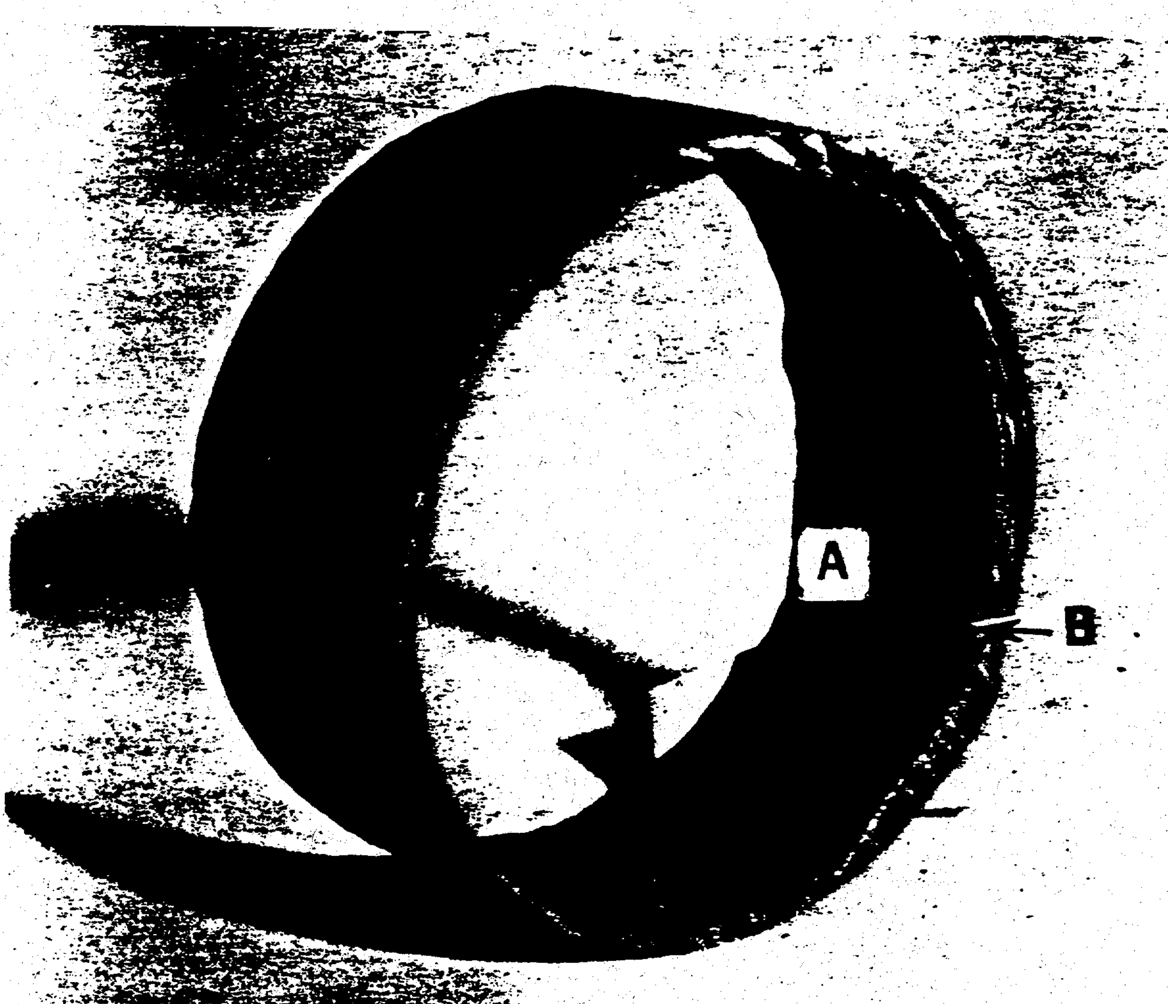



Figure 14. Severe erosion (A) and erosion-corrosion in a 2 in. water pipe at its connection to a 6 in. header. Metal loss due to water impact at the junction. Location B shows full wall thickness.

Figure 15. Photograph showing leak at overhead insulated water line.

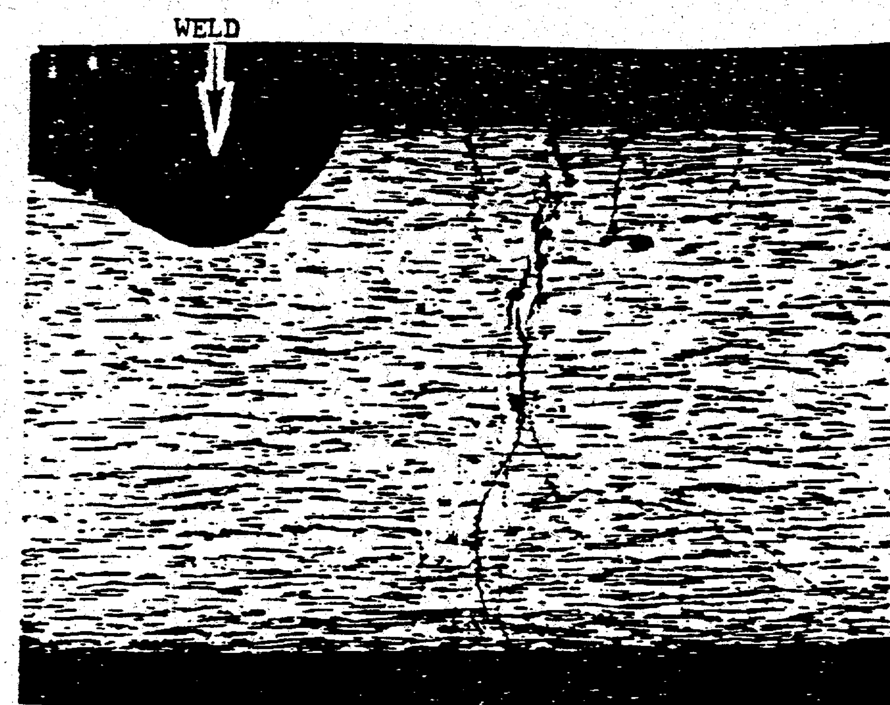



Figure 16. Chloride stress corrosion cracking in stainless steel pipe initiated under an ID tag on the external surface. Source of the chloride was external thermal insulation. Magnification: 20X.

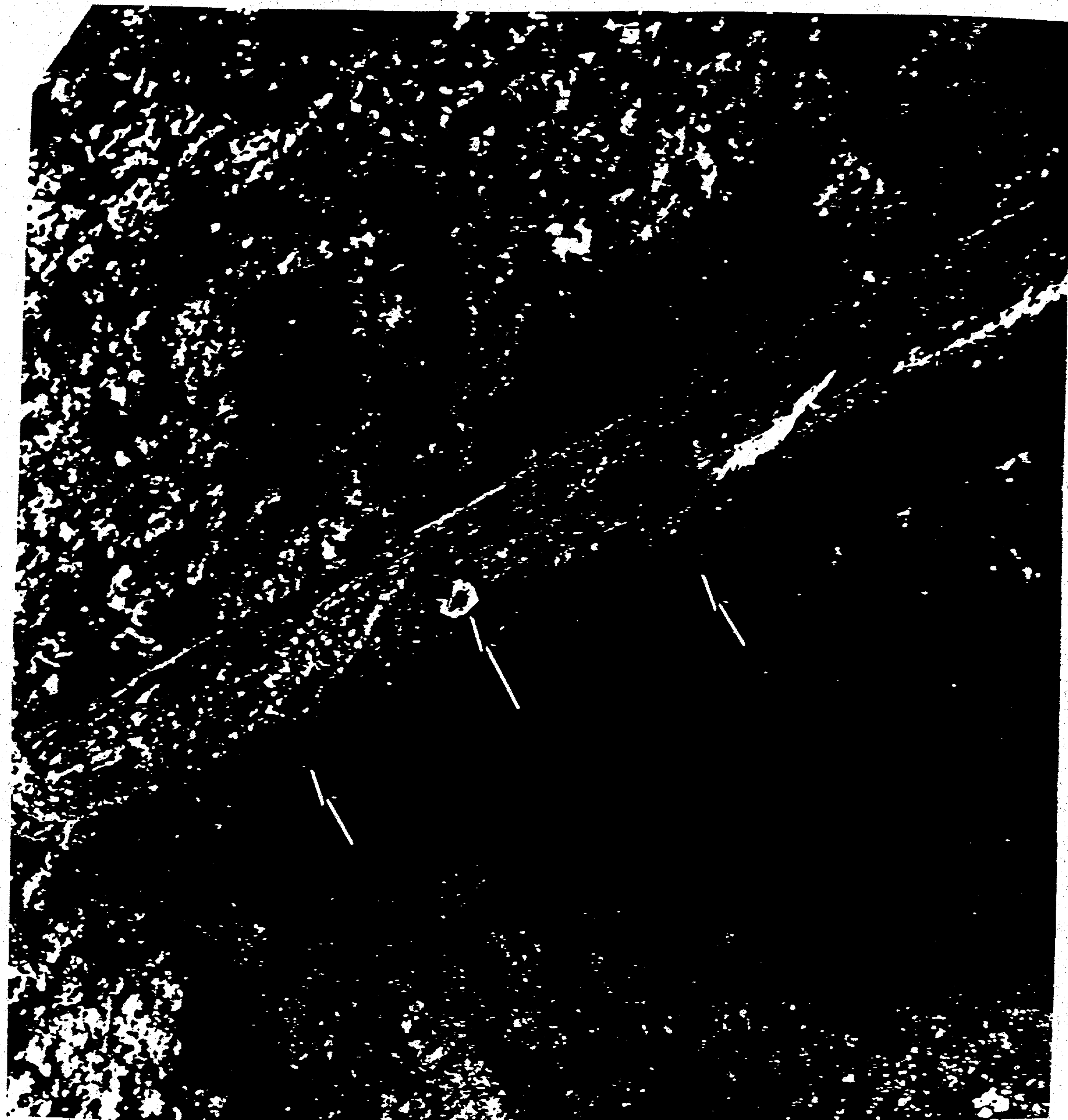


Figure 17. Pitted waste discharge piping. A poorly applied corrosion coating is obvious.