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Forensic Engineering – Part D  
**Case Histories: Corrosion Failure Analyses**

By

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## **Introduction**

This course provides five case histories of root-cause failure analyses in the areas of corrosion-related failures. The objective is to show the practical use of the principles that were presented in the previous SunCam courses: *Forensic Engineering Parts A and B* as well as *Corrosion Control and Tactics*. The earlier *Forensic Engineering Part C* course provided different cases to those presented here but with the same objective.

It is strongly recommended that the user of this course either has working knowledge of metallic corrosion failures or is familiar with the SunCam courses cited or equivalent information. The critical principles involved in each case are discussed here but it is assumed that the reader has basic background experience and knowledge.

Typically, the Scientific Method of approach to solving problems was used in each case.

The presentation sequence used is as follows:

- Background Information
- Possible Causes
- Evidence Gathered
- Results and Analysis
- Conclusions
- Recommendations (where appropriate)

As in the earlier case histories course, most of these cases are based on actual failure analyses. True identities of participants, brand or trade names of equipment and actual locations of the incidents are not used to protect the parties involved. In addition, some of the cases entailed legal actions but many of those details are omitted here. Instead, the present objectives are to illustrate the methodology and technical aspects of finding the root-cause of the given failure.

When appropriate, references sources consulted or that may be used in failures of the given type are cited. This is to allow the reader to gather more information if desired.



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## **Failure of a Fire Protection Sprinkler System**

### *Background*

Approximately four years after initial installation, the overhead piping in a financial services building used in the fire protection sprinkler system failed via pin-hole leaks at some but not all locations in the system. The holes were assumed to be due to corrosion. The entire piping system, including branch sections, had a length of almost one-half mile. The piping was located above foam, false ceiling tiles with vertical sprinkler heads projecting down just below the tiles into the various rooms. Soaking wet foam tiles fell at the pipe failure sites which were not at the sprinkler heads. Water then sprayed out widely at pipe failure sites. The sprinkler heads did not open. In several rooms critical financial records were kept as computer tapes on large disks. Many of the disks were ruined.

This sprinkler system was a “dry” type also known as a pre-action variety. Water was intended to be released into the overhead piping only when heat was detected by sensors in the building rooms. This in turn would automatically open upstream water feed valves that flooded the piping in appropriate portions of the system. A compressed air blanket was maintained in the system. That air was specified to be dry, i.e., having very low humidity. All the piping material was bare Schedule 10 carbon steel. All the failed pipe sections had either 3 or 4-inch nominal diameters.

Soon after the failures, on-site inspections and gathering of all of the known failed pipe sections as well as nearby unaffected sections were removed from the system and replaced with new piping. It was initially unknown if a partial or complete piping system replacement would be necessary.

The management of the financial firm was shocked at news of the failure. It was going to be very time consuming for them to try to re-establish the lost data. There also could be major physical renovations or even complete replacement costs for the sprinkler system that their liability insurance might not cover. Certain types of accidents including losses due to microbiological influenced corrosion (MIC) were excluded from their policy. Determining if MIC played a role in the failure was critical.

The situation was especially surprising because this was a “dry”, pre-action sprinkler system that normally was only supposed to contain compressed air. There had been no fire at any location in the building. However, water had been released from the overhead piping in specific rooms and



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not others. A legal suit, involving several parties, was initiated by the building's owners. Engineering experts representing the various parties were assigned to evaluate the failure and identify the root cause.

Some aspects important to the operation of a "dry" fire prevention system recorded here may not apply currently. In addition, certain technical factors related to MIC were not understood when the original analysis was done. Many uncertainties about MIC still remain. The primary objective in his case is to illustrate the process of a thorough failure analysis investigation, especially one that may involve MIC.

*Possible Causes*

- The bare carbon steel piping was defective and this contributed to slow internal corrosion. That corrosion occurred due to water condensation from the internal compressed air that was not dry as specified. The process took place in only certain pipe sections.
- The sprinkler piping system was not properly drained after the hydrostatic pressure test done after piping installation. This occurred because some piping was not properly sloped during installation. Therefore, some piping drain valves, that may have been located as specified, could not completely drain certain pipe sections.
- The city water source, that was used for the hydrostatic test and was intended for normal use in the case of a fire, had chemical or biological characteristics that made it more likely to cause failure by some corrosion process including MIC.

As in any failure analysis, it is critical that no potential cause is initially assumed to be certain or is assumed to be impossible. During the analysis, potential causes should be eliminated, original causes confirmed or new ones defined. Keeping an open mind throughout is always essential.

*Evidence Gathered and Indications*

Initial, on-site inspections of failed and removed sections of the sprinkler piping were conducted in the building. Pipe samples were taken from random locations in the system where corrosion had occurred and from adjacent areas where there was little or no corrosion. Various quantities of residual water were found inside the pipes. Quantities observed ranged from just small



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amounts at the bottom at the “6 o-clock” positions of some sections to other pipe that was almost half full of water.

Many of the pipe samples had at least some internal amounts of an uneven but generally flat and irregularly spaced brown-reddish deposit. The sizes of these areas generally correlated to the location and to the extent of water found in different pipe sections. Many of the examined pipe samples had internal brown-reddish colored tubercles located in water-covered and deposit-covered areas. Tubercles are generally round or semi-conical shaped raised deposits consisting of the chemical results of corrosion. i.e., they are specific types of corrosion products.. Here the tubercles protruded out from the more uniform and generally flat brown-reddish deposits.

During the on-site inspections of removed pipe sections, different types of evidence was taken from the various locations for later examination. Certain sections were removed entirely so as to later do metallographic cross-section evaluations of the metal itself to check for material deficiencies, the extent of wall thickness loss nearby the pin-hole sites and to better define the morphology of the corrosion attack sites. When sufficient water was available, both water and solid corrosion product, including tubercle samples, were taken. These samples were intended to permit later analyses of both the chemical and microbiological characteristics of each type sample. The planned biological analyses were intended to address the possibility of MIC in the failure.

Samples of the city water feed to the sprinkler system were taken so as to later compare its chemical and biological characteristics to those values of the water recovered from the removed piping sections.

While some experts representing the various parties in the law suit were gathering evidence from the removed pipe sections other experts were assessing the installed slope of the sprinkler piping and the locations of installed drain valves.

No fire had occurred in the building since the sprinkler system was installed. It was confirmed that no automatic feed valves in the system had ever opened to flood the system – with one exception. That occurred when the system was hydrostatically pressure tested to confirm the structural integrity of the piping and joints after installation. After that test was completed, drain valves placed at low points in the system were specified to be fully opened to release all test water. The system was then to be pressurized with dry compressed air.



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It was discovered that an electrical contractor had done work in the same overhead spaces as the sprinkler system piping after most of the sprinkler installation was done. However, this contractor ran wiring and conduit in some overhead areas during a two-week period after the sprinkler piping was installed but before the hydrostatic pressure test and draining were completed by the sprinkler contractor. There was the possibility that the electrical installation tasks had resulted in changes to the original slopes of certain piping sections but not others.

*Results and Analysis of the Evidence Gathered*

The varying amounts of water, brown-reddish coating and tubercles found inside the removed pipe sections clearly indicated that some type of steel corrosion had occurred. Tubercles can be formed by a MIC process but they can also form during other types of corrosion such as pitting when no MIC is involved. All pin-hole leaks were found to be located under tubercules.

The examination of the metallographic cross-sections of the pipe indicated that the steel was generally normal and without clear defects. At areas without corrosion, the pipe samples were found to have the proper wall thickness of 0.120-inch for Schedule 10, 3 and 4-inch pipe. At areas where there was incomplete penetration of the wall thickness, the depth of metal penetration due to corrosion varied from 8% to 63% of the original value. The morphology of the pipe cross-sectional areas at corrosion attack sites was generally typical of pitting corrosion of carbon steel. That is the pits were much wider in cross-section than their depths. The opposite is generally true for pitted stainless steels.

Chemical analysis indicated there was a wide range of concentrations of dissolved iron ions in the removed pipe water, i.e., about 8 to 1600 ppm of iron. These values indicated two things. First corrosion of the iron-based steel clearly had occurred. Secondly it showed that the corrosion processes were almost zero in some sections and significant in others. The wide range of dissolved iron ions corresponded to the very different quantities of water that were found in pipe at different locations. By contrast, the city feed water to the sprinkler system had less than one ppm of iron ions.

Analysis of the water in the pipes, at all locations, indicated it was soft water, i.e., it had low concentrations of calcium and magnesium as carbonate compounds. The values found ranged from about 19 to 50 ppm. Waters having from zero to about 75 ppm carbonates are classified as soft. Hard waters have concentrations of carbonates of these two ions that are above about 150 ppm. Hard waters often produce scaling on a pipe surface, due to precipitation out of solution of calcium and magnesium carbonates. This scaling can provide protection from corrosion if the



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scaling is continuous. Here this water was definitely soft and no scaling would be expected. Therefore, it was concluded that the water in this sprinkler system was generally more corrosive than hard water might have been.

Other chemical variables in the water samples that are important in causing corrosion were found to be non-aggressive. The concentrations of chloride, sulfate and sulfide ions were each less than 100 ppm in all samples. The pH values of all water samples varied over a range of 6.9 to 7.2. It is generally seen that iron and steel plus many other metals have low rates of corrosion in corrosive liquids having a pH above 5 but less than 10 when other variables that affect corrosion rates are equal.

Another variable necessary for metal corrosion to occur was available. This was the oxygen in the compressed air that was always maintained inside the piping system. An amount of the oxygen above wetted areas in the piping was dissolved in the water in contact with the steel. Electrochemical reduction of the dissolved oxygen would permit the essential cathodic reaction needed for a corrosion process to occur.

While not a chemical variable, raised water temperature generally accelerates corrosion rates. All of this sprinkler piping was in an ambient temperature environment due to the building's HVAC system so temperature was not a factor in the corrosion found.

The biological analyses of both water and solid deposits removed from failed pipe sections provided critical information. There was controversy over the data because of the two different techniques that were used by the opposing legal parties. One party used a culturing method and the other party used a DNA comparison technique.

The culturing method is used for defining the kind and approximate quantities of bacteria microbes that have traditionally been associated with MIC. In summary, this method consists of collecting samples in the field and delivering them at a controlled, low temperature to a microbiological laboratory within a specified, brief time period. The separate samples are then put into multiple, small containers that contain a special chemical medium that is a nutrient for many types of live bacteria. This allows the live microbes present to multiply during a given time period. At the end of that time of "culturing", the presence and approximate quantities of live microbes in the containers are counted using a light microscope.



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The DNA method has the same goals as the culturing method. However, here there are no requirements that the collected samples be kept at a given temperature or delivered to the lab within a given period. This is because both live as well as dead microbes are identified by this method. Once at the lab, special procedures are completed to identify the DNA of bacteria in the separate collected samples. All resulting DNA present are then compared to a pre-defined database of the DNA of microbes known to be associated with MIC. These comparisons allow the lab analyst to determine if MIC-related bacteria are present in the recovered samples. The approximate quantities of other bacteria, i.e., those that may or may not be involved in MIC, are also identified and counted. The approximate percentage of each different type of bacteria in each sample can then be estimated.

In this case the culturing method indicated that the numbers of certain microbes of bacteria traditionally associated with MIC, i.e., sulfate reducing, nitrate producing, acid producing, slime producing and others, were either present only in very low quantities or absent completely. The DNA comparison method agreed that sulfate reducing bacteria were present in very low quantities BUT other bacteria related to MIC were found to be present in significant numbers. There was disagreement between the parties' experts about the importance of sulfate reducing bacteria (SRB). These bacteria have been strongly associated with MIC on buried steel and iron materials in certain soils. SRB are common in soils so their presence or absence in applications not in soil are sometimes treated as the only important indicator of for MIC. That assumption is incorrect

As expected, both bacteria detection methods indicated that greater quantities of all types of bacteria were in the solid deposits in both tubercles and other solid deposits as compared to those in the different recovered water samples. This is because most of the bacteria in non-moving water eventually settle down onto a pipe's inner surface and increase the population there to a much greater extent than in the static water above.

It was found that the source of the water seen and collected from the different failed pipe sections must have been residual, non-drained water from the delayed hydrostatic pressure test. That was because it was confirmed that the electrical contractor had in fact changed the slope of certain piping sections while doing his work and this occurred before the hydrotest was done. The sprinkler contractor did not know until after the fact about the timing of the work by the electrical contractor. The drain valves were correctly located based on the original, intended slope of the piping but they could not fully release water in all pipe sections due to the changes in slope.



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*Discussion and Interpretation of the Evidence*

Two of the assumed root-causes of the failures were eliminated. The organization that supplied the carbon steel pipe was released from the suit because the pipe had the proper wall thickness and was not defective in any other way. It was also confirmed that the sprinkler contractor had installed dry compressed air in the piping. That contractor had not known of the previously changed slope of certain pipe sections by the electrical contractor when the hydrotest and draining functions as specified were completed. However, while the change in slope and inability to properly drain all the piping was not the fault of the sprinkler contractor, this provided water in parts of this “dry” system. The sprinkler contractor was ultimately released from liability. The consequences for the electrical contractor were unknown to the engineer that assisted the attorney that represented the building’s owners.

The remaining question was what type of corrosion produced the failure and was MIC involved. This can be analyzed by going back to the evidence gathered and related information.

The chemical characteristics of the water found in the pipe section, by themselves, were not sufficient to explain the corrosion that occurred. Specifically, the concentration of chloride, sulfide, sulfate and nitride ions were each less than 100 ppm and those levels are typically non-aggressive to carbon steel. The pH of the water in the range of 6.9 to 7.2 will usually generate only low rates of corrosion in aerated water. The softness of the water may have had a minimal negative effect but that is doubtful in light of the other factors. Finally, the water temperature was always near ambient and this is non-aggressive to steel.

The uneven and irregularly spaced solid deposits inside the removed pipe sections provided first clues to the type of corrosion that occurred. The early inspections found solid red-brown deposit areas, many with tubercles, that were adjacent to areas that had little or no corrosion. This pattern is consistent with oxygen concentration cell corrosion. In this form of attack the area under a solid deposit is essentially blocked from easy access to oxygen from the water above. At the same time the nearby areas are freely exposed to that oxygen. This produces an electrochemical cell. The anodic chemical oxidation reaction occurs under the thick deposits (many with tubercles) while the necessary oxygen reduction reaction occurs on the nearby freely exposed area that represents the cathode of the cell. The difference concentrations of oxygen at the anode and cathode areas initiate the corrosion process under the solid deposits.

It was found from examination of the tubercles by the DNA method that the concentrations of bacteria known to be involved in MIC were significantly greater under them than in solid deposit



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areas without tubercles. This indicates that in this case the tubercles were associated with MIC as is often seen.

There were at the time of this case (and there still are) much that is not known about the fundamental mechanisms involved in MIC. It can be estimated that in this case the failure occurred as follows:

Non-drained, stagnant water from the hydrotest that was found in some pipe sections with compressed dry air above provided the basic ingredients for some type of corrosion in the bare carbon steel pipe. The DNA bacteria detection method confirmed that the feed water to the piping contained different types of bacteria that are known to cause MIC plus many bacteria that may or may not contribute to MIC. High levels of SRB were not necessary in this application.

After some time in the non-drained water, slime-forming bacteria precipitated out and deposited a microscopic thickness layer on the bottom portions of affected pipe. This slime, called a biofilm, consists mostly of water but it also includes nutrients necessary for many types of bacteria to multiply. The biofilm is also sticky. Bacteria in the water precipitate out of solution and increase the thickness of the slime deposits over time at discreet areas. Oxygen concentration corrosion cells begin at these separate areas. It is unclear to researchers how the process always occurs but apparently bacteria associated with MIC accelerate corrosion that in their absence would go at a slower rate. Where bacteria densities are highest, tubercles begin to form and corrosion that has a morphology like pitting generally occurs under each tubercle. Penetration into the steel continues to varying extents in different locations depending on the amount of water and density of bacteria present at the given spot.

### *Conclusions*

This failure occurred due to a combination of oxygen concentration cell corrosion and MIC. It is difficult to judge which form of attack was more significant as a root-cause.

The DNA method of identifying the types and estimating the approximate quantities of bacteria known to be associated with MIC is more reliable than the traditional culturing method. Other bacteria may also contribute to the MIC process besides the ones known to do so.

Much is unknown about the fundamental mechanism(s) of MIC. A potential scenario for the possible steps that occurred in this failure has been presented. The best analysis of MIC requires joint contributions from experts in microbiology, electrochemistry of corrosion and metallurgy.



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*Selected References (many others exist)*

P.J. B. Scott, “Expert Consensus on MIC: Prevention and Monitoring, Part 1” and “Expert Consensus on MIC: Failure Analysis and Control, Part 2”, *Materials Performance*, March and April, 2004.

Brenda J. Little, et al. (A Review) “Microbially Influenced Corrosion – Any Progress?”, *Corrosion Science*, July 1, 2020.

### **Corrosion of Natural Gas Steel Piping in a Small Industrial Facility**

#### *Background*

The final products of a small, job-shop type manufacturing plant were gold-based jewelry. The initial step in the overall production process was a metal refining process done by heating gold-containing compounds in a special liquid, aqua regia, so as to allow recovery of gold for use in the jewelry. Aqua regia is a mixture of nitric and hydrochloric acids. Gold-containing compounds were placed in specially designed bowls containing small amounts of aqua regia and heated from below with natural gas-fired burners. This mixed acid solution is very corrosive especially when heated. After an exposure period in the aqua regia nothing remained in the bowls of the initial compounds except essentially pure gold.

During the heating of the bowls, nitric and hydrochloric acid vapors were produced in the relatively small room used for the refining process. That room was separated from the rest of the plant. Negative-pressure exhaust hoods made of non-metallic materials were used above the bowls to remove acidic vapors from the room. Recently gold production rates had been increased to meet demand. This increase required the use of more refining bowls. It was then suspected that the exhaust system did not have enough capacity to remove the increased quantities of acid vapors from the room. The same refining process and exhaust equipment had been used for twelve years since the facility first started refining.

Carbon steel piping in sizes from  $\frac{3}{4}$  to 3-inch diameter was used to convey natural gas into the refining room and to separate burners under the refining bowls. The gas pressure in the piping was 2 psig. This piping had been painted initially, twelve years ago, but now the coating was seen to be missing entirely or the paint had partially peeled off of most piping sections. There were obvious, large deposits of solid corrosion products on the piping at the missing and



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defective coating areas. Gradual corrosion had been observed by plant workers and reported to the plant's owners. However, no action had been taken during the most current six years when the coating condition gradually became worse.

Recently the owners had become concerned that the corrosion seen on the gas piping had penetrated the pipe wall thicknesses so that gas leaks might soon occur and cause a serious condition. So far no gas leaks had been detected. As a preventative measure, the owners retained a corrosion consultant, George Patterson, P.E., to evaluate the situation, define the factors that produced the external corrosion and make indicated recommendations. No legal action was involved.

*Possible Cause of the Corrosion*

- The present exhaust system could not remove all of the hot acidic vapors generated during the all of the gold refining period of twelve years. These vapors plus warm, humid ambient air in the room condensed on gas piping. This gradually produced large, solid corrosion products seen on the peeling and unpainted portions of the gas piping.
- The exhaust system had always had enough capacity for any production rate but the raised temperature and humidity of the ambient air in the room alone was sufficient after condensation to slowly produce large, solid corrosion products on bare portions of the gas piping.

*Inspection and Evidence Gathered*

Patterson visited the site to gather information. He interviewed workers and the owners separately. The separate interviews were done in an attempt to get completely honest input from the workers as this might not happen if the owners were in the same meeting. During the approximate twelve-year work period in the refining room there had been no natural gas leaks. The gas piping was initially painted but no repair painting had ever been done. This was true even though the workers noticed gradually increasing corrosion product during the last seven years when the paint began peeling. They notified the plant owners but nothing was done to redo the paint. The current increased demand for refined gold began about two years earlier but no changes were made to the exhaust system. Workers were in and out of the refining room when the process was on-going but no one remained there continually.

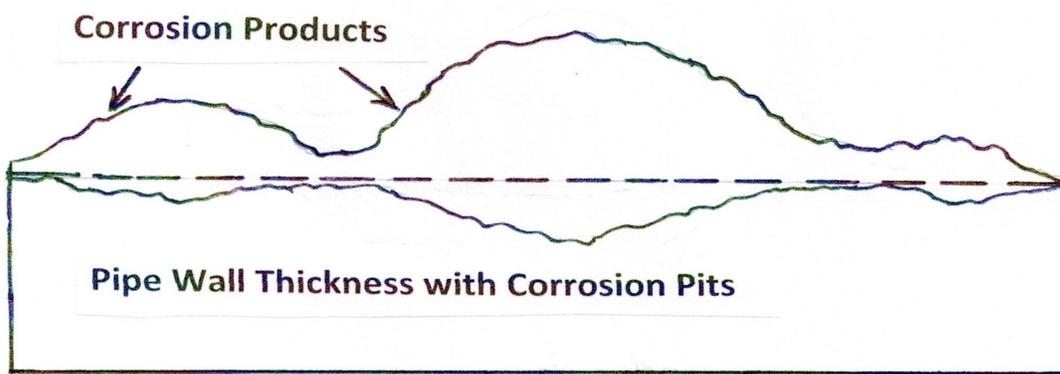


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Warm, humid air existed in the refining room when the refining was on-going. Currently the work was done continuously during days and often during nights. Outside ambient air was usually cooler during nights. The refining room, separated from the rest of the facility, was very poorly insulated so the inside and outside air temperature generally changed in a similar pattern. When the outside air temperature decreased the temperature inside the refining room did also but to a slightly lesser degree. When refining was done during a cool night the lower inside temperature increased the relative humidity there and thus condensation in the room became more probable.

The pressure of the natural gas inside all of the gas piping is now 2 psig downstream of the outside gas meter. This value had not changed during the twelve-year service life of the refining room.

Patterson found that all the gas piping was plain carbon steel and specified to be standard Schedule 10. He scraped off voluminous corrosion product deposits at multiple locations on bare sections of the gas piping with some volume variations at different spots. See Figure 1. Typically, there were corrosion pits to various depths at the inspection sites. He used an ultrasonic non-destructive evaluation (NDE) instrument to measure pipe wall thickness at spots with little or no pitting. This indicated the non-corroded piping of each size was Schedule 10, as specified. A manual pit gauge was used to measure the depths of the pits at the various inspection sites. He saw that the deepest pit was approximately 5/64 of an inch (0.078-inch), and this was on a 3-inch diameter pipe. A manual corrosion pit gauge can correctly measure to this accuracy if handled carefully.



**Figure 1.** Schematic of a cross-section of corroded pipe wall  
Figure 1 shows the approximate size of corrosion products (iron oxide hydrates) formed from the corrosion pits indicated. These products are sometimes called “Rust Bloom”. No dimensional scale is intended in Figure 1.



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*Analysis of the Evidence*

Patterson evaluated the environmental conditions that applied in the case. Especially during night operation of the refining process, when both inside and outside ambient air typically were cooler, there was a greater possibility of indoor air temperature decreasing and becoming more humid than normal. When the room temperature air was low enough it reached its water saturation point, i.e., its Dew Point temperature. At that point, and lower temperatures, condensation began. This provided the water necessary for corrosion on bare portions of the gas piping. This continued during nights and possibly some days, to varying extents, whenever refining was in progress. The extent of corrosion that then occurred would depend on how effective the exhaust system functioned to remove acidic gases.

A conservative maximum, average corrosion rate on the unpainted sections of the piping can be estimated by dividing the maximum measured pit depth (5/64-inch) by the time period (seven years) when the pipe paint was in marginal or poor condition. Doing this calculation produces a corrosion rate of about 11 mpy. Patterson knew that this is not a high corrosion rate for plain carbon steel exposed to only fresh water at normal ambient temperatures. Even so, here the temperatures in the refining room were somewhat raised and that might have increased the rate slightly. Other pits Patterson measured had smaller depths and, therefore, would be associated with a still lower estimated corrosion rate for the same exposure period of seven years. If the exhaust system did not have enough capacity to remove most if not all of the acidic vapors those vapors would have mixed with the condensed water and created a much more aggressive corrosive environment. Therefore, he concluded that a corrosion rate higher than 11 mpy would have been expected.

He completed a calculation to define the maximum allowable internal pressure necessary to cause a nominal, 3-inch, Schedule 10 steel pipe to exceed its yield stress based on the hoop, or circumferential, tensile stress generated by that pressure. The traditional Barlow's formula for allowable internal pressure =  $P = [\text{Allowable stress (wall thickness after corrosion loss)}] / \text{internal pipe radius}$  was used. The variables were as follows:

The entire circumferential, remaining wall thickness used was the result of subtracting the maximum pit depth (0.078) from the original wall thickness (0.120- inch); the allowable yield stress of the steel was 10 ksi (after applying a safety factor of 3.0). The normal internal pipe radius was 1.63-inch. Using these variables in Barlow's formula, Patterson found a calculated allowable pressure of the corroded pipe to be above 250 psi. Clearly the 5/64- inch of metal loss



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due to corrosion on the largest diameter gas piping represented no safety issue given the actual pressure in the gas piping of 2 psig. He also knew that similar calculations for smaller diameter piping would predict even higher allowable internal pressures.

It might be logical to ask why the volume and thickness of the corrosion product on this pipe were so large. These products were easily seen but yet the penetration of the pipe, even the maximum value, was found was only 5/64-inch after the assumed seven-year period of attack. The consultant knew that this was because of the fact that aqueous corrosion products of steel are primarily iron oxide hydrates. See Figure 1. The volumes of these products are much greater than the volumes of the solid metal from which they are formed. The volumes of iron oxide hydrate corrosion products vary with specific conditions but it is not unusual for their volumes to be 2 to 4 times the total volume of the solid iron that was consumed in the corrosion process. Thus, a cursory visual inspection of the amount of corrosion product present is often a poor indicator of the extent of actual penetration and structural damage.

#### Conclusions

The natural gas piping slowly corroded on generally bare surface areas primarily because of water vapor condensation generated from high humidity air in the refining room. This occurred especially during cooler night operations, and possibly during cooler days, of the refining process when the lowered temperatures raised the relative humidity to the Dew Point temperature of the humid air and then condensation occurred..

The generally low rate of corrosion that was estimated indicated that the acidic vapor exhaust system had sufficient capacity to function as intended even with increased refining rates. Otherwise, the acidic vapors generated from the aqua regia plus water condensation would have created a much more aggressive environment. This would likely have caused much higher average corrosion rates than the 11 mpy maximum rate estimated.

The Barlow formula calculation of the maximum allowable internal pressure that included the maximum measured metal loss from corrosion on the largest pipe diameter indicated all the piping was completely safe from exceeding its yield strength given the normal internal 2 psig gas pressure. Smaller diameter piping would have even higher allowable internal pressures using the same calculation and assumptions.

The voluminous size of the corrosion product seen on the piping was not in itself a cause for alarm. In a water and air environment, it is common for steel corrosion products (iron oxide



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hydrates) to have a volume that is 2 to 4 times the volume of the solid metal from which they form. Often that relationship is not recognized.

*Recommendations*

Patterson advised the plant owners to protect all the gas piping in the refining room from future corrosion upsets, such as a malfunctioning acid vapor removal system, by repainting the piping and maintaining its updated condition. He indicated the repainting should start by completely removing all peeling paint, cleaning all bare and previously peeling surfaces and finally applying a primer and top coat(s) as recommended by a competent coating contractor.

***Corrosion of Rotating Drum Water Filters in an Aquaculture Facility***

*Background*

An aquaculture plant, Fresh Sockeye, Inc. (FSI) raised salmon for sale. Small enclosures with fresh water were used for fish eggs to develop into fingerlings. Other much larger enclosures with saltwater received fingerlings that were feed and kept there for approximately eighteen months until they reached marketable size. The saltwater areas produced much solid wastes from the fish that had to be removed so that clean, recycled water could be pumped back for reuse in the enclosures.

Cleaning of waste water from the growing enclosures was done by a series of rotating drum filters that operated in parallel. See Figure 2. The drum filters were purchased and fabricated by outside vendors at different times during the life of the facility. The newest two drum filters had been in operation for only six months when they developed extensive corrosion that appeared as pitting. It was uncertain how much longer those two drum filters could be used before they had to be replaced. Older drum filters that handled the same type of waste water had been in use without any significant corrosion for over seven years. The management of the FSI facility hired an outside corrosion consultant, Meagan Ridout, P.E., to analyze the potential failures and provide conclusions.

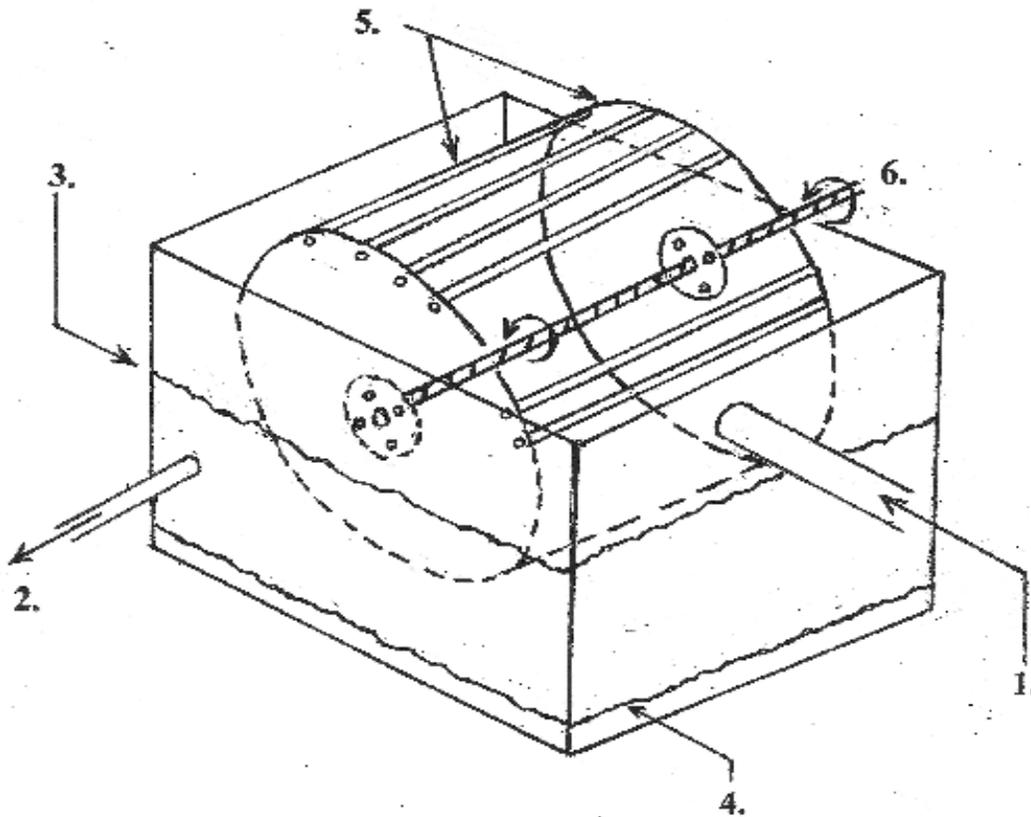
Each drum filter was relatively expensive to purchase. In addition, a larger cost would occur if the necessary growth period for marketable fish was extended because one or both of the newer filters had to be taken out of operation. Fish deaths or longer growth periods might be expected if solid waste was not removed from the filter enclosures at the required frequency. There was no



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legal action as yet by facility management regarding the supplier of the two new drum filters but FSI considered that a future option.

FSI purchased the two newest drum filters from a retail aquatics firm, ABC, Inc. based on competitive bidding. ABC did not make the two drum filters themselves but they subcontracted the tasks out to a metal fabrication shop, XYZ Brothers, LLC. The aquaculture firm had not bought from ABC in the past but they received the purchase order because of their generally good reputation and ABC submitted the lowest cost bid. Information on the expected capacity and other general specifications for the filters were included in the request-for-purchase (RFP). FSI provided some initial information verbally. ABC in turn forwarded all information to XYZ.



**Figure 2.** Schematic sketch of the confirmed characteristics of each of the corroded rotating drum water filters inside, open-top “boxes”, each 10 x 6 x 4 - feet, made of aluminum plates.

Three pumps are not shown. As shown in the figure, 1. Dirty water in via stand-off pipe, 2. Clean water out, 3. Clean water level with sensor control, 4. Bottom waste sludge and floor outlet to a slurry pump, 5. Stainless steel slats bolted to aluminum, circular end plates (slats covered with stainless steel wire mesh), 6. Stainless steel shaft driven by an electric motor (not shown).



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*Possible Causes*

- The fabrication of the filters was deficient in some way such that rapid corrosion occurred.
- The metallic materials supplied in fabricating the filters were not sufficient to resist the corrosion that could be expected in the application.
- Incorrect information about the specific operating conditions of the filters was supplied by FSI to ABC or from ABC to XYZ Brothers.

*Evidence Gathered*

Ridout completed visual inspections of the two units during periods when each was temporarily taken out of service. There was considerable pitting corrosion inside the aluminum “box” of each unit. There was also significant corrosion on the end plates especially around most of the stainless steel bolts used to attach the stainless steel slats to the aluminum end plates. She saw that no electrical insulators were installed between these bolts and the end plates. The slats and the drive shaft had also suffered significant pitting corrosion

Interviews with owners of FSI indicated that they specified to ABC that the filters should be fabricated from stainless steel for the drive shafts, slats and mesh screening and that the “boxes” and end plates were to be aluminum. The owners said they verbally reviewed their overall operation with all bidders for the new filters. They indicated this review, included brief descriptions of both the fingerling production phase as well as the growth phase for the salmon, but they were clear in communicating that these filters were to be used during the growth phase for the fish in saltwater. FSI’s written request-for-purchase (RFP) did not specify which specific stainless steel or aluminum alloys were required and did not indicate the type of water that would be used in the two filters.

Ridout completed a separate interview with ABC personnel but this provided different information versus that from FSI’s owners. Separate interviews with each knowledgeable party in a failure case are usually advisable to obtain the most unfiltered and objective information. ABC claimed they were verbally told the new filters were to be used in filtering fresh water as used for the fingerlings. Further, they provided the consultant both the RFP document and the purchase order. These documents did not specify specific alloys required or mention usage in either fresh or in saltwater. Because of the information on the RFP, ABC decided to supply a



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common, lower cost stainless steel – Type 304 – instead of a higher cost but more corrosion resistant alloy. For similar reasons, ABC decided to use the 5052 aluminum alloy that typically offers good corrosion resistance in many environments. ABC claimed they would have offered a higher cost bid that included a more expensive but higher corrosion resistant stainless steel alloy if they had known the filters were to be used in saltwater. Lacking this critical information, ABC said they passed on the use of 304 stainless steel and the 5052 aluminum material information to XYZ. Later, an independent interview with XYZ confirmed that they had used those alloys in fabricating the two filters.

*Analysis of the Evidence*

Type 304 austenitic stainless steel is a widely used alloy that offers many good properties including low cost but its corrosion resistance often is marginal depending on the specific application. This stainless alloy would be expected to suffer significant corrosion in saltwater relatively quickly. The 5052 aluminum alloy would be expected to provide more resistance than the 304 alloy in saltwater. In each alloy the corrosion likely would be pitting. Both 304 stainless and 5052 aluminum alloys resist corrosion by the formation of protective passive films. Chloride ions breakdown passive films at distinct sites and a corrosion pit initiates and grows at each location. It is well known that the concentration of chlorides and thus chloride ions are much higher in saltwater than in fresh water.

Carbon steels also form passive films but their films are much weaker and less robust than the films formed on many stainless steels or aluminum alloys. In plain carbon steels their passive films breakdown even in fresh water. Then the damage may not be localized to specific spots but it often takes place over large areas. General corrosion is typically the result. However, pitting can also occur on carbon steels depending on other application variables.

In this case the pitting took place on both the aluminum and the stainless steel components used for the filters. The most obvious issue was clear galvanic corrosion of the aluminum end plates immediately around the stainless steel bolts that connected the slats to the end plates. Aluminum is anodic, i.e., more electrochemically active, compared to stainless steels. Accelerated attack of the aluminum was due to the absence of any electrical insulating material such as plastic washers between the two dissimilar metals. The consultant knew this was a fundamental mistake by the filters' fabricator, XYZ.

Fortunately, here a favorable area ratio existed between the stainless steel bolts and the aluminum end plate connections on the rotating drums. That is the aluminum anodic area was



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much larger than the small area of each cathodic stainless steel bolt. In galvanic corrosion a small area ratio formed by a small anodic metal area (aluminum) electrically connected, without an insulator in between, to a large cathodic metal area (stainless) would create severe corrosion of an aluminum bolt. The opposite situation occurred here. At least the more aggressive galvanic area ratio relationship was avoided.

Significant pitting inside the walls of the aluminum “box” enclosures was seen just above and just below the approximate clean water level/air interface shown in Figure 2. This was because of the easy availability at that level of both water and free air. At that level the common cathodic reaction of oxygen reduction could occur unhindered by the simultaneous availability of both water and oxygen that exists immediately below and above the interface. The same detrimental situation is found in the splash zone on vertical portions of steel piers exposed to coastal sea water.

All of the 304 austenitic stainless steel used here had significant pitting corrosion. This alloy has been shown to be susceptible to both pitting and crevice corrosion in high chloride solutions such as saltwater. By contrast other stainless alloys that contain the element molybdenum (Mo) typically provide resistance to chloride pitting in direct proportion to the amount of Mo present. This element is generally the most impactful compared to other additions to stainless steels for providing pitting resistance. Type 304 stainless has no molybdenum. The next steps up in providing pitting and crevice corrosion resistance (and typically also in costs compared to 304) are Types 316 and 317 stainless steels. It may have been that one of these alloys had previously been used in other drum water filters that were still giving good service. That possibility was not investigated.

Besides molybdenum, it is known that higher percentages of other elements in the compositions of austenitic (as well as duplex) stainless steels are also important for imparting pitting resistance in chloride environments. Empirical studies have been completed to establish relationships that define what is known as a Pitting Resistance Equivalent Number (PREN). The resulting equations can be used to make approximate comparisons of the relative chloride pitting and crevice corrosion resistances of different wrought austenitic and duplex stainless steels in terms of the weight percentages present of alloyed Mo, chromium (Cr) and nitrogen (N). When present, nitrogen is only added in very small amounts compared to Cr and Mo. Different PREN equations have been developed that can have slightly different coefficients. Two of the commonly used versions follow and are provided in the ASM Vol. 13B, page 58 of the reference source cited at the end of the case:



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$$\text{PREN} = \% \text{Cr} + 3.3 \cdot \% \text{Mo} + 16 \cdot \% \text{N} \quad \text{and} \quad \text{PREN} = \% \text{Cr} + 3.3 \cdot \% \text{Mo} + 30 \cdot \% \text{N}$$

It is acknowledged that PREN predictions should only be used to make approximate comparisons of the likely resistances of different alloys. This is because of the effects of other factors such as alloy heat treatments used and different service variables in a given application.

Besides the galvanic effects on the aluminum end plates immediately around the stainless steel bolts plus at the water/air level interface, the consultant recognized that it likely might be surprising to find so much pitting on all areas of the inner walls of the “boxes” fabricated of 5052 aluminum. This was true because the 5052 aluminum alloy is typically relatively corrosion resistant in saltwater. Further the aluminum was away from the galvanic effect at the bolted connections and most of it was either above and below the water/air level in each “box”. See the ASM International reference, page 99, for the properties of 5xxx alloys cited at the end of this case.

Ridout explained the rapid and extensive pitting of the 5052 aluminum. The result was likely due to a cementation process. This is a less well-known corrosion process that causes galvanic attack on aluminum. It has nothing to do with Portland cement or concrete. Instead, corrosion by cementation involves free-floating heavy metal ions, i.e., from the corrosion of metals such as iron, copper, lead and mercury, that collect at spots on aluminum alloys and initiate pits. Aluminum is anodic to every other metal except zinc and magnesium and so iron ions are cathodic to aluminum that they settle onto. In this case iron ions were generated in the saltwater due to the pitting corrosion of the 304 stainless steel present. This may have been generated especially from the large amount of stainless wire mesh on the drums. The result was accelerated pitting on the aluminum at many separate spots where iron ions settled after generation by pitting corrosion of the 304 stainless components. Cementation is discussed by Dillon in the reference provided below.

What could the corrosion consultant say about the issues of purchase miscommunications and the lack of written confirmation of the specific corrosion conditions - salt versus fresh water – for fabrication of these filters? These are critical matters but outside of the technical issues Ridout would address. Those issues will likely be resolved in a future legal suit.

### *Conclusions*



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Clearly these potential corrosion failures may be traced to interacting and regrettable deficiencies. All of the possible causes had roles in the situation.

The material choice of Type 304 stainless steel could not provide sufficient corrosion resistance in saltwater. Alternatively, the use of either Types 316 or 317 stainless alloys would very likely have provided good service in the application because they contain molybdenum with the associated good resistance to chloride pitting.

The absence of electrical insulators between the aluminum end plates and stainless steel bolts assured that accelerated galvanic corrosion of the more active aluminum would occur. This was a basic mistake by the fabricator of the filters.

Accelerated pitting over much the interiors of the filters' "boxes" and end plates was caused by a cementation process. The resulting galvanic-based corrosion of the aluminum was produced by iron ions created by pitting attacked on Type 304 stainless steel (iron based) components in the filters.

The lack of good communications and/or specific, confirming documentation between the FSI owners of the aquaculture facility and the ABC organization were critical to the failures. Sadly, these types of seemingly obvious mistakes happen too often.

*Recommendation*

It is unfortunate but corrective actions for new filters can be summarized very briefly. Ridout stated that doing the opposite of what was actually done in each of the failure areas provided in the conclusions would very likely have prevented the premature corrosion that occurred..

*References*

ASM International Handbook, Volume 13B, Corrosion: Materials, 2005, pages 54 – 70, and page 99.

Dillon, C.P., Corrosion Control in the Chemical Process Industries, Second Edition, published by the Materials Technology Institute of the Chemical Process Industries, Inc. and NACE International, 1994, page 109.

***Acid Spill Due to Fracture in a Tanker Trailer***



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*Background*

Several years ago, a small steel tanker trailer using an older design was traveling on a rural road in Pennsylvania. The tanker split open vertically at its midpoint. This released approximately 6,000 gallons of hydrochloric acid (HCl) being transported. The tractor driver received severe acid burns on his ankles as he quickly left the cab and sought a safe location. Much of the acid drained from the sloped road into a nearby river. Later there were fish kills and other ecological damage for two miles downstream.

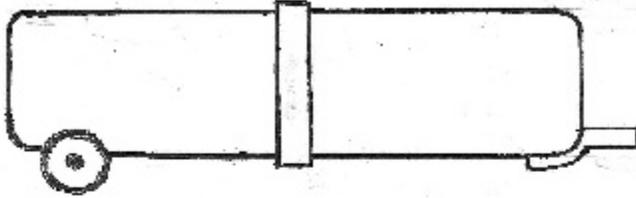
Legal actions were brought by the truck driver and the state against two defendants, the trucking company and the manufacturer that fabricated the trailer. The trucking company retained Robert Barton, P.E. to assist their attorney as an expert witness in the case. Barton had experience in mechanical engineering and metallurgy. The trailer had an internal rubber liner. As shown in Figure 3, the trailer had an external, rolled steel reinforcement, shaped much like a structural channel, to strengthen the shell at its critical midpoint.

*Possible Causes*

- Incorrect liner material selection or a defect in it or its installation
- Defect in the steel shell material
- Corrosion due to some design deficiency

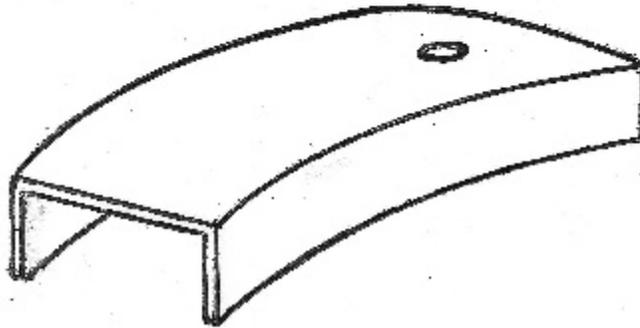


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**Portion of Reinforcement, Inverted**

**One 1-inch Hole on Bottom**



**Figure 3.** Schematic of the trailer plus one section of the rolled carbon steel reinforcement that was welded all around its base onto the trailer shell

Figure 3 as shown is a general illustration for purposes of this case. Other practical features of the actual tanker trailer that did not affect the failure are omitted.

*Evidence Gathered*

Specification documents for the trailer indicated its size to be approximately 30-feet in length and 6-feet in diameter. The shell wall thickness was to be 0.625-inch. The rubber liner thickness was to be 0.188 -inch. The steel used for the shell and for the reinforcement was to be plain carbon steel of a common ASTM specification. Certified welders had been specified for fabrication of all parts of the trailer. Barton conducted an interview with the trailer manufacturer and received the steel mill material certification and welding certification documents. If used each would be acceptable. The fabricator claimed that material had actually been used for the trailer construction. Barton planned to later verify that material claim.



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The trailer fabricator stated that the trailer had been delivered to the trucking company fifteen years before the failure. Previously, the trucking company had confirmed they received the trailer at that time and it had been in continual service since. This trailer, with different truck tractors, had been used over a range of geographic regions and in all seasons before the failure.

Inspection indicated that the shell of the trailer was split almost totally in half except for a small intact area at the top of its circumference. The majority of the irregular but near vertical fracture surfaces of the shell were located in an area that was formerly covered by the rolled reinforcement sections. The rubber liner was stretched and torn apart in the area of the shell fracture near the lowest portion of the shell. Barton saw that the rubber liner was completely intact in upper areas of the shell's circumference. These findings seemed to indicate the shell fracture initiated at the lower portion of the circumference, i.e., at the "six o'clock" position. Significant metal deformation on each side of the vertical separation in the steel indicated that the final failure mode was primarily ductile fracture. Only small amounts of metal deformation typically are seen when brittle fracture occurs.

During the inspection it was seen that the external areas of the entire shell including the reinforcement were painted. That paint was in good condition. However, there was no paint on the shell under the area formerly covered by the reinforcement. On the upper shell area without paint there were streaks of red-rust that ran down towards the bottom of the circumference. At the lowest portion of the exterior shell circumference, in the unpainted region, there was a large area of generally continuous deposits of corrosion product. There was also a circular area of significant corrosion product inside the reinforcement around the 1-inch diameter hole at the bottom.

Thorough inspections of the rubber liner beside the shell fracture and areas further away from the separation were done. Except for the torn area immediately beside the path of the shell fracture, the liner was in good condition. Adherence of the liner to the inside of the shell was found to be good except near the shell failure area. Written information provided by the trailer fabricator indicated the type of rubber used for the lining was soft natural rubber.

During the field inspections, exemplar sections of the steel shell were cut out for later laboratory examinations. These included a portion of the intact steel away from the fracture and one immediately adjacent to the fractured area near the bottom of the circumference plus similar samples from an upper area of the circumference, i.e., near the 12 o'clock position, of the shell. Using the exemplars, it was first planned to carefully measure the shell plate thicknesses. Determination of the chemical composition of the steel was also planned. Examination of the



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steel microstructures at the different locations was planned by evaluating prepared cross-sections. The objective of the microstructural evaluations was to find if there were any clear metallurgical differences in the steel at the apparent failure initiation location versus the material at the top area where the metal remained intact.

Barton asked trucking company personnel about normal maintenance they performed on the trailer. They stated that all of their tractors and trailers were regularly washed and cleaned of dirt and road salts to prevent excessive corrosion and to maintain the appearance of the equipment. They also claimed to regularly inspect all painted areas and to redo the paint coating as needed. They were asked about their inspections of the area under the rolled reinforcement on the trailer. They said it was unreasonable to inspect under the reinforcement due to the very limited accessibility through the single 1-inch diameter hole. They said that area was “essentially hidden”.

*Results and Analysis*

Metallurgical laboratory personnel examined the chemical composition plus metallurgical properties and thicknesses of the two types of steel exemplars that had been cut out. As is always recommended in the work for a failure analysis, the work proceeded from non-destructive evaluation of the evidence to destructive tasks. The first simple evaluation was of material plate thickness by micrometer measurements. The plate thicknesses at spots away from the fracture area, where corrosion and plastic deformation thinning of the steel had not occurred, were found to be 0.625-inch, as specified, at both the top and bottom locations on the shell’s circumference. As expected there was obvious plate thinning immediately nearby the failure path due to the primarily ductile failure mode.

Investigation steps that required some evidence destruction were completed next. Optical emission spectroscopy (OES) was used to define the chemical composition of the steel at the two sampling locations. Alternative methods for determining the chemical composition of the steel that might have been used were the inductively coupled spectrometer (ICP) or atomic absorption (AA). The latter two methods cost more than OES to perform but they require only very small amounts of the material to complete valid analyses. There was no shortage of steel available in the samples here so the lower cost OES method was used. These three methods are discussed in the ASM Handbook, Vol. 11, pages 430 and 431, cited at the end of the case.



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The main alloying element of concern was the percentage of carbon present in the trailer shell material. That was because the amount of carbon present would be the primary element in determining the strength of this plain carbon steel for a given design thickness. The original design thickness was apparently adequate because the trailer had been operating successfully for about fifteen years before the current failure. If instead of plain carbon steel a somewhat higher strength steel had been used then certain specified amounts of other elements such as manganese, silicon or copper, in addition to carbon, would be necessary to attain the desired strength using a given heat treating process. Here the percentage of carbon present was the most critical bit of information. The OES results showed that this steel had the proper amount to reach the strength as defined in the ASTM specification provided.

Metallurgical cross-sections through the steel samples from the locations on the shell circumference were prepared. This included progressively finer polishing of the surfaces of cross-sections of the metal samples followed by etching each so as to reveal their microstructures. The microstructures at all locations were normal and as expected for plain carbon steel of this specification. The evaluation also indicated that the steel had no excessive number or sizes of inclusions. Inclusions are non-metallic particles, usually a compound such as an oxide, sulfide or silicate, that are foreign to the normal metallic microstructure of a metal. Cracks inside a metal can initiate at inclusions that eventually lead to ductile fracture. See the ASM Handbook, Vol. 11, page 591 for a discussion of inclusions and ductile fracture. That reference is cited at the end of this case.

Completing standard tensile tests of the exemplars to establish the yield and ultimate tensile strength of the steel were not judged to be necessary. This was because the steel's chemical composition and microstructure had been found to be within specification and normal in quality, the specified plate thickness was actually used and, finally, the original design thickness of the steel plate was judged to be sufficient because the trailer had been in successful service for several years before this failure. All of these findings supported the conclusion that neither the steel nor the structural design of the trailer was responsible for the failure.

The visual inspection of rubber liner inside the split trailer shell had indicated that it was in good condition and had good adherence inside the shell except immediately on both side of the fracture path. Any tear or penetration of the lining would have caused rapid corrosion of the plain carbon steel shell by the HCl. Likely this would have occurred over a large area. Therefore, damage to the rubber liner or defective installation of it were ruled out as being causes of the failure. This was supported by the fact that the trailer had been used to transport acidic products for fifteen years before the current problem without a problem.



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Soft natural rubber was a good choice for high resistance to the hydrochloric acid used in this application. Besides this resistance, this material offers lower cost, excellent abrasion resistance and it remains flexible down to very low temperatures. Other alternative linings such as semihard natural rubber, hard natural rubber, neoprene and chlorobutyl rubber each have different properties that would have made them less desirable for this usage. See the ASM Handbook, Vol. 13B, pages 605 -606 cited at the end of the case.

After elimination of other possible causes, external corrosion of the shell area under the rolled reinforcement was the apparent cause of this failure. The confirming evidence was the rust streaks on higher areas of the shell, corrosion product around the hole inside the reinforcement and, most importantly, the large area of concentrated shell corrosion itself near the bottom of the circumference.

The failure likely occurred by a slow process of general corrosive thinning of the unpainted shell plate thickness due to water condensation inside the partially open but essentially enclosed, rolled reinforcement. For several years the trailer was used in a range of geographic areas where it was exposed to diverse conditions that could produce little or significant humid air condensation over time. This service caused a slow rate of corrosive attack. In the absence of corrective maintenance by the trucking company the damaging corrosion was cumulative.

Condensation and gravity produced the greatest extent of metal loss near the “six o’clock” position on the shell. This was because most of the condensate collected there and stayed longer before dripping off compared to higher locations. The fracture apparently initiated at this low area when insufficient intact metal remained. This was true even with the rolled reinforcement in place. Once the shell opened down low, the fracture path ran generally upward until the weight of the acid diminished with its release and stopped the fracture path growth. The thin rubber liner was not able to resist the applied force for long after the shell fracture started growing.

### *Conclusions*

The cause of the failure was external general corrosion on the trailer’s steel shell under the rolled reinforcement. The corrosive liquid that produced the attack was simple water condensation from exposure to ambient air in variable geographic and temperature conditions. This likely occurred in a stop-and-go but cumulative attack on the unpainted steel.

The failure would not have occurred if certain alternative actions had been taken. For one, the trailer fabricator might have used a different type of midpoint reinforcement. Two examples



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might have been to use the same general design but without the bottom hole or simply to weld a section of rolled plate directly all around and onto the shell at its midpoint to increase the thickness of the steel plate at that critical area.

Alternatively, the fabricator might have foreseen the condensation problem with the hole in the reinforcement. The trucking company should have also seen possible problems with the hole in the reinforcement before accepting it initially or done regular inspections of the shell surface condition under the reinforcement. Inspections might have been done simply with a small flashlight pointed up towards the bottom opening at that critical low location.

Robert Barton, the consultant, was not made aware of how the legal case was resolved or how liability for the failure was split between the two defendants. That result is common for expert witnesses in legal cases..

*References*

ASM International Handbook, Volume 11, Failure Analysis and Prevention, 2002, pages 430 – 431, and page 591.

ASM International Handbook, Volume 13B, Corrosion: Materials, 2005, pages 605-606

***A Corrosion Failure Investigation Involving Chinese Drywall Used in Homes***

**Note:** This case covers a legal action that took place in the early 2000's. It describes the development of evidence by the plaintiff in that action. The plaintiff's law firm retained an engineer as their potential expert witness. They assumed the engineer would find solid evidence that supported their client's claim. If that assumption was wrong the law firm would not use the engineer as their expert. The engineer (a P.E.) was professionally obligated to first find and report the truth whether or not he/she was eventually named as the plaintiff's expert witness.

*Background*

Many recently-built private homes in the Gulf coast of the U.S. had experienced unusual problems. The primary issues were early failures of new HVAC units and failures or erratic operation of several types of electrical appliances in the homes. These problems started a few months after restoration of damaged homes in multiple housing developments following hurricane Katrina. During that restoration period the demand for residential drywall had greatly



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depleted domestic supplies. To meet the demand, additional drywall was imported from China. Those imports were sold along with the residual domestic drywall in U.S. building supply stores. Drywall installation contractors in turn got product from these stores and used it in completing restored and new homes.

In this case RST, Inc. was a large housing builder and developer in a Gulf Coast state in the U.S. RST had experienced several early failures of the new HVAC units in many of their new or recently rebuilt homes. The rebuilding was done a few months after hurricane Katrina. Some electrical appliances had failed and several had operated in an on-and-off manner in those same homes. Homeowners reported they noticed faint odors somewhat like sewage or rotten eggs in the homes. They also reported seeing black spots on copper tubing and some wiring.

RST had environmental air quality surveys completed in the affected homes. These surveys detected small amounts of sulfur compounds. It was initially thought these compounds might originate from small leaks in the homes' natural gas systems. Mercaptans are intentionally added to natural gas to indicate leaks. They contain sulfur compounds and produce a rotten egg odor when released with natural gas. However, no natural gas leaks could be located and no other causes for the unusual odors and black spots were identified by the surveys.

DEF and Sons was RST's subcontractor for drywall installation as part the rebuilding process following the hurricane. Soon after the environmental air surveys were completed, DEF confirmed that they had used Chinese drywall (hereafter referred to as CDW) from one supplier in China for some of their work in RST homes. This particular CDW was used either totally or in combination with domestic product in different restored homes. DEF provided information to RST on the particular homes that had only the CDW installed or had a combination of CDW and domestic drywall. However, DEF claimed the imported drywall did not cause the problems seen.

RST initiated a suit against DEF after hearing about other developers in the region that had similar problems that they believed to be caused by the use of imported Chinese drywall. RST incurred costs of replacing HVAC units and drywall in over 100 homes. RST's total loss was over 3 million dollars. All interior walls in the affected homes typically had to be stripped down to the bare wooden studs in order to assure that all possibly damaging drywall was replaced.

RST had examined failed HVAC units that they removed from "problem" homes after only a few months service. They found varying degrees of corrosion on the copper U-bends in the evaporative coils of those units. They believed that since DEF had used defective CDW in their



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homes, those products had caused the corrosion and failures they experienced. However, RST did not know how the corrosion occurred.

RST was the plaintiff in the law suit so they had the burden of proof that the claim to recover costs from DEF and Sons was valid. DEF was the defendant in the case so they had the typically less difficult task of showing that RST's claims were unfounded. The developer had hired a legal firm to represent them in their suit and that firm then retained, Harry Smith, P.E., a corrosion engineer to act as a potential expert witness for RST.

*Evidence Gathered*

RST had removed and was in the process of replacing approximately 80 failed HVAC units from homes they had built in the large housing development at issue. These were in homes in the development that were still in various stages of having the original drywall replaced with domestic drywall. Some of the partially restored homes initially had all CDW or a mix of CDW and domestic product installed. RST and Smith had information from DEF on which specific homes were in each category. The corrosion engineer began by visiting a few of the different RST homes. There he made visual inspections, took photographs and obtained cut-out samples of both known CDW and known domestic drywall plus copper components from the HVAC units for later laboratory analyses.

As is true in many corrosion failure analyses, it was planned to consult traditional and specialized engineering literature references early in the investigation. These inquiries centered on the possible effects of sulfur compounds on the corrosion of HVAC units and specifically on the copper used in them. Literature on the causes of failure or erratic operation of electrical and electronic devices was also going to be identified and consulted.

Smith visually inspected the particular components of the failed HVAC units that had suffered corrosion and presumably had produced failures in the units. These components were the copper U-bends in the evaporative coils of the units. RST provided him with records they had kept on how long each of the removed HVAC units had been in service before they failed. During these visual inspections the engineer also selected and obtained exemplars of U-bends from different evaporator coils for more detailed examination in a metallurgical lab.

In the same homes that had experienced HVAC failures, the owners had made complaints of complete failures or erratic operation of electronic devices such as stereo components, TV's and small electric kitchen appliances. Smith obtained samples of these devices that RST had removed



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and retained from the homes before starting restoration work. The plan was to have two competent electronic repair and troubleshooting organizations independently analyze the devices for the cause of their malfunctioning.

The potential issue of problems caused by the use of CDW in homes had appeared months before RST's problems occurred. These were seen in other geographic areas although most were in Gulf Coast states. This generated intervention by the federal government and specifically the Consumer Products Safety Commission (CPSC). The initial concern was that CDW might be causing health issues for homeowners due to the release of toxic gases. Fortunately, bad odors and coughing experienced by homeowners were found to be the only immediate health effects of the CDW. However, potential negative long-term health effects of the imported products were neither established or refuted. Therefore, replacement of the CDW was recommended.

It was not clear whether or not the CDW could be causing the corrosion problems seen or, if it was responsible, what was the specific corrosion mechanism. The CPSC contracted with national laboratories to study the corrosion issue. The results of that work were available when the RST case stated and Harry Smith planned to review that information. He was going to review general and specialized corrosion literature sources on the susceptibility of copper to sulfur compounds as well as the corrosion of electronic devices in light of the specific issues in this case.

*Results and Analysis*

During his visit to RST homes that were in various stages of restoration after originally having all CDW or only a portion that was CDW, the engineer made the photographs in Figures 4 and 5. These show a typical HVAC unit and the extents of black deposit corrosion on copper U-bend tubes in the evaporation coils in a home with 100 % CDW. Black spots were also seen on the copper tubing used for natural gas and on bare copper wires formerly in closed electrical outlet boxes. When operating HVAC units had their enclosure plates attached, the air inside of the units was approximately 150<sup>o</sup>F in temperature. Due to the Gulf Coast location, the local ambient air typically had high humidity and thus moisture was often present on the outer surfaces of the AC evaporative coils' U-bends.



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**Figure 4** - A damaged HVAC unit (enclosures removed) showing the evaporative coil in the upper area with copper U-bends. This unit had failed and was later replaced..



**Figure 5** - Close-up view of the blackened copper U-bends on the end of the evaporative coils shown in Figure 4. Some of the bends were later cut out and examined in a laboratory.



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When documenting evidence in any failure analysis, it is often better to initially take one or more photos that illustrate the overall scene followed by close-up shots that provide important details of the failure. Smith did that in this case. This approach provides very helpful context to persons reading the report that may not be familiar with the equipment in question or with specific aspects of the failure. That reader may not have any technical background or little knowledge of the equipment being discussed.

A review of standard corrosion reference sources indicated that reduced sulfur compounds in the presence of oxygen and moisture cause corrosion of copper and silver alloys. A reduced chemical compound is formed after an element gains electrons, i.e., its valence becomes more negative, during a chemical oxidation/reduction reaction and the new compound is created. A typical reduced sulfur compound is hydrogen sulfide ( $H_2S$ ). The rate of corrosion of copper is accelerated when a reduced sulfur compound is present in generally humid air along with a raised temperature.

The literature indicated that the appearance and morphology of corrosion on copper due to reduced sulfur compounds in ambient air and possibly with water vapor will be relatively uniform black tarnish films of various thicknesses. In more severe conditions a combination of black tarnishing and corrosion pits may occur. In similar conditions tarnishing of silver occurs but without pits. The tarnish film thicknesses that form on the two types of metals depend on the intensity of the attack which often varies from one location to another on the metal surface.

During the visit to the homes, Smith took several solid samples from drywall sheets that DEF confirmed to be CDW and others that were confirmed to be domestic product. These were sent to a lab to define the chemical elements present in each type of drywall. The energy-dispersive spectroscopy (EDS) auxiliary to a scanning electron microscope (SEM) was used. There were high, distinct peaks on the EDS spectrum results for the element sulfur in the CDW samples but no distinct spectrum peaks for sulfur were found in the domestic drywall samples. EDS provides approximate relative concentration levels of the elements present, as indicated by the different peak heights. EDS can identify only elements and not compounds.

Smith contacted a laboratory that had been working on an innovative analytical techniques related to CDW issues in previous cases to see if their assistance might be helpful. That lab had developed a procedure in which drywall samples were put into closed, sterile containers where controlled levels of relative humidity and temperature of contained air could be maintained for



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different exposure periods. Conditions inside the containers were designed to simulate conditions in a closed HVAC unit next to evaporator coils. Any sulfur gases that were emitted from the drywall samples were secured and collected from the separate containers to make comparisons. The gases were then analyzed by a gas chromatography/mass spectrometry (GC/MS) procedure according to the ASTM D 5504 testing standard. The procedure allowed the total mass of gaseous sulfur compounds emitted from the sample in each container to be closely defined as well as identification of the different sulfur compounds that existed in the container. These measurements were able to be done with a high levels of precision.

Three CDW samples and three domestic drywall samples taken from RST homes being rebuilt were sent to the lab and analyzed using the above gas detection procedure. Elemental sulfur was found in the three CWD gas samples to be 1300, 1700 and 1900 mg/Kg, respectively. By comparison the elemental sulfur in the three domestic drywall gas samples were 4, 6 and 5 mg/Kg. The same lab had found similar comparative results in past work it had done for other clients concerned with CDW when using the same test procedure. Using the smallest level of sulfur found in the three CDW samples (1300 mg/Kg) and the largest level of sulfur found in the domestic drywall samples (6 mg/Kg), the resulting ratio showed that the minimum concentration of elemental sulfur in gases from the CDW samples was 216 times greater than in the domestic drywall.

The above lab procedures also identified specific reduced sulfur compounds in gases from the RST samples. In the CDW samples these compounds were hydrogen sulfide ( $H_2S$ ), carbon disulfide ( $CS_2$ ) and carbonyl sulfide ( $COS$ ) but none of these were found in the domestic samples. The lab had found these same three reduced sulfur compounds in CDW samples provided to them by past clients while using the same testing procedure.

While the various laboratory tests were being done the corrosion engineer visually inspected all the removed HVAC evaporator coils and specifically the condition of their U-bends. A total of 72 removed coils were available at that time. The goal was to obtain a rough estimate of how widespread severe corrosion damage had been so far. Smith assigned each coil to one of three categories based on the relative extent of coverage by black corrosion deposits he estimated to be present on the different U-bends. The three categories were light, medium and high.

This type of evaluation was admittedly approximate. However, Smith had over thirty years of professional experience in analyzing corrosion failures and accessing corrosion damage on different metals in varied applications. He was expected to be accepted as an expert witness in the suit. It was believed that his opinions in this simple comparative evaluation would be



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accepted as valid. In addition, this belief was supported because his judgements were found to be consistent with other independent findings about the CDW.

The visual inspection of the U-bends indicated there were three coils in the light class, fifteen in the medium class and fifty-four in the heavy class. Therefore, over 95% of all the coils removed so far were in the medium or heavy relative corrosion categories.

RST provided spreadsheet records that indicated the three U-bends with only light corrosion deposits had been in service for only a few months before the complete HVAC units were removed and the engineer's inspections were done. Those units were in homes where two or three AC coils had previously been replaced before the current study of CDW effects began. It was common in all the RST homes that at least one AC coil had been replaced before this legal case started. Thus, the rates of corrosion in homes with CDW differed significantly. This might have been caused by the fact that the percentages of installed CDW versus domestic product differed between the homes. When 100% CDW was installed corrosion rates might be expected to be higher than in homes with a much smaller percentage of CDW.

The corrosion engineer reviewed an earlier report by a national laboratory, commissioned for work by the CPSC, regarding CDW in homes in prior legal cases where the imported product had been used. One portion of that study measured the microscopic thicknesses of black corrosion tarnish on cross-sections of bare copper wires used in electrical outlets in the homes. A scanning electron microscope (SEM) was used for the measurements. The tarnish thickness was found to average 20 microns. This value is equal to approximately 0.0008-inch. The report provided macroscale photographs of the appearance of the copper wires in that study and they were very similar to the appearance of bare copper wires seen in the RST homes. In addition, it is reasonable to conclude that if a 20 micron tarnish thickness was found on copper wiring inside of covered electrical outlets exposed to CDW then similar thicknesses might be expected on the contacts inside of electronic device enclosures in RST homes that were similarly exposed.

An average black tarnish of 20 microns thickness may seem like an insignificant value. However, Smith concluded that this needed to be judged on the basis of a relevant ISA reference he discovered and that is cited below. That document defines four classes of severity of thicknesses of gaseous corrosive tarnishes on electrical contacts in terms of their effects on operation of the devices. The most detrimental tarnish thickness class in the ISA document that is expected to have severe negative effects on proper electronic device operation is known as GX. It includes tarnish thicknesses that are 0.2 microns (approximately 0.000008-inch) or more. The average 20 micron (about 0.0008-inch) thickness measured on copper wires in the earlier study is 100 times greater than the minimum GX severe effect level defined in the ISA document.



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Electrical and electronic contacts usually are made of silver and copper because these metals typically offer low electrical resistance and good corrosion resistance. However, as seen here, the presence of reduced sulfur compounds in ambient air produce tarnish, i.e., corrosion product, on copper and silver at very severe levels of thicknesses as compared to the criteria in the ISA standard cited. This increases the electrical resistance at each contact point. This in turn would be expected to result in complete failure or on and off “glitches” in continual normal operation of such devices as TV’s, audio equipment, microwave ovens and personal computers. From his research, Smith found that these devices generally operate at low voltages. Therefore, low electrical resistance at each contact point is necessary for proper current flow and device operation.

Several failed or erratic operating electronic devices from RST homes with CDW were sent to two different electronic service and repair shops. The shop owners were not given any information other than requests to diagnose the reason why the different devices were not operating properly. Both shops reported that multiple contacts had been found with high electrical resistance that they said seemed to be due to corrosion at those points.

*Conclusions*

Harry Smith wrote a report that provided these findings and later provided a deposition as requested by the attorney for the plaintiff, DEF.

The attorney for DEF recommended to his client that the case be settled in favor of RST because the sum of the evidence presented by RST was sufficient to demonstrate that the CDW used by DEF caused the damage claimed. Thus, the cost of going the next step – to a jury trial – was not justified.

Financial settlement favorable to RST was initially discussed by the parties. However, DEF ‘s insurance company (it would make the payment) initiated a new, follow-on suit against RST. That action ended the initial settlement discussions. The second legal case is not covered here.

*References*

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