

# Four Types of Heat Exchanger Failures

. . . mechanical, chemically induced corrosion, combination of mechanical and chemically induced corrosion, and scale, mud, and algae fouling

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Heat exchangers usually provide a long service life with little or no maintenance because they do not contain any moving parts. However, there are four types of heat exchanger failures that can occur, and can usually be prevented: mechanical, chemically induced corrosion, combination of mechanical and chemically induced corrosion, and scale, mud, and algae fouling.

This article provides the plant engineer with a detailed look at the problems that can develop and describes the corrective actions that should be taken to prevent them.

**Mechanical**-These failures can take seven different forms: metal erosion, steam or water hammer, vibration, thermal fatigue, freeze-up, thermal expansion, and loss of cooling water.

*Metal Erosion*-Excessive fluid velocity on either the shell or tube side of the heat exchanger can cause damaging erosion as metal wears from the tubing. Any corrosion already present is accelerated as erosion removes the tube's protective films, exposing fresh metal to further attack.

Most metal erosion problems occur inside the tubes. The U- bend of U-type heat exchangers and the tube entrances are the areas most prone to erosion. Figure 1 shows the metal loss in a U- bend caused by high temperature water flashing to steam.

Tube entrance areas experience severe metal loss when high-velocity fluid from a nozzle is divided into much smaller streams upon entering the heat exchanger. Stream dividing results in excessive turbulence with very high localized velocities. High velocity and turbulence produce a horseshoe erosion pattern at the tube entrance. Fig. 2.

Maximum recommended velocity in the tubes and entrance nozzle is a function of many variables, including tube material, fluid handled, and temperature. Materials such as steel, stainless steel, and copper-nickel withstand higher tube velocities than copper. Copper is normally limited to 7.5 fps; the other materials can handle 10 or 11 fps. If water is flowing through copper tubing, the velocity should be less than 7.5 fps when it contains suspended solids or is softened.

Erosion problems on the outside of tubes usually result from impingement of wet, high-velocity gases, such as steam. Wet gas impingement is controlled by oversizing inlet nozzles, or by placing impingement baffles in the inlet nozzle.

*Steam or Water, Hammer* -- Pressure surges or shock waves caused by the sudden and rapid acceleration or deceleration of a liquid can cause steam or water hammer. The resulting pressure surges have been measured at levels up to 20,000 psi, which is high enough to rupture or collapse the tubing in a heat exchanger. For example, 3/4 in. x 20 BWG light drawn copper tubing has a burst pressure of 2100 psi and a collapse pressure of 600 psi.

Damaging pressure surges can result from a cooling water flow interruption. The stagnant cooling water is heated enough to generate steam, and the resumption of the flow causes a sudden condensing of the steam and produces a damaging pressure surge, or water hammer. Cooling water flow should always be started before heat is applied to the exchanger.

Fluid flow control valves that open or close suddenly also produce water hammer. Modulating control valves are preferable to on-off types.

Fig. 1. Metal erosion in U bend.

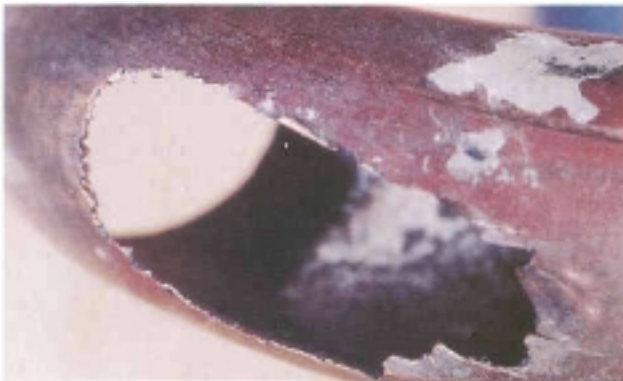
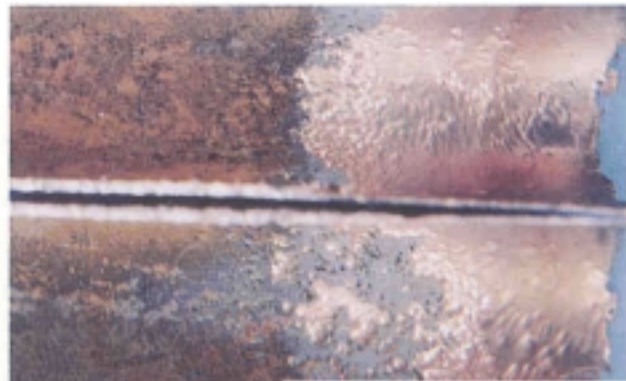


Fig. 2. Metal erosion at tube entrance.



Vacuum breaker vents must be provided if condensables are handled in either the shell or tubes; they prevent steam hammer damage resulting from condensate accumulation. Figure 3 shows typical tube damage caused by steam hammer. In this case, condensate accumulated in the shell and rapidly accelerated, producing a high-pressure shock wave that collapsed the tube and caused the tear holes.

Properly sized steam traps with return lines pitched to a condensate receiver or condensate return pump should be installed to prevent this type of damage.

**Vibration**-Excessive vibration from equipment such as air compressors or refrigeration machines can cause tube failures in the form of a fatigue stress crack or erosion of tubing at the point of contact with baffles. Heat exchangers should be isolated from this type of vibration.

Shell-side fluid velocities in excess of 4 fps can induce damaging vibrations in the tubes, causing a cutting action at support points with baffles. Fig. 4. Velocity-induced vibrations can also cause fatigue failures by work hardening the tubing at baffle contact points or in U-bend areas until a fatigue crack appears.

**Thermal Fatigue** --Tubing, particularly in the U- bend area, can fail because of fatigue resulting from accumulated stresses associated with repeated thermal cycling. This problem is greatly aggravated as the temperature difference across the length of the U-bend tube increases.

Figure 5 shows an example of thermal fatigue. The temperature difference causes tube flexing, which produces a stress that acts additively until the tensile strength of the material is exceeded and it cracks. The crack usually runs radially around the tube, and many times results in a total break. In other cases, the crack occurs only halfway through the tube and then runs longitudinally along it.

**Freeze-Up** -- These failures are most common in evaporators or condensers; however, they can occur in any heat exchanger in which temperatures drop below the freezing point of either fluid in the unit. Freeze-up results from failure to provide thermal protection, a malfunction of the thermal protection control system or protective heating device, improper drainage of the unit for winter shutdown, or inadequate concentration of antifreeze solutions.

For example, assume a chiller has improper settings or malfunctioning controls that cool the water to a point below its freezing point. Ice forms and exerts tremendous pressure in the tubing, which causes it to rupture or collapse. Collapse in an evaporator, Fig. 6, usually occurs near the tube sheet where the tube is not protected by an inner splint.

Freeze-up failure in a condenser tube is shown in Fig. 7. In this case, cooling water was circulating inside the tube, refrigerant was condensed on the externally finned surface, and the unit was not properly drained for winter shutdown. The tube distortion indicates that it was exposed to excessive pressure caused by the freezing water.

This type of failure is also caused by the sudden release of refrigerant pressure from the condenser. The sudden release caused by a line break or relief valve discharge suddenly drops the pressure below the boiling.

point of the refrigerant. Boiling extracts heat from water in the tubes and the liquid freezes.

**Thermal Expansion**-These failures are most common in steam heated exchangers; however, they can occur in any type in which fluid being heated is valved off without provisions to absorb thermal expansion.

In steam-heated systems, cooling down or condensing residual steam in the shell after the steam control valve closes continues to heat water or other fluids on the tube side. Continued heating causes thermal expansion, which creates pressures far in excess of the strength of tube sheets, cast heads, and other heat exchanger components. Cast iron parts usually fracture because of lack of ductility: steel tube sheets become bowed or permanently distorted because the material's yield point is exceeded. Figure 8 shows thermal expansion failure of a cast iron heat exchanger head.

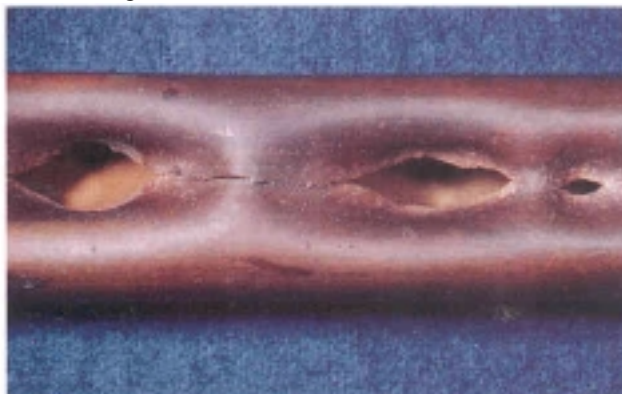


Fig. 3. Tube damage from steam



Fig. 4. Velocity-induced vibration cut of tube.

Fig. 5. Thermal fatigue failure in U bend.





Relief valves are installed in the heated fluid system to prevent this kind of failure. It is also advisable to provide some means to absorb fluid expansion. For example, installing a tank in the heated fluid system prevents periodic discharge of relief valves, which results in loss of system fluid and places an undue burden on the valve. These devices are installed between the heat exchanger and any shutoff or control valves.

*Loss of Cooling Water*-Compressed air aftercoolers and gas coolers should always have a supply of cooling fluid before a flow of hot gas is started. High gas temperatures melt or warp the tubing if there is not an adequate supply of cooling fluid.

Figure 9 shows the tube warping that results without enough cooling fluid. Temperature actuated modulating control valves should be used to regulate cooling liquid flow.

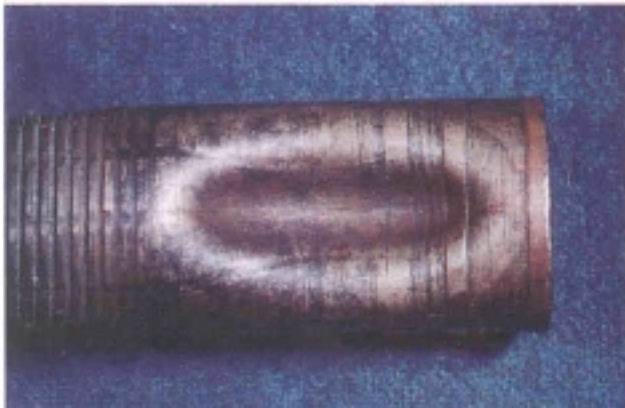


Fig. 6. Collapse of evaporator tube because of freeze-up.

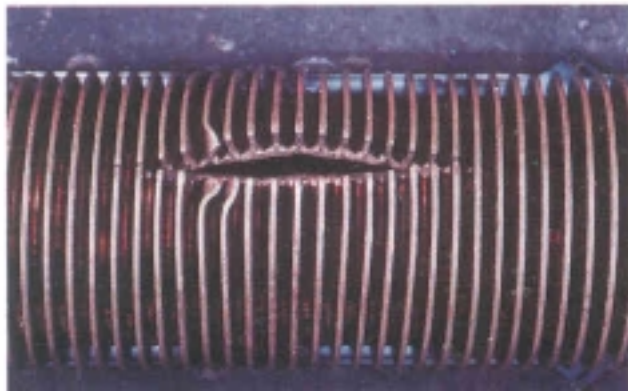


Fig. 7. Rupture of condenser tube because of freeze up.

Fig 8. Thermal expansion failure of cast iron head.



**Chemically Induced Corrosion** -- These failures result from the complex chemical interaction between the materials of the heat exchanger and the fluids circulated through it. There are seven types of chemically induced corrosion failures: general corrosion, pitting corrosion, stress corrosion, dezincification, galvanic corrosion, crevice corrosion, and condensate grooving.

*General Corrosion* -- This type of corrosion is characterized by a relatively uniform attack over the tube, tube sheet, or shell, and there may be no evidence that corrosion is taking place. Figure 10 shows a tube that became so thin it actually tore down the middle.

Fairly stable aggressive conditions generate this type of attack. Low pH (less than 7) combined with carbon dioxide or oxygen produces the attack on copper. The blue or bluish-green color on the tubes in Fig. 11 shows the results of carbon dioxide attack on the inside of a copper tube. Various chemicals, such as acids, also produce this type of metal loss.

Selecting a material with adequate corrosion resistance for its environment, along with using proper treatment chemicals, maximizes heat exchanger life.

*Pitting Corrosion* -- Localized pitting is frequently encountered in ferrous and nonferrous metals. It results from the electrochemical potential set up by differences in oxygen concentration within and outside the pit, and is frequently referred to as a concentration cell. The oxygen-starved pit acts as an anode and the unattacked metal surface as a cathode. A small number of pits may be present; however, any one can cause a heat exchanger failure.

Pitting corrosion is most likely to occur during shutdown periods when there is no flow and the environment is most suitable for the buildup of concentration cells. The susceptibility to pitting corrosion is further enhanced by scratches, dirt or scale deposits, surface defects, breaks in protective scale layers, breaks in metal surface films, and grain boundary conditions.

Figure 12 shows an oxygen pitting attack on a copper tube, and Fig. 13 illustrates a carbon dioxide pitting attack on a copper tube.

*Stress Corrosion* -- This form of corrosion attacks the grain boundaries in stressed areas. Heat exchanger tubes usually have both avoidable and unavoidable residual stresses. These stresses are the result of drawing or forming the tube during manufacture, forming U bends, or expanding the tubes into tubesheets.

Failures from this corrosion take the form of fine cracks, which follow lines of stress and material grain boundaries. Figure 14 shows stress corrosion failure in admiralty tubing.

The corrodent that causes stress corrosion on stainless steel tubes is the chloride ion, which is potentially present in any compound formulated with chlorine. All naturally occurring waters contain the chloride ion in varying degrees. The chloride stress corrosion phenomenon is not well understood, but it is known that the frequency of occurrence rises with an increase in temperature and chloride ion concentration. Keeping tube wall temperatures below 115 F (calculated with maximum, not average, fluid temperatures) prevents stress corrosion cracking problems with chloride ion concentration up to 50 ppm. Figure 15 shows stress corrosion cracking in a type 304 stainless steel U bend.

The corrodent that causes stress corrosion cracking on copper or copper alloy tubes is ammonia. Very small concentrations (1 ppm or less) can create a problem.

The vacuum breaker used on steam-heated exchangers draws in ammonia from any leak in the ammonia refrigeration machine. The ammonia causes stress cracking problems, particularly in the inner U bends of the heat exchanger tubes. Copper-nickel alloys have good resistance to stress corrosion cracking and should be used in applications where low concentrations of ammonia are expected.

*Dezincification* -- This problem occurs in copper-zinc alloys containing less than 85 percent copper when they are in contact with water having a high oxygen and carbon dioxide content, or in stagnant solutions. The effect tends to accelerate as temperature increases or pH decreases below 7.

Dezincification creates a porous surface in which the zinc is chemically removed from the alloy. The remaining copper has a sponge-like appearance. Dezincification is prevented by using a brass with lower zinc content or a brass containing tin or arsenic to inhibit the chemical action, or by controlling the environment causing the problem.

*Galvanic Corrosion* -- This type of corrosion occurs when dissimilar metals are joined in the presence of an electrolyte, such as acidic water. Galvanic corrosion usually produces a higher rate of reaction on the less noble metal. For example, if a simple galvanic cell composed of copper and steel is immersed in a solution of sulfuric acid, the less noble steel corrodes quickly and the more noble copper is virtually unattacked.

The galvanic chart shows the relative potential of materials to support this type of corrosion. Metals grouped together have relatively little tendency to produce galvanic corrosion: when two metals from substantially different groups are coupled together in an electrolyte, substantial corrosion of the less noble metal results.

Figure 16 shows an example of galvanic corrosion on a steel baffle. In this case, the less noble steel baffle was sacrificed at its point of contact with the copper tubing

*Crevice Corrosion* -- This type of corrosion originates in and around hidden and secluded areas, such as between baffles and tubes, Fig 17, or under loose scale or dirt. A localized cell develops and the resulting corrosion appears as a metal loss with local pits, often giving the impression that erosion is taking place. This condition is in contrast to a vibration failure in which the metal is sharply cut and there are no pits. Relatively stagnant conditions must exist for crevice corrosion to occur.

The attack can often be controlled by making sure that velocities are adequate to prevent stagnation or the accumulation of solids.

*Condensate Grooving* -- This problem occurs on the outside of steam-to-water heat exchanger tubes, particularly in the U-bend area. It is recognized by an irregular groove, or channel, cut in the tube as the condensate drains from the tubing in the form of rivulets. A corrosion cell usually develops in the wetted area because of the electrical potential difference between the dry and wet areas.

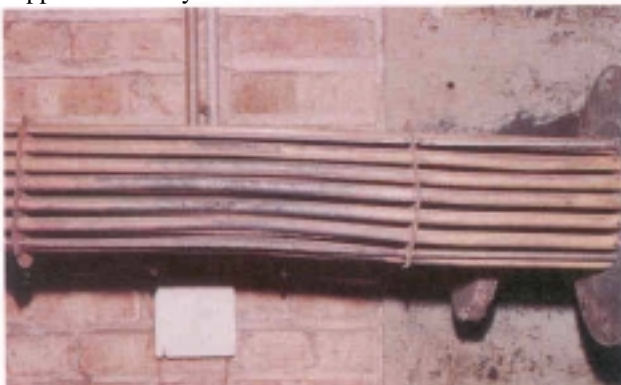


Fig. 9. Tube Warping because of insufficient cooling water



Fig. 10. Thinning of tube because of general corrosion.

Fig. 11 General corrosion inside copper tube because of CO<sub>2</sub>.

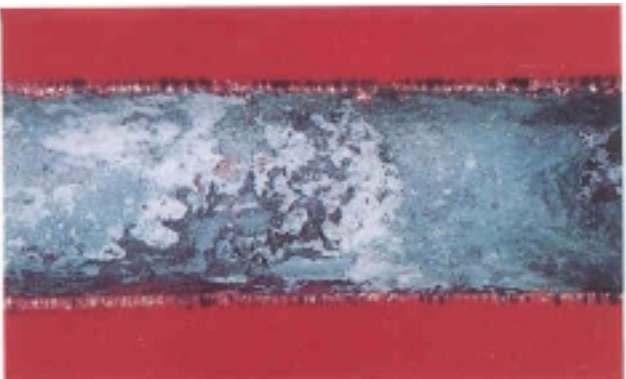


Fig. 12. Oxygen pitting attack on copper tube.





Figure 18 shows condensate grooving and the pitting attack. The condensate, which must be aggressive for this grooving to occur, wears away the protective oxide film as it drains from the tubing.

Controlling condensate pH and dissolved gases and cleaning the tube bundle outside surface to remove oils that prevent uniform wetting of the tube usually reduce the problem potential.

**Combination Mechanical Failure and Chemically Induced Corrosion** -- In many instances heat exchanger failure is not from a single cause, but a combination of more than one condition. For example, a pitting attack, galvanic attack, and crevice corrosion attack could occur simultaneously at one or more locations. Quite often, a mechanical problem combining with a corrosion problem produces a quicker failure than either of them alone. There are two common types of combination

mechanical and corrosion failures; erosion-corrosion and corrosion-fatigue.

*Erosion-Corrosion* -- Any corrosion is greatly accelerated if the protective films are worn away by excessive velocity, suspended solids, or mechanical vibration. Erosion-corrosion is usually found in the entrance area of tubes, below the shell inlet nozzle, at the point of contact with baffles and tubes, and inside the U-bend area of tubes, particularly the tighter bends,

Figure 19 shows an erosion-corrosion attack. The bright copper surface at the tube entrance is erosion; the yellowish deposit inside the tube is corrosion.

*Corrosion-Fatigue* -- In this dual failure mode, stresses associated with fatigue are the result of externally applied mechanical loads- such as vibrations from machinery, expansion or contraction because of temperature cycles, or light water hammer. In most environments where only

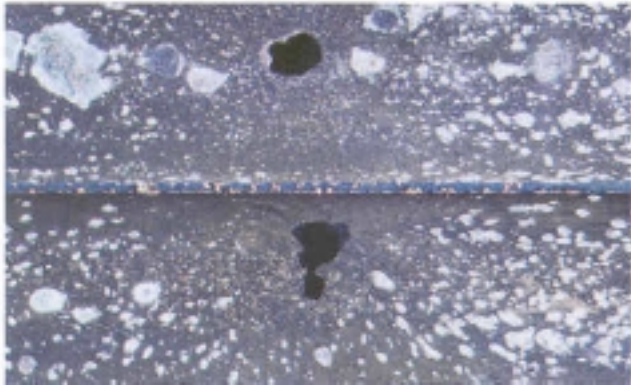


Fig 13. Carbon dioxide pitting attack on copper tube.

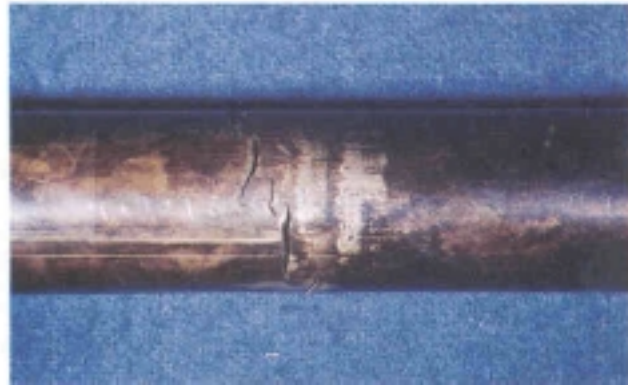


Fig. 14. Stress corrosion failure in admiralty tube.



Fig 15 Stress corrosion cracking in stainless steel U bend.



Fig. 16. Galvanic corrosion on steel baffle.

Fig, 17. Crevice corrosion at contact between tube and baffle. Fig.18. Condensate grooving and pitting attack on tube.





Fig. 19. Erosion-corrosion attack on tube.

corrosion occurs, corrosion products and films block or retard further attack. However, in corrosion-fatigue, Fig. 20, cyclic stresses rupture the protected areas and make them permeable; this action subjects open areas to accelerated corrosion.

Improperly supported tube bundles in domestic hot water storage tanks often suffer from this kind of failure. Vibrations may not be very severe; however, resulting stresses act additively to the existing internal tensile stresses. The stress level is raised beyond the strength of the material and cracking or a fracture results.

**Scale, Mud, and Algae Fungus-** Various marine growths deposit a film or coating on the surfaces of heat transfer tubes. The film acts as an insulator, restricting heat flow and protecting corrosives. As a result of this insulating effect, tube wall temperatures go up and corrosion increases.

Scale is the result of dissolved minerals precipitating out of heat transfer fluids. The solubility of these minerals is altered by forces within the heat exchanger, such as changes in temperature or chemical reactions. For example, when calcium bicarbonate, a common constituent of many waters, is heated, carbon dioxide is released and the material is reduced to calcium carbonate, a relatively insoluble compound that precipitates and coats heat transfer surfaces. Experience shows that the rate of precipitation is reduced with increasing fluid velocity. Fluid velocity must be matched to the tube material's ability to withstand the erosive effects of velocity.

Suspended solids are usually found in the form of sand, iron, silt, or other visible particles in one or both of the heat transfer fluids. If velocities are not high enough to keep them in suspension, particles settle out, causing the same kinds of problems associated with scale from dissolved solids. In addition, suspended solids are very abrasive to tubing and other heat exchanger parts. If abrasive suspended solids are handled in the heat exchanger, fluid velocity must be kept low enough to prevent erosion.

Algae and other marine growths are a serious problem if they get in the heat exchanger. In many cases, the environment in the heat exchanger is conducive to rapid proliferation of the algae or other marine growths, which restrict flow and impede heat transfer. Chemical algicides, such as chlorine, are effective in controlling algae and other marine growths; high fluid velocities also discourage their attachment and expansion.



Fig. 20. Corrosion-fatigue attack on tube.

### GALVANIC CHART

#### **Anodic (active) corroded end**

Magnesium  
 Zinc  
 Galvanized sleet  
 Cadmium  
 Aluminum  
 Mild steel  
 Wrought iron  
 Cast iron  
 18-8 stainless steel type 304 (alive)  
 18-8-3 stainless steel type 316 (active)  
 Lead  
 Tin  
 Muntz metal  
 Naval bras  
 Nickel (active)  
 Yellow and red brasses  
 Admiralty and aluminum brasses  
 Copper  
 Silicon bronze  
 70-30 copper, nickel  
 90-10 copper, nickel  
 Silver solder Nickel (passive)  
 Monel  
 Titanium  
 18-8 stainless steel, type 304 (passive)  
 18-8-3 stainless steel, type 318 (passive)  
 Silver  
 Graphite  
 Gold  
 Platinum

#### **Cathodic (noble) protected end**