

Interoffice Letter

SERVICE SUPERVISORS (A)
SERVICE ENGINEERS (A)
ZONE TECHNICAL SERVICES MANAGERS (B)
ZONE MANAGERS (B)

Date: 8/23/76
From: CHARLES D. MILLER
Office: MSD SERVICE ENGINEERING, SYRACUSE
Subject: SADDLE DAMAGE TO COOLER TUBES
FIELD EXPERIENCE REPORT 76-5

Nick Chashin

The attached reprint from the March 1976 issue of the ASHRAE Journal clearly defines the initiating cause of saddle damage to cooler tubes as corrosion resulting from free water in the cooler.

This article can and should be given to customers whose machines suffer this type of failure.

Additional reprints can be obtained from:

Estelle Hobson
MSD Service Engineering
TR-1, Room 214

C. D. Miller

CDM:eh
Att.

FILING INSTRUCTIONS: CENTRIFUGAL FIELD EXPERIENCE REPORT MANUAL,
COOLER-CONDENSER-ECONOMIZER

ASHRAE Journal

HEATING, REFRIGERATING AND AIR-CONDITIONING

MARCH/1976

"Saddle Damage of Cooler Tubes"

By Darwin G. Traver
member, ASHRAE

Charlie D. Miller

*Reprinted by permission of ASHRAE JOURNAL from
March, 1976 issue.*

This article shows the real cause of saddle damage to cooler tubes is moisture inside the sealed chiller. This moisture causes the formation of acids which enlarge the holes in the steel tube sheets. In turn, this permits vibration of the copper tubes within the hole and subsequent wear and damage.

The remedy: Close monitoring of moisture content and fast repair of leaks and defective purge systems.

SADDLE SADDLE

This article discusses "saddle damage," a term which refers to the physical characteristics of the damage pattern encountered on tubes which are subjected to "wet" corrosive environment in the presence of vibration.

DARWIN G. TRAVER
Member ASHRAE

CHARLIE D. MILLER

TUBE wall failures in flooded type coolers of centrifugal refrigeration machines may be the result of several basic causes:

- Defective tube due to tube manufacturing process or material;
- Water-side corrosion or erosion;
- Freeze-up. Water freezing inside the tube causing rupture;
- Excessive vibration resulting in

fatigue failure; the magnitude of vibration in these failures may be evidenced by tube-to-tube abrasive wear (See Figs. 1a and 1b);

- "Saddle damage" resulting from corrosion at the tube support sheet.

EQUIPMENT OPERATION

In order to understand the nature of saddle damage and the environment in which it occurs, a discussion of the equipment design and its operating conditions is necessary.

A centrifugal refrigeration unit (Fig. 2) basically comprises two horizontal shell and tube heat exchangers and a centrifugal compressor. Liquid or gaseous refrigerant is on the outside of the tubes in the shell space of both exchangers. One exchanger is the cooler in which liquid refrigerant is evaporated, thereby cooling water which is circulated through the tubes. The compressor draws the refrigerant vapor from the cooler and pumps it to a second exchanger, the condenser. The condenser cools and condenses the compressed refrigerant gas to below

its saturation temperature. The condenser cooling medium is usually water which is circulated through the tubes.

The condensed high pressure liquid refrigerant in the condenser does not accumulate to a significant degree but passes immediately through pressure reducing devices as it flows back to the cooler. When a high pressure liquid near its saturation temperature passes through a pressure reducing device enroute to the cooler, part of the liquid immediately flashes into a gas. Thus, the fluid entering the cooler is a two-phase fluid, part liquid, part gas. This two-phase fluid is distributed uniformly along the length of the cooler at the bottom. The liquid portion of this flow is boiled off in the cooler proper, producing the refrigeration effect desired.

The cooler consists of a cylindrical mild steel shell with a bundle of copper tubes occupying the bottom half of the shell. These tubes are supported periodically along their length with mild steel tube support sheets (Fig. 3). These copper tubes are usually of the integral fin type. Such a tube is made from a blank tube from the O.D. surface of which are extruded integral fins resembling screw threads. The finning is discontinued at the tube sheet and

D. G. Traver is Senior Staff Engineer and C. D. Miller is Senior Service Engineer, Carrier Machinery and Systems Div., Carrier Corp., Syracuse, NY.

DAMAGE OF COOLER TUBES

DAMAGE OF COOLER TUBES

tube support sheet locations, leaving the original tube blank intact at these locations. Such tubes are referred to as skip-fin integral finned tubing. The intermediate "skipped" or "unfinned" sections are referred to as "lands," and the tube end lands as "bells." The tube end bells are rolled into tube sheets to form a water-tight joint.

Liquid refrigerant in the cooler covers all but the upper tube rows in the bundle when the machine is inoperative (Fig. 4a). When the machine is running, the water circulating through the cooler tubes causes the pool of liquid refrigerant to boil and vapor thus generated passes up through the bundle filling the top half of the shell enroute to the compressor. This boiling displaces the liquid level upwards until the entire bundle is just submerged in boiling refrigerant (Fig. 4b). This boiling provides a natural exciting force to cause tube vibration or motion. Under the influence of this exciting force, the tubes deflect between their supports. For this reason, tubes are expanded into the support sheet to restrain them and resist this naturally-occurring vibration. As soon as the machine is shut down, the level drops several rows, depending on the unit design.

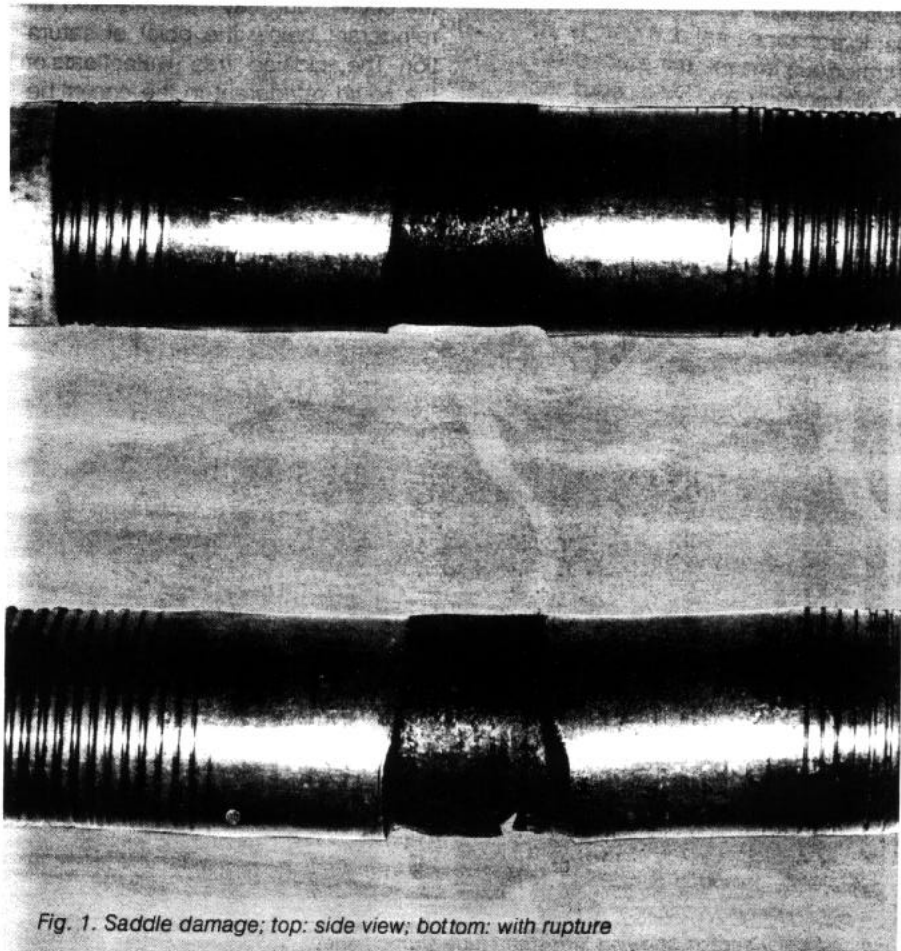


Fig. 1. Saddle damage; top: side view; bottom: with rupture

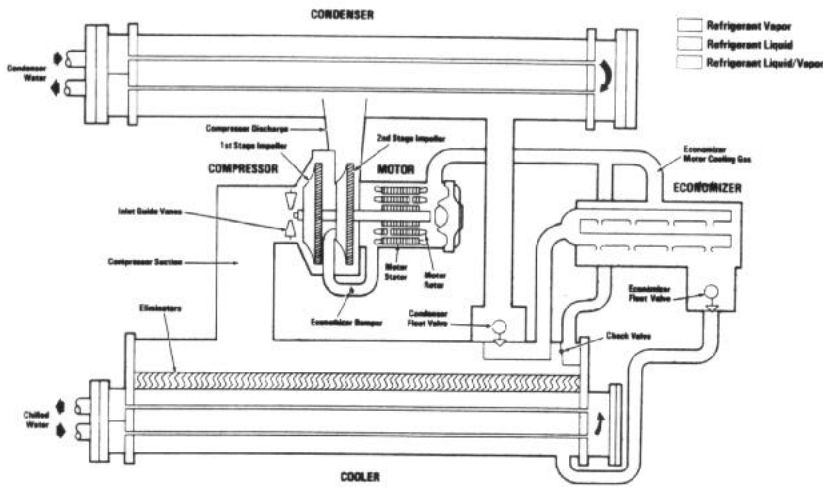


Fig. 2. Hermetic centrifugal refrigeration unit

WATER AND TUBE FAILURE

"Free" water (in the cooler) will react with the refrigerant by the process known as hydrolysis to form decomposition products, typically hydrochloric acid and hydrofluoric acid. A "wet" machine is one which has "free" water present in the cooler. In contrast, a "dry" machine has no "free" water in the cooler, but may have water in the refrigerant below the point of saturation. The acidified "free" water floats on the liquid refrigerant in the cooler because it is less dense. There is normally

* That quantity of water in excess of that which can be dissolved in the refrigerant. For R-11 at 80°F, only 1.8 ounces of water can be dissolved in 1000 pounds of liquid R-11 (See Table 1).

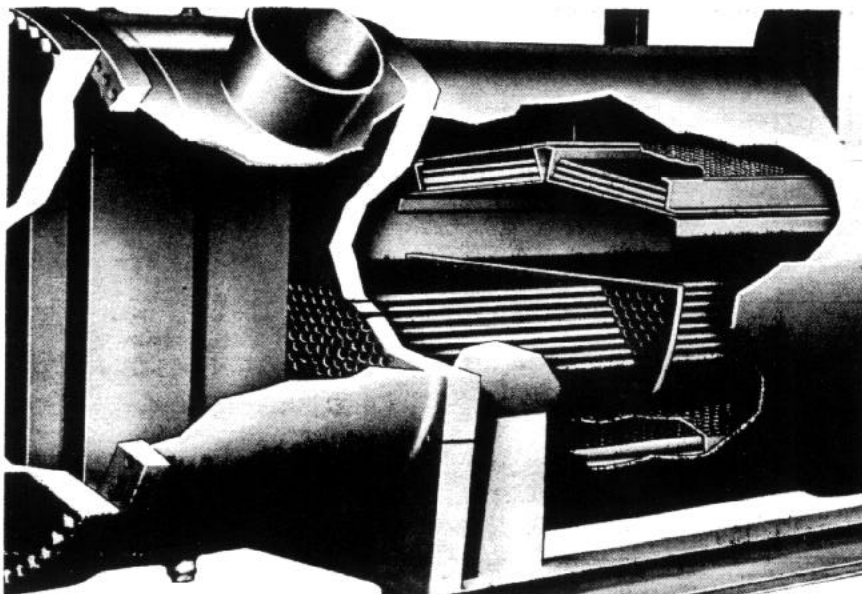


Fig. 3. Cooler section showing tubes and tube support sheet

no liquid refrigerant accumulation in the condenser. Liquid water tends to collect in the cooler because, on shutdown, any liquid in the system drains or migrates to the cooler, the coldest and usually the lowest point.

In the cooler, as noted above, there is a higher refrigerant level when the unit is operating and a lower refrigerant level when the unit is shut down. This gives rise to a periodic wetting of the upper tube support sheets and tubes by the acidified water as the level drops on shutdown. This acidified water tends to be drawn — by capillary action — into the tube support sheet to tube interface areas. This brings together all the ingredients for classical galvanic corrosion, *i.e.* two dissimilar metals (steel and copper) and an electrolyte (acidified water). This system has the characteristic of high solubility for the anodic reaction products and a low hydrogen over voltage for the cathodic reaction insuring a high reaction rate. Recall that the electrolyte floats on top of the refrigerant. The liquid refrigerant itself is a non-conductor and, hence, is not an electrolyte in this environment. We should expect galvanic corrosion only at this interface because this is the only place where all the necessary ingredients exist. The steel, being more active than the copper, will corrode preferentially to the copper tube. The most extensive tube support sheet corrosion occurs at the bottom of the hole because the acidified water collects at the bottom of the hole due to gravity.

The result of this galvanic corrosion is that the steel tube support sheets will be corroded, loosening the tube in its hole. When the tube becomes excessively loose, the vibratory forces resulting from the natural boiling of the refrigerant will cause accelerated mechanical wear. Because the copper tube is softer than the steel support sheet, mechanical wear will be concentrated on the tube.

The tube that fails is normally confined to the top few rows of tubes in the bundle. This is evidence that this failure relates to a corrosive environment that contains an electrolyte or corrodent that is confined exclusively to this area. This could only be acidified water. A continuously submerged tube will not have appreciable contact with "free" water and, hence, does not ex-

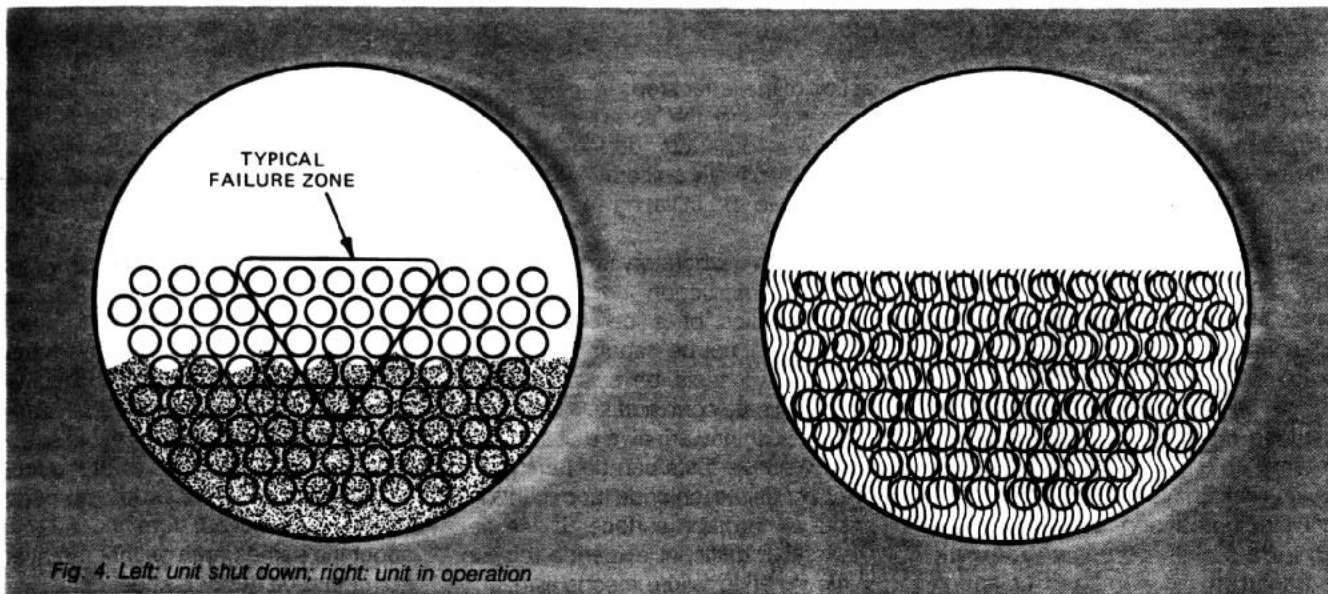


Fig. 4. Left: unit shut down, right: unit in operation

perience this type of failure. Another fact is that the tubes that actually fail from this cause are confined to the center of the bundle, not to the sides (Fig. 4a). This is believed to be due to the increased boiling that takes place in this area due to the greater tube depth in the bundle at the center. The greater the tube depth, the greater the amount of heat transferred causing boiling. Once the tubes become excessively loose, the primary failure mechanism is mechanical wear, and it is in this center portion of the tube bundle where wear will be most active due to the greater boiling activity than found at the cooler sides. Hence, the failed tube and the most severely damaged tubes will be in that portion of the bundle experiencing the most boiling after initial loosening caused by corrosion of the tube support sheet.

We have occasionally seen this type of failure over the years and have investigated this matter very thoroughly. This article is a summary of these investigations. Thousands of coolers have been built, with a failure rate from this cause being a small fraction of one percent. When these failures are encountered, they are usually traceable to poor operating and maintenance practices, particularly as related to the purge* and its ability to keep the unit free of water.

NATURE OF FAILURE

Saddle damage or corrosion at the tube support sheet (sometimes called crevice corrosion, fretting, or wear) as

* A device to remove non-condensable gases and concentrate liquid water for removal by the machine operator. Most centrifugal refrigeration machines are equipped with a purge.

currently understood is sequential in nature and includes the following steps:

- Water in excess of saturation (in the refrigerant) enters the machine and becomes acidified as a result of the breakdown of refrigerant by "free" water. This process is known as hydrolysis. The decomposition products include hydrochloric and hydrofluoric acids. The breakdown rate and decomposition products vary considerably from one refrigerant to another.

- The acidified water enters the tube support sheet to tube interface area. This provides an electrolyte linking two dissimilar metals (steel tube support sheets and copper tubes). This is the classic environment for galvanic corrosion.

- Corrosion proceeds at this interface destroying any of the mechanical bond and resulting in excessive looseness between the tube support sheet and the tube. In this phase, corrosion is occurring primarily in the steel tube support sheet. This corrosion process is primarily that of galvanic corrosion in which steel is attacked preferentially to copper. Fretting corrosion and cavitation may also contribute to the initial loosening process. The tube support sheet holes become enlarged and elliptical (Fig. 5a and 5b).

- Damage proceeds due to vibration or to a combination of vibration and corrosion. In this phase, the damage is occurring primarily in the tube, resulting in the saddle-type wear pattern on the underside of the tube. All operating coolers contain actively boiling refrigerant which causes unavoidable tube vibration.

Ultimate failure of the tube occurs when the tube cross-section can no longer support the load imposed by the forces due to vibration or hydrostatic pressure. (Fig. 1b).

Tubes removed from a unit which has experienced this type of failure will show a wide variation in the extent of damage. The failed tube will obviously be at step 5 in the sequence of failure. While there are several support sheets per tube, only one unfinned land will have failed. Some tubes will be in advanced stages of step 4, while others will be at step 2 or 3.

Typically, tubes from the top few rows near the center region of the bundle horizontally will show evidence of saddle damage of step 4 (See Failure Zone, Fig. 4a). The visual appearance of the saddle area is typically of a matte, dull finish showing surface roughness and possibly pits. There may also be imbedded particles. The tubes in the top rows at the sides of the bundle will usually not show a saddle pattern and will be at a stage of step 3 in the sequence of failure. The visual evidence at this step is a black surface deposit of iron oxide on the tube from the tube support sheet.

All the tubes in the upper rows of the bundle which have been exposed to acidified water will exhibit positive evidence of chlorides. This can be detected by a silver nitrate test or electron microprobe analysis. The finned tube surface may also show greenish deposits of copper chloride.

Tubes which have been continuously submerged in liquid refrigerant, show no "saddle damage" in our experience.

When tubes showing the characteristic saddle damage pattern are examined by a metallurgical laboratory, it will usually report that the cause of failure was due to wear caused by vibration. This is factual, in part, in that this is what can be expected from steps 4 and 5. However, this is not the initiating cause of the failure sequence. The lab will often report work hardening in the saddle area and may substantiate this with a photomicrograph showing the distorted grains from this cause or will present microhardness test results proving this same point. A loose tube that is being banged around by boiling refrigerant will certainly be work-hardened in the damaged or saddle area.

This analysis is not surprising since the laboratory will usually have at its disposal only one, or at most a few, tube sections that have gone to failure or near failure. The combination of the

action of the latter steps in the damage sequence and the scraping away of corrosion products during tube removal will usually obliterate most of the clues as to the initiating failure mechanism.

Unless a laboratory is made aware of the construction and operating characteristics of a centrifugal unit, samples will not be handled in a manner, nor will tests be specified, that would indicate corrosion as a contributing factor. If they are aware of this possibility, simple tests can be performed to substantiate chloride and iron deposits on the tube surface. These deposits are significant evidence relating to the initiating failure mechanism.

If, as only rarely occurs, a portion of the tube support sheet is available to a lab for metallurgical examination, the ovalness of the holes in the area subject to galvanic corrosion will be evident. This ovalness is in the vertical di-

rection and is most pronounced on the bottom half of the hole (Fig. 5a). Often, the original machining marks are in evidence on the upper portion of the hole. (Fig. 5b). This hole enlargement has occasionally been reported to be the result of a wear mechanism. It is difficult to reconcile the wear of a relatively hard steel hole from abrasion by a relatively soft copper tube. In extreme cases, tube support sheet holes will have elongated over 0.100". By comparison, the total tube wall thickness is about 0.050". More usually, at the time of tube rupture due to saddle damage, the metal removed from the tube is about the same depth as that removed from the tube support sheet hole.

Micrometric measurements have always shown tube support sheet hole ovality when a "saddle damage" tube failure has occurred.

On "wet" machines we have observed tubes free to move 0.075" vertically in the hole with the metal removal about equally divided between the support sheet and the tube. On the other hand, we have seen tubes removed for inspection from a "dry" machine after the same years of service at the same location that had a saddle only 0.001" deep notwithstanding that they had not even been expanded (through human error) into the tube support sheet. Thus, the extent of damage under conditions of vibration due to boiling is negligible in a dry machine, but will be greatly accelerated when "free" water is present to create acids and cause corrosion.

The damaging effect of "free" water in a machine is not limited to saddle damage or corrosion at the tube support sheet. "Free" water will cause acidification of the oil with subsequent acid attack on the bearing surfaces. Initially, a black film appears on the bearing surface, and when the acid level increases, etching and dissolution of the bearing surface will occur. If the bearing shows any sign of black film, it is probable that the machine is dangerously wet.

Acidified water can also cause corrosion and binding of the centrifugal compressor inlet guide vane assembly. The motor insulation is not immune to acidified water attack either. Motor failure can result from insulation breakdown in a "wet" machine. Acidified water can cause corrosion at the bearing or pivot of the purge float valve, sticking it in a fixed position. A similar

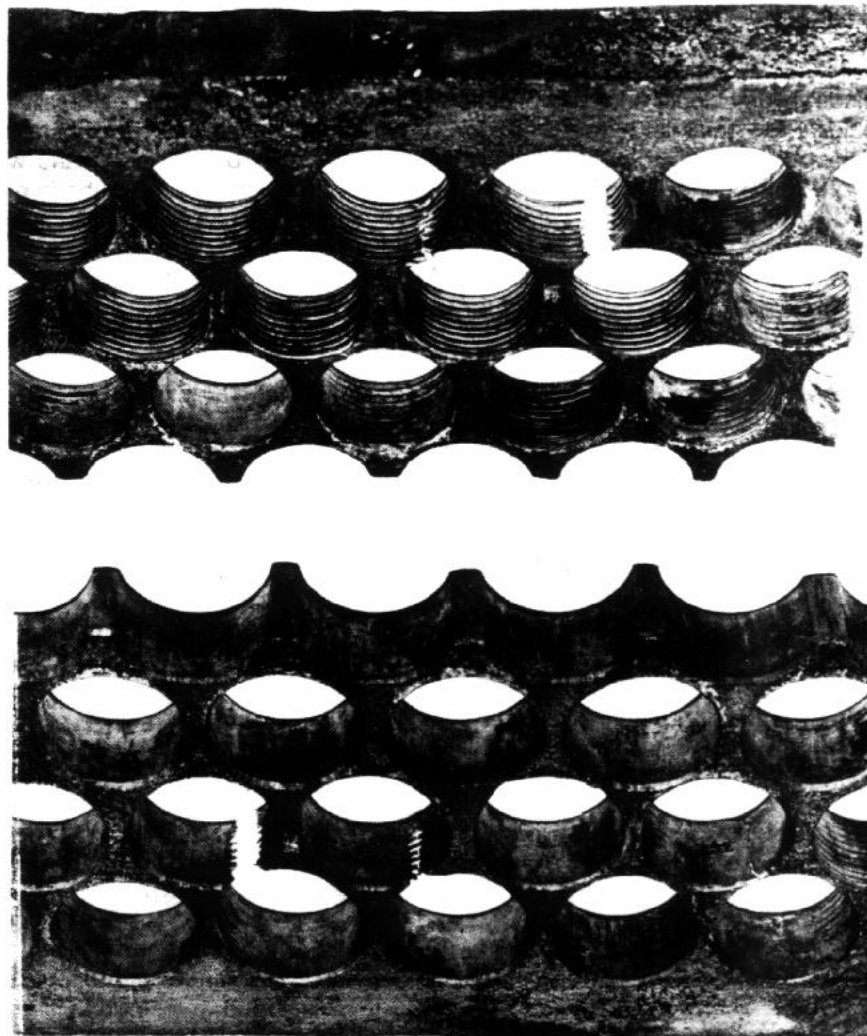


Fig. 5. Grooved tube support sheet; top: anterior view; bottom: posterior view

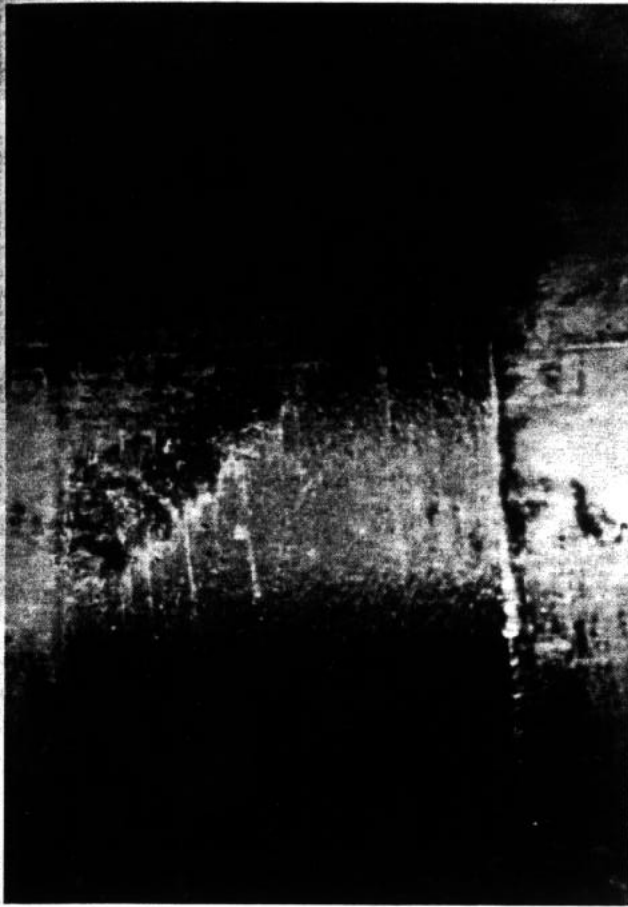


Fig. 6. Side view of early stage of saddle damage

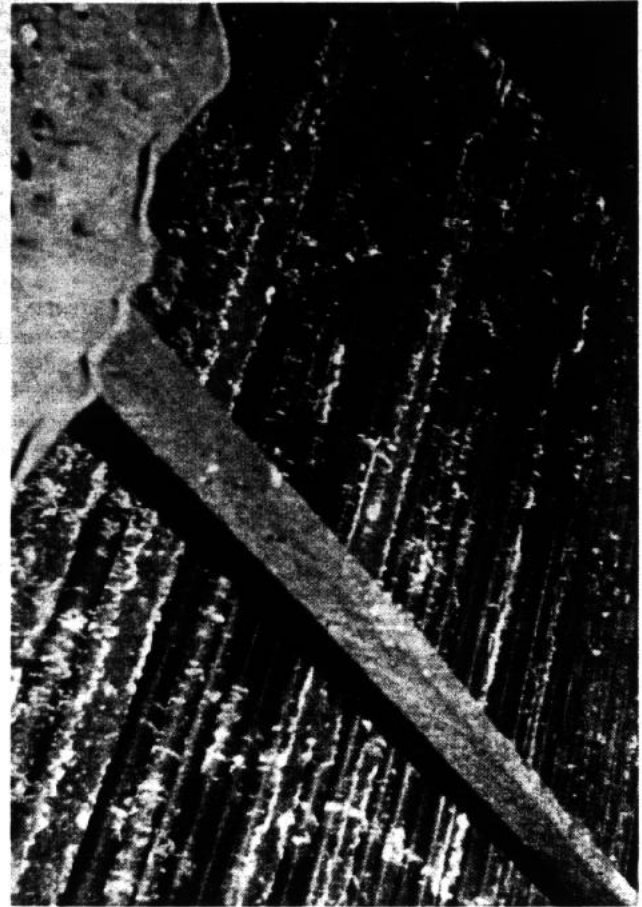


Fig. 7. Scale encrusted tubes from rust flaking off "wet" cooler shell

result can occur on either the condenser or economizer float valve. (Fig. 2).

Acidified water can cause extensive and severe corrosion to the inside of the cooler shell. The scale formed can and does flake and fall off, clogging tube fins, areas between tubes (Fig. 7), and the eliminators. These deposits become hard and reduce heat transfer and restrict the flow of refrigerant gas. The upper rows of tubes, subject to the periodic wetting from the change in level of the floating acidified water, are sometimes corroded and covered with a green corrosion deposit of copper chloride. Such a deposit obviously reduces the heat transfer surface area and heat transfer rate. Since these deposits are hygroscopic, this factor makes total water removal more difficult.

We also point out that oil can break down due to excessive temperature, and generate acids as well. However, different acids are evolved in this reaction and by chemical analysis this case can be distinguished from acids resulting from refrigerant hydrolysis.

HOW MUCH "FREE" WATER?

How much "free" water is dangerous in

a machine? Any "free" water is potentially dangerous! We are not talking about gallons or quarts of "free" water. We are concerned with a mere few ounces of water. Table 1 shows the relatively minute amount of water required to saturate 1000 pounds of liquid refrigerant. Bear in mind that even new refrigerant will already be partially saturated with water.

One or two ounces of "free" water will cause damage. If the purge needs annual internal painting or descaling to control rust, the machine has not been dry enough. If the purge sight glasses are even visibly filmed with a rust deposit, the machine should be considered "wet."

The subsequent service record of machines that have failed from saddle damage due to corrosion at the tube support sheet and have been retubed has been outstanding. In our experience, no repeat failures from this cause have been noted. The reasons attributed to this record are as follows:

1.) Once a machine has failed, the owner and machine operators recognize the serious consequences of operating a "wet" machine and subsequently are far more alert and vigilant to see that the machine is kept dry.

2.) Desiccant driers are installed to dry out these machines and are usually left on and maintained. Incidentally, if a desiccant drier needs cartridge changes more often than once a month, the chances are good that water is entering the machine in excessive and potentially dangerous quantities. Remember, we are concerned with ounces of water, not gallons. The large four cartridge driers that are frequently used will absorb only about 10 ounces of water.

SOURCES OF WATER

Water, which is a contaminant in the system, may enter the machine from a variety of sources, such as:

- Leakage at the rolled joint at the cooler tube sheet. Water pressure must exceed the refrigerant pressure for this to occur. In most installations, this is the case.

- Condenser tube roll at tube sheet leakage. Water pressure must exceed the refrigerant pressure for this to occur. In many installations this is the case, however it is less frequent with the condenser than with the cooler.

- On machines using low pressure refrigerant (defined as having any

Solubility of Water in Liquid Refrigerant in Ounces per 1000

Temperature °F	Refrigerant		
	R-11 & R-113	R-114	R-12
30	0.54	0.40	0.27
40	0.67	0.53	0.51
50	0.88	0.69	0.67
60	1.12	0.88	0.88
70	1.41	1.14	1.17
80	1.76	1.46	1.53
90	2.24	1.90	2.71

portion of the refrigerant system, typically the cooler, below atmospheric pressure), air can leak into the machine. Air will contain a small amount of water vapor which can condense on the cool refrigerant in the cooler.

- When any machine is charged with refrigerant, this refrigerant will always contain some water, usually at levels below saturation. This is the best that any refrigerant manufacturer can do. With low pressure refrigerants, shipped in barrels, it is possible for water to enter the barrel due to inleakage at the bung during shipment and storage. All too frequently, refrigerant which is reused from machines which have undergone repairs will be contaminated with "free" water, and this water can inadvertently be recharged into the unit. Measures should be taken to prevent this type of water contamination.

- The rupture disc on coolers provides a cold surface on which water from normally moist air on the outside of the disc can condense. If a minute leak occurs at this disc and the cooler pressure is below atmospheric pressure, this condensed water will migrate into the cooler.

- The cooler liquid level gauge glass sweats during normal operation on its outside surface. Water vapor from air condenses on this surface and runs down the gauge glass to the gasketed metal joint. If this gasket is not leak tight, the condensed water vapor will be drawn into the cooler if it is below atmospheric pressure. This also applies to any other exposed sweating joint on the cooler.

- Leakage from the water cooled oil cooler into the oil.

- Failure to properly dehydrate after flooding from causes such as freeze-up.

Moisture can enter a machine with air from an air leak. However, the quantity is small. R-113 (a low pressure refrigerant) machines usually have both the cooler and condenser at sub-atmospheric pressure, while R-11 machines usually have only the cooler

at sub-atmospheric pressure. R-114 machines have a cooler that is very near atmospheric pressure, so that the leakage gradient is very small if it exists at all. The fact we have seen no corrosion at the support sheets on R-113 machines is indicative that moisture from air leakage must be of significantly less importance as a source of free water in machines than water leaks. R-113 machines are low tonnage units with relatively few tubes.

Failure rate is related to machine size. This leads us to believe that the number of tube joints must be a significant variable in the occurrence of saddle damage. The greater the number of tubes, the greater the statistical chance of a tube sheet leak developing during the operating life of a unit.

PREVENTIVE MEASURES

Since the basic cause of saddle damage is water, the basic preventive measure is to keep the machine dry.

A purge unit is furnished to collect and separate liquid water from the liquid refrigerant, as well as collect and remove noncondensable gases. Many years of experience have proven that the purge is capable of doing this if it is properly operated and maintained. As regards water, the purge is actually an indicator. The purge unit is not designed to remove large quantities of water from the machine. Its capacity is such that it will remove water which enters through an occasional leak or during repairs. Continuous water removal indicates there is either a direct water leak or a reasonably large air leak into the machine. If the water is a result of air leakage, this should be indicated by frequent air purging. Any leak which results in continuous water removal at the purge should be located and repaired as quickly as the machine can be conveniently shut down for repairs.

The purge unit should be kept in good repair with all float valves in good working order, all sight glasses clean and clear, orifices and strainers unplugged and valves properly positioned.

The purge water sight glass should be checked at least twice a week, and any water observed should be drained into a container so an estimate of the amount can be made. Amounts of water removed and the frequency should be recorded.

When the machine is shut down for an extended period, as during the winter, the chilled water and condenser water lines should be shut off at the unit and the water pressure relieved in the water boxes. This is particularly important on machines with purges which are not operable during machine shutdown. On these, the presence of a destructive water leak would not be discovered until after startup. By then, considerable internal corrosion could occur.

On machines which are not given close operator attention, or where operators inexperienced in refrigeration equipment are used, a secondary precaution would be to install a large desiccant drier with moisture indicators. These are most effective if the refrigerant flows from the cooler through the drier and back to the cooler. This arrangement requires the use of either an eductor or a small refrigerant pump. When the moisture indicators indicate "wet", the drier should be serviced.

Refrigerant analysis is not always indicative of excess water in a machine. Water in excess of saturation will float, so the sample removed will probably at best be saturated. If the sample is removed at 70F, for example, (machine shutdown), the analysis might show 60% of saturation and this might be considered acceptable. However, the cooler operates at about 35F-40F on most comfort cooling applications. At this temperature, refrigerant that was 60% saturated at 70F will be 100% saturated when cooled to 40F and below and, in addition, free water will form. Over the years we have found refrigerant analysis an unsatisfactory monitor of machine conditions, particularly prior to an actual tube failure. □ □