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Investigating Absorption Refrigerator Fires (Part 2)

Introduction

ATLANTIC BEACH, FLORIDA—In "Investigating Absorption Refrigerator Fires Part I"[1], the reader was introduced to the nuances of Recreational Vehicles (RV) absorption refrigerators and failure modes encountered when inspecting such systems at a fire scene. Based on the initial inspection at the scene, additional testing and analysis of the refrigerator requiring disassembly and/or sectioning (cutting) may be necessary. While some of the disassembly and sectioning can be performed in the field, an appropriate testing facility is required for much of the work. It is strongly recommended that appropriate notification be given to all potential parties prior to conducting any inspection that alters the evidence or requires disassembly, in accordance with NFPA 921 and ASTM E 860[2-3]. Figure 1 shows a diagram of an absorption refrigerator and its component parts.

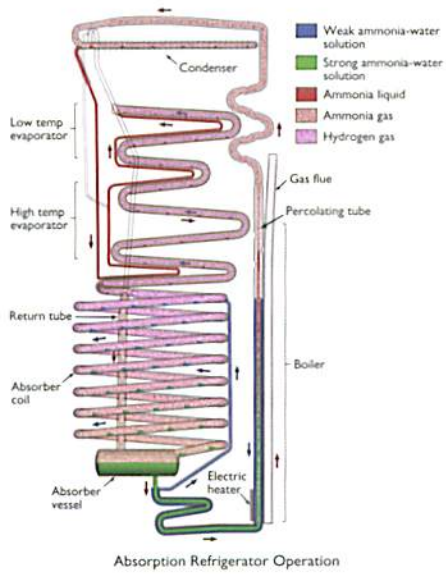

FIGURE 1—*Diagram of absorption refrigeration operation.*

Thermal Cycle Flow

It is helpful to understand the thermal cycle and the temperatures at various points on the cooling unit. One would expect failures preferentially in areas with the highest temperature and areas where the temperature fluctuates. Failure processes such as corrosion, which are electrochemical in nature, can be sensitive to temperature. Many corrosion reactions are possible and/or occur at significantly faster rates at higher temperatures[4]. Further, materials tend to lose strength at higher temperatures. Most structural steels lose more than half their strength by the time they reach 1112° F (600° C)[5]. Finally, steels, like most materials, expand and contract as the temperature changes. The extent of expansion per degree of temperature change is called the coefficient of thermal expansion, which for steel is approximately 6.5 X 10^{-6} in/in-degrees F[6].

To monitor the temperature at various points on an operating absorption refrigerator, AEGI instrumented an operable Dometic Model RM2852 refrigerator. Thermocouples were attached at various parts of the cooling unit and to the interior of the freezer and refrigerator compartments. A FLIR ThermaCAM EX300 was used to image the temperature of the cooling unit during operation.

Figure 2 is a Thermograph of the unit while it was operating. Note that the insulation has been removed from the boiler and gas flue to image that area. As can be surmised, the hottest area of the cooling unit is in the boiler region.

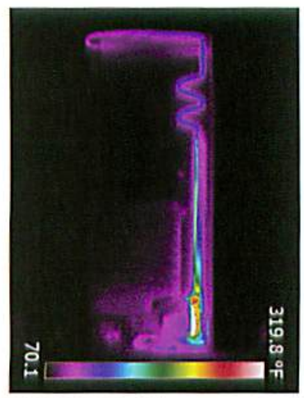

FIGURE 2—*Thermograph of absorption refrigerator with boiler insulation removed. Note evaporator coils are not visible because they are cold and located in the freezer/refrigerator compartments.*

The thermal imaging also shows that the temperatures are not steady state, but are cyclic. Much like an old style percolating coffee pot, it takes time to heat up the ammonia-water solution and get percolation from the ammonia gas bubbles forming and combining in the percolating tube. After the percolation event, the released hot ammonia gas travels up to the condenser and the water in the percolation tube goes into the annulus around the percolating tube, causing the hot water in the annulus to travel toward the return tube. Water from the reservoir gets preheated by the return water and goes into the percolation tube, for another heating cycle. The series of thermographs in Figure 3 show temperature variations at different times in the cycle. Interestingly, the cycle progresses relatively slow, with a period of several minutes.

From the above discussion, it is clear that an area susceptible to failure would be in the boiler region. The heat from the electric heating element and propane burner is transferred to the boiler region by conduction from the heater well and gas flue through the attaching fillet weld. The weld, which is several inches long in the axial direction and a fraction of an inch wide, constitutes the hottest area and likely the area of greatest temperature fluctuation. Add to that any metallurgical effects on the boiler tube from the welding process and this area becomes even more prone to failure.

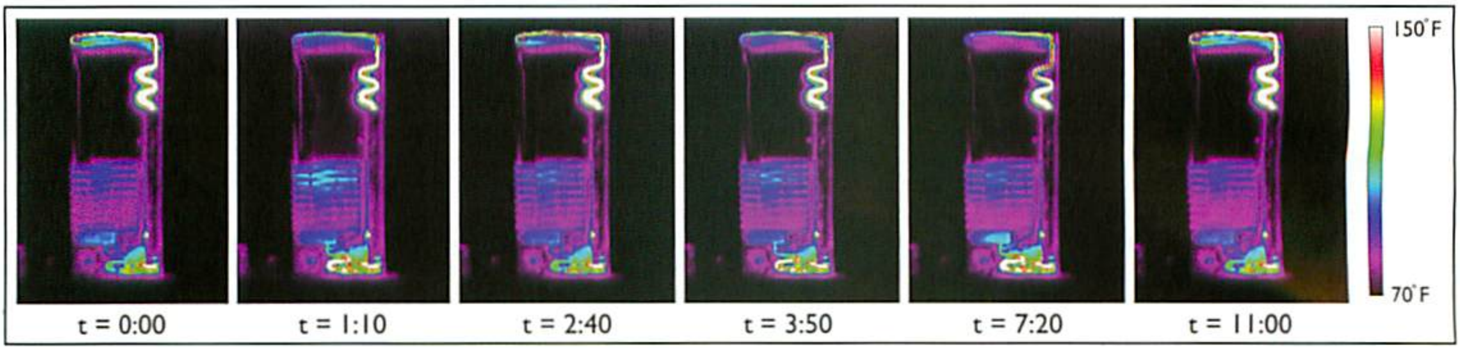

FIGURE 3—*Series of thermographs showing temperature variation.*

Inspections

When the fire patterns indicate the origin of the fire is near the absorption refrigerator, various fire causes must be considered. The inspections can broadly be categorized into those which are performed in the field, those which can be performed in the field and/or lab, and those which are performed in the lab.

Field Inspection

Several systems must be examined in the field during the preliminary inspection to either rule them in or out as a potential cause of the fire.

• Electrical System

Perform an inspection of the electrical system of the RV including the high voltage alternating current (AC) and the low voltage direct current (DC) circuitry. It is common for electrical conductors to be routed through a chase adjacent to the boiler area and/or behind the refrigerator. Identifying areas of electrical activity can help isolate the area of fire origin. The electrical inspection should include but not be limited to the shore power supply, AC/DC distribution panel(s), AC/DC appliances and wire runs. Figure 4 is an example of electrical discharge activity of a 120 volt AC conductor located behind an absorption refrigerator.

• Gas System

The gas system should be examined and if possible pressure/leak tested. This includes to the extent practical components and appliances from the propane container to each appliance it supplies. Like electrical discharge damage, overload ruptures in the gas lines (specifically copper supply lines) can be helpful in isolating the area of fire origin.

• Refrigerator Boiler Inspection

Evidence of boiler failure was discussed extensively in the previous article[1]. Evidence of sodium chromate, scaling, cracking, and heat patterns on the galvanized steel sheet metal should be documented. Figure 5 depicts a crack along the electric heater tube weld of an absorption refrigerator involved in a fire.

FIGURE 4—*This unit exhibited evidence of electrical discharge damage. The area of electrical activity was consistent with the area of fire origin in this particular fire.*

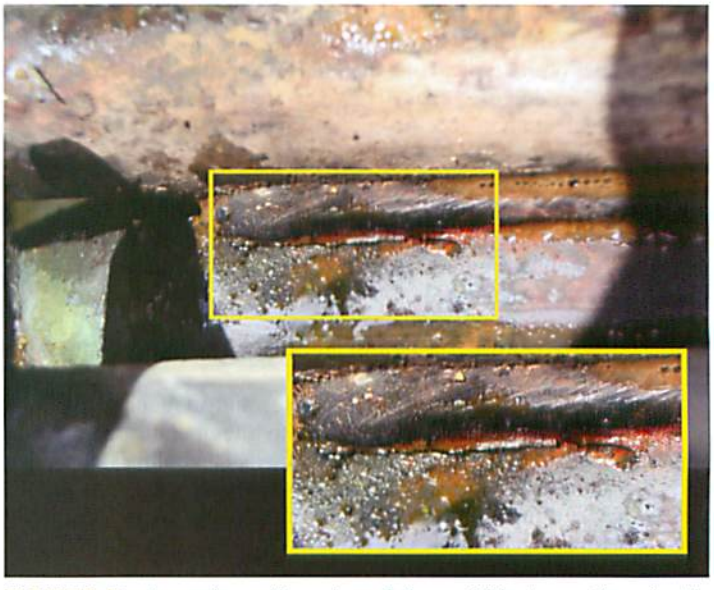

FIGURE 5—*A crack on the edge of the weld between the electric heater and boiler tubes of a Dometic RM2862.*

Field and/or Laboratory Tests

If time and circumstances permit, testing for sodium chromate at the fire scene as well as a pressure/leak test of the cooling unit can be performed. This is always favorable as these tests confirm the condition of the evidence prior to transportation and potential long term storage.

● *Test Cooling Unit for External Presence of Sodium Chromate*

Confirmation of the presence of sodium chromate on the exterior of the cooling unit during the preliminary inspection and prior to transport is helpful in identifying whether the refrigerator is a candidate for further examination. Sodium chromate inarguably identifies a breach of the cooling unit. A unit maintaining positive pressure yet testing positive for the presence of sodium chromate is indicative of the unit re-sealing after a partial de-pressurization event. It is helpful to know this in the field so that appropriate steps are taken in the laboratory examination to locate the re-sealed failure. It is preferable to acquire suspected sodium chromate samples during the preliminary inspection, as this will minimize future contamination arguments and the potential loss/degradation of the sodium chromate if present on the unit.

● **Test Cooling Unit for Positive Pressure and Leakage**

The fill valve on the reservoir (Dometic units) can be cracked open and quickly closed to determine if the cooling unit is holding positive pressure. This is a go or no-go field test, normally done with concurrence of all parties, but can be delayed until the laboratory examination. Using an isolation/service valve, the cooling unit pressure can be measured. An isolation/service valve also facilitates proper venting and disposal of any refrigerant. If the cooling unit has no pressure, a gas can be used to pressurize the cooling unit, at which time a leak detection solution can be used to check for the location of leaks. This may require plugging and isolating sections of the cooling unit that were breached as a result of the ensuing fire. It may be appropriate to remove the boiler section to test, if all parties concur.

Laboratory Tests

While the testing procedures outlined above are recommended for field inspections when possible, the analytical procedures mentioned below require equipment which is not readily available at fire scenes and are generally reserved for a laboratory setting.

● *Analysis of Sodium Chromate Samples*

There are several methods of confirming whether sodium chromate is present in a sample, such as Energy Dispersive X-ray Spectroscopy (EDS) or Fourier Transmission Infrared Spectroscopy (FTIR). Various chemical tests can also be used.

Laboratory - Materials Analysis

If the field inspection observations and associated evidence suggest that a failure in the cooling unit was the most likely cause of the fire, then a subsequent materials inspection can provide additional information to help identify why the failure occurred. The materials inspection is designed to determine the mechanism for the particular material failure. The inspection should start with the least intrusive techniques, and leave the most intrusive techniques for last. Finding the exact mode of failure can help confirm whether the cooling unit was the source of the fire or whether it was a result of an ensuing fire. The steps below are typical of a materials inspection, but by no means are the steps in this list exhaustive or mandatory, since every inspection is dependent upon specific circumstances of the failure.

● **Initial Visual Inspection of the Evidence**

It is expected that the initial visual inspection of the evidence will consist of verifying that the condition of the evidence has not changed following the field inspection. Any changes noted should be documented and discussed with all parties.

● **Visually Examine the Boiler Section After the Insulation is Removed**

Check for scaling, sodium chromate, and evidence of bluing. Steel can exhibit a blue color if exposed to a temperature range from approximately 1112-1472° F (600-800° C)[7]. The color is dependent upon the thickness of the iron oxide (Fe_3O_4) layer formed on the surface, which is a function of the temperature to which it was exposed. See Figure 6 for an example of bluing.

● **Pressure/Leak Test**

A pressure/leak test will be performed with a gas to identify and or confirm the location of the leak site. It is important to pinpoint the area of leakage, such that further materials analysis and destructive sectioning do not accidentally damage areas of interest. If the cooling unit does not display a leak from the pressure test, consideration should be given to all non-destructive methods for finding the leak.

● **Remove Boiler Region**

If the physical evidence and pressure tests indicate a leak is or was present in the boiler region, the boiler would typically be cut from the cooling unit. It is desirable to index and label the areas to be cut to document the orientation of the boiler. Repeat the Pressure/Leak Test identified above if necessary to pinpoint the failure location. Because the boiler region contains several welds and attached tubes, visual examination of the boiler is made significantly easier when it is removed from the cooling unit.

● **Perform Non-destructive Tests**

Visual and optical microscopy analyses should be considered first when observing the failure. If the failure is difficult to see, liquid dye penetrant testing (PT) can be used on the exterior surfaces to elucidate the location and size of the failure on the exterior wall of the boiler tube. Figure 7 is an example of a crack found on visual inspection.

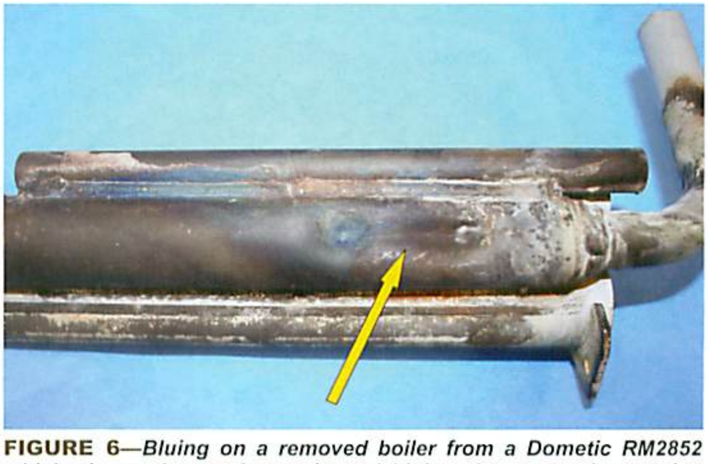

FIGURE 6—*Bluing on a removed boiler from a Dometic RM2852 which shows the steel experienced higher than normal operating temperatures. Note the axial indentation in the tube, commonly called a dimple.*

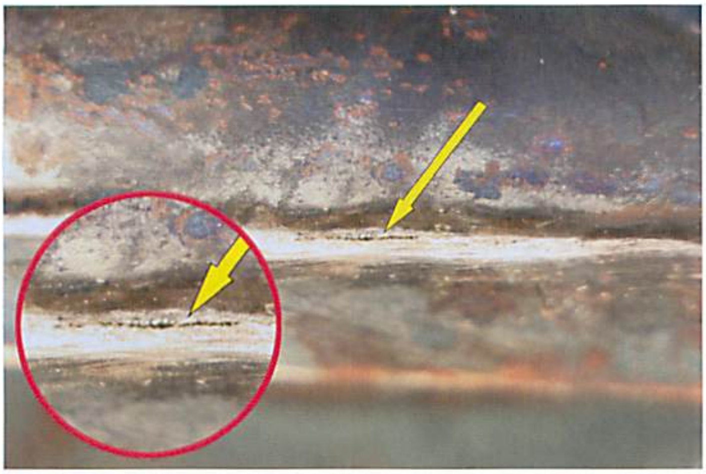

FIGURE 7—*Macrograph of a boiler tube crack adjacent to a heater tube weld.*

Scaling, rust, and other debris on the external surface of the tubing may make it difficult to find the failure without cleaning. Care must be taken when cleaning the area near the failure as to not accidentally damage an important surface. Radiographic testing (RT) has also been shown to be useful in determining the dimensions of a failure on the inside radius of the boiler tube. Ultrasonic cleaning and abrasive cleaning may be considered and performed as necessary with each step of the sectioning operation.

● Section the Boiler Axially

The previous steps should reveal the location of the failure, and conversely areas that don't contain the failure. To determine the mechanism of failure, it is often necessary to view the interior of the tubing. To achieve the best view, the sample can be sectioned. It is desirable to select an axial cut plane which will avoid all areas of interest. Non-destructive analysis can be repeated for the inside of the tubing once the axial sectioning is complete. The nature and location of the breach should be determined. Figure 8 is an example of an axially sectioned boiler, while Figure 9 shows a view of a boiler crack revealed after the axial cut.

FIGURE 8—*Upper portion of a boiler which has been sectioned axially to view inner surfaces.*

● Trim Sample

The sample can be trimmed to allow for a thorough analysis of the leak location. Selecting cut locations is an important decision at this juncture of the inspection. Cuts that are remote from the defect are unlikely to affect further analysis. For example, cutting a cross-section in a region away from the leak of the boiler and heater well tubes and the associated welds allows metallography and hardness testing. Metallography can show grain size, phases present, weld penetration, and weld quality. Hardness testing can yield information on work hardening or bulk metal strength. Figure 10 and Figure 11 are samples which have been trimmed to facilitate further analysis.

● Examine the Defect

Visual means can be used to examine the defect surface and/or cross-section. Metallography as well as electron and optical microscopy should be considered. It may also be desirable to make a cross-sectional cut through the defect for metallography of mating edge surfaces of the defect, even though it limits other observations of the defect. Figure 12 shows a polished and etched cross-section of a crack at the edge of a weld.

EDS can be useful in confirming elements present in the alloy, oxide layers, and/or corrosion products. Figure 13 shows an EDS mapping of a cross-sectioned boiler specimen with independent elemental graphs created from a region analyzed with SEM.

● Expose the Defect

For a crack type failure, it may be desirable to expose the two fracture surfaces for further evaluation. The sample can be bathed in liquid nitrogen until it has reached its ductile-to-brittle transition temperature. The sample can then be bent to cause brittle fracture of the ligaments between the ends of the crack and the sample ends. The newly fractured surfaces will have a brittle fracture appearance under microscopy, distinguishing it from the surfaces of the original defect. See Figure 14 and Figure 15 for an example of an exposed crack surface. Figure 16 and Figure 17 are SEM micrographs which show one side of the crack after it was mounted and polished in a non-conductive polymer.

FIGURE 9—*Crack revealed on the inside of a boiler after axial sectioning.*

● Examine the Dimple (Dometic only)

Dometic absorption refrigerators have an axial indentation in the lower boiler tube, which reportedly assists conductive heat transfer from the boiler tube to the inner percolating tube. This indentation is commonly referred to as a 'dimple.' In several absorption refrigerators which have been in RV fires, the axial center of the dimple has returned to its cylindrical position, and looks as if it has 'popped.' Figure 6 shows an example of a popped dimple. This indicates that there was sufficient pressure inside the cooling unit to overcome the strength of the steel. Importantly, it is the combination of pressure and temperature that causes the dimple to pop, as metal strength is dependent upon temperature. Metallography and micro-hardness testing on this dimple may be warranted to determine the extent to which some regions have been cold-worked or stressed more than others.

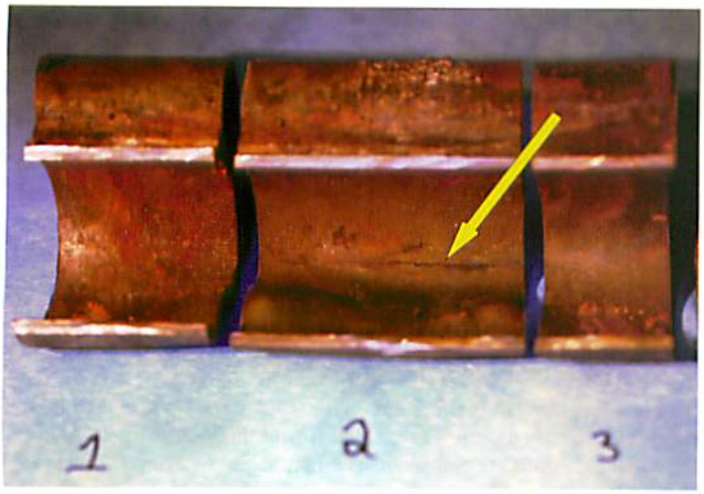

FIGURE 10—*Sample trimmed just past the edges of a crack on the interior of a boiler.*

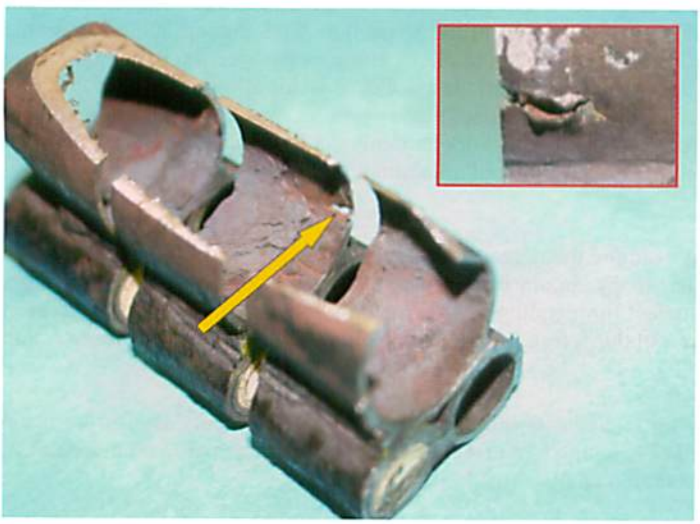

FIGURE 11—*Corrosion in a Norcold 6162 thinned the sidewall of the boiler to the point it ruptured with a lip. Inserted photograph in the upper right corner is an exterior view of the rupture.*

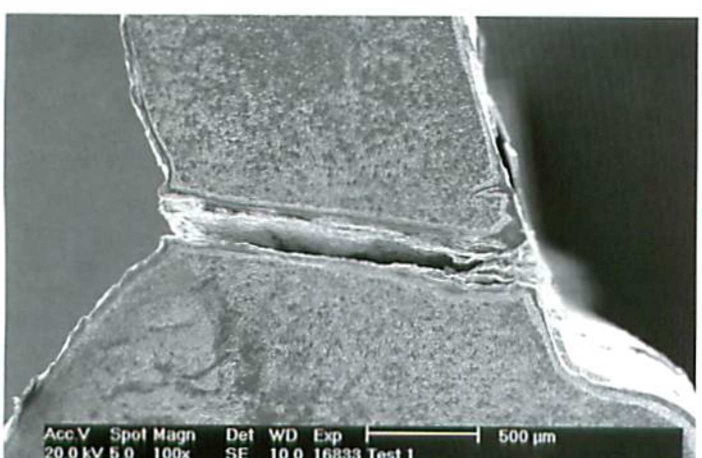

FIGURE 12—*Scanning Electron Microscope (SEM) micrograph of a cross-sectioned crack at the edge of the electric heater weld.*

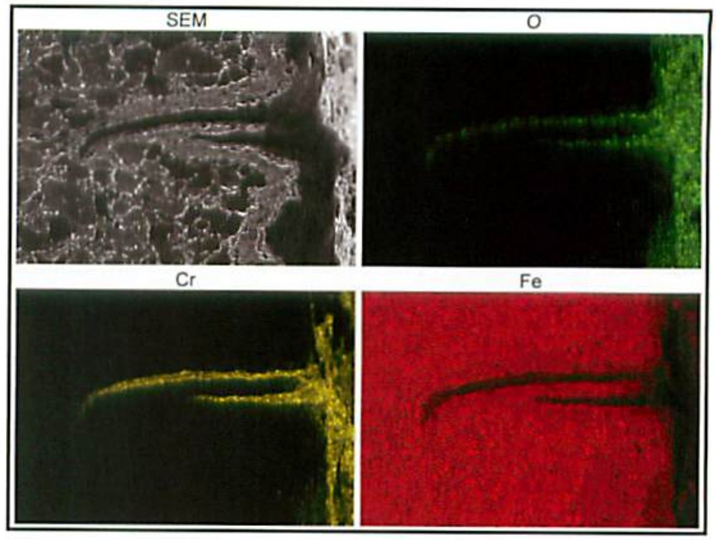

FIGURE 13—*EDS map of a cross-sectioned boiler specimen showing regions where oxygen (green), chromium (yellow), and iron (red) were detected.*

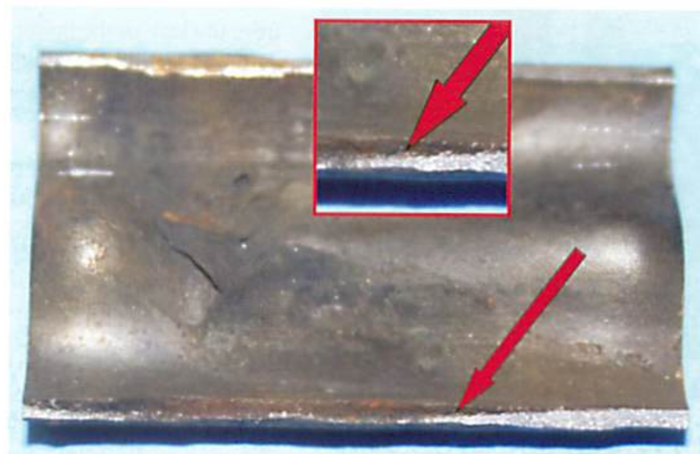

FIGURE 14—*A crack surface on a boiler tube exposed after being embrittled with liquid nitrogen. Note the color difference between the corroded portion and the fresh fracture. The interior of the dimple is present. The line at the dimple is shadowing from scale buildup.*

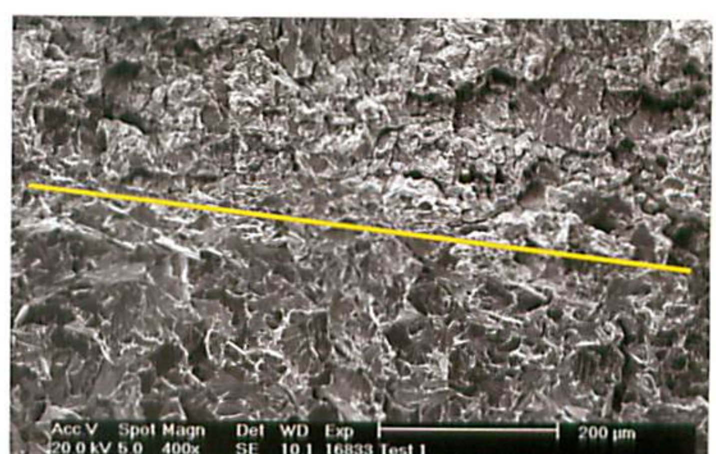

FIGURE 15—*SEM micrograph of the mating crack surface to Figure 14. The top portion shows corrosion while the bottom portion shows cleavage fracture from the liquid nitrogen embrittlement.*

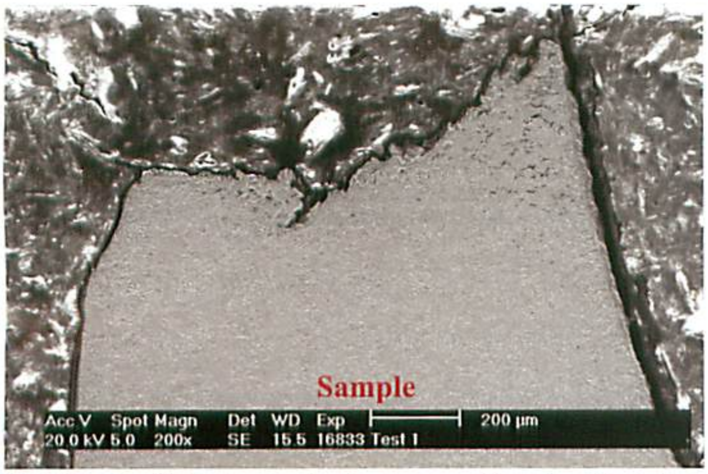

FIGURE 16—*SEM micrograph of a cross-sectioned crack surface. The right side is the interior surface of the tube and the left side is the exterior. The crack, top, progressed from interior to exterior.*

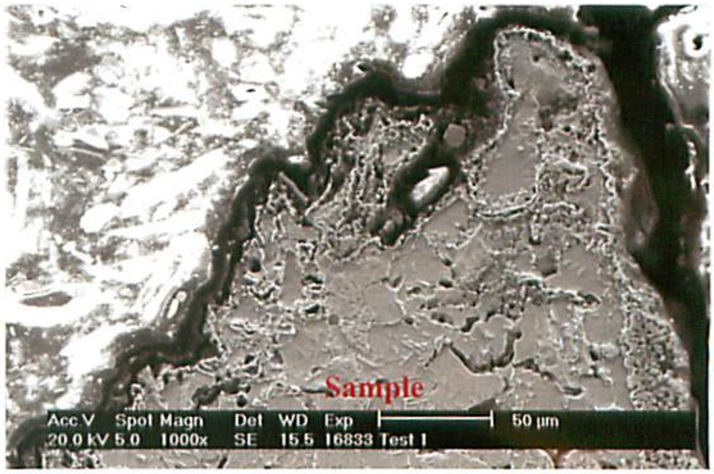

FIGURE 17—*Magnified view of the crack origin in Figure 16. The right side is the interior tube surface. Note the corrosion and intergranular (between the grains) separation.*

Examine the Welds

Welds are examined visually and under stereomicroscopy to check for common defects, such as undercutting, porosity and cracking through the weld. Metallography and micro-hardness testing on a boiler/heater tube weld cross-section can be used. Weld penetration, lack of fusion, extent of the heat affected zone (HAZ), porosity, cracking and grain size can be seen easily if the sample is polished and etched properly.

It is important to note that the direction that a metallurgical inspection will take varies greatly upon what is identified at each step and the preference of the expert involved. Frequently, items of interest will be explored further than noted above and items listed above may be deleted because they will not produce additional insight into the failure. Once all the information is analyzed, the mechanism of the failure can be identified.

Conclusion

The purpose of this article and the previous article is to give the fire investigator insight into the methods and techniques used to evaluate absorption refrigerators as a potential cause of the fire[1]. The initial field inspection should be able to place the area of fire origin as well as determine the likelihood that various ignition sources were the cause of the fire. From the data collected in the field and following laboratory testing and materials examination, a breach in the cooling unit can be verified and the factors that contributed to the failure can be determined. Material overload failures, fatigue failures, and corrosion failures all have their own unique indicators which can be evaluated by the materials expert. The failure mode can then be used to determine if the breach in the cooling unit occurred before the fire and is therefore the likely cause of the fire, or if the breach was a result of the fire. ●

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