Orion P. Keifer
Peter D. Layson
Charles A. Wensley

Investigating Absorption Refrigerator Fires (Part I)

ATLANTIC BEACH, FLORIDA—In today's recreational vehicles (RV), the most common refrigerator uses absorption refrigeration technology, primarily because this type of system can operate on multiple sources of power, including propane when electrical power is unavailable. These refrigerators have been under intense scrutiny in recent years due to numerous reported fires, apparently starting in the area of the absorption refrigerator. Both the Dometic Corporation and Norcold Incorporated, two manufacturers of RV refrigerators, have been required by the National Highway and Traffic Safety Administration (NHTSA) to recall certain models of refrigerators which have been identified as capable of failing in a fire mode. In summary, the three NHTSA recalls indicate a fatigue crack may develop in the boiler tube of the cooling unit which may release sufficient pressurized flammable coolant solution into an area where an ignition source is present. The NHTSA Recall Campaign ID Numbers are 06E076000 for Dometic *(926,877 affected units)*, and 02E019000 *(28,144 affected units)* and 02E045000 *(8,419 affected units)* for Norcold.

Applications Engineering Group, Inc. (AEGI) has been retained in several cases to help identify components within a RV which may have caused or contributed to a subsequent fire event. Many of these cases have had the fire origin placed in the vicinity of the absorption refrigerator. The purpose of this article is to give fire investigators a better understanding of the inner workings of RV absorption refrigeration systems, and show unique indicators which may be helpful in the investigation of such fires.

Components of The System

The absorption refrigerator cooling unit, which consists of tubes, fins and a small tank, is a sealed system. It is schematically represented in Figure 1. Contained within the cooling unit are four separate chemicals: water (H_2O), ammonia (NH_3), hydrogen (H_2), and sodium chromate (Na_2CrO_4). Ammonia, similar to freon in conventional refrigeration systems, is transported around the unit, giving off heat in some regions and absorbing heat in others. The water, located in the bottom portion of the unit, readily absorbs ammonia when cold and then expels it when percolated in the boiler. It is this action of the water which makes the ammonia flow. The hydrogen in the refrigeration coil maintains a positive pressure of approximately 300-375 PSI (2.07-2.59 MPa) when not in operation and, due to its low partial pressure, promotes the evaporation of the liquid ammonia. It should be noted that unlike conventional refrigeration systems which extensively use copper due to its high thermal conductivity, the tubing in an absorption system is made of steel. The sacrifice in thermal conductivity of steel is required because ammonia is corrosive to copper and copper alloys, while ammonia and steel are relatively stable together. The sodium chromate is a corrosion inhibitor which helps protect the steel from corrosion caused by the water environment.

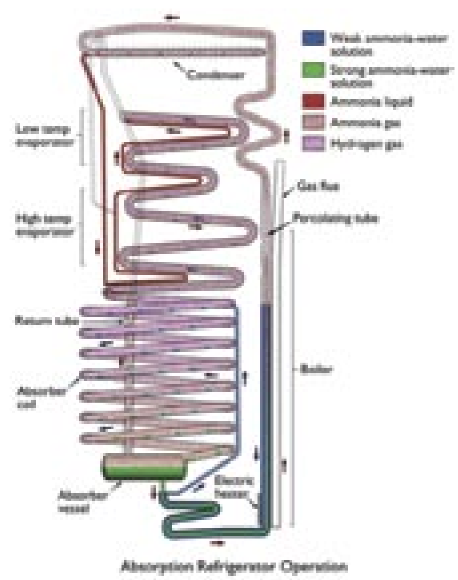


FIGURE 1—The absorption cycle of an absorption refrigerator.

Operation

The boiler region of the refrigerator, which can house one or two electric heating elements and a propane gas burner, provides the main driving force for the circulation of ammonia in the absorption refrigeration cooling unit. It is in this area that heat energy is applied to boil[1] a strong ammonia-water solution up through the percolating tube. This heating process liberates the ammonia from the strong solution into a gaseous state while the percolating action assists with the flow of

1. The percolating or boiling action is primarily due to the ammonia becoming a gas and expanding. The water does not reach its boiling temperature, which is approximately 422° F (217° C) at 300 psig (2.07 MPa) and 442° F (228° C) at 375 psig (2.59 MPa)[1].
2. Similar to water, the saturation temperature of liquid and gaseous ammonia increases with pressure, and the saturation temperature is about 127° F (53° C) at 300 psi (2.07 MPa)[2]. The pressure of the system provided by the hydrogen gas ensures that the ammonia will condense with convective heat transfer to the ambient air.

liquid solution through the boiler region. The majority of the ammonia is now a hot gas which rises to top of the cooling unit, while the weak ammonia-water solution flows by gravity back via the annulus around the percolating tube and then up the weak ammonia-water return tube where it is discharged into the absorber coil to re-absorb ammonia gas. At the top of the cooling unit, the hot ammonia gas from the boiler passes through the condenser at which point heat is removed from the ammonia gas by the cooling effect of natural circulation of the ambient air. As cooling progresses, the ammonia gas condenses into a liquid state[2]. From here, the liquid ammonia flows downward to the evaporator where it is introduced into a region of larger cross-sectional area and greater volume, occupied by hydrogen gas. The increase in volume and relatively low partial pressure associated with the hydrogen gas causes the liquid ammonia to evaporate into a gas and diffuse into the hydrogen rich atmosphere. This change from the liquid state to the gaseous state requires heat energy known as the latent heat of vaporization. This phase change extracts heat from the immediate environment producing a cooling effect. The ammonia, which is now in a gaseous state, moves down to the absorber vessel via the return tube. Ammonia gas not absorbed in the absorber vessel travels up the absorber coil in a direction counter to the weak ammonia-water solution flow. The ammonia gas is absorbed into the returning weak ammonia-water solution, producing a strong ammonia-water solution by the time it enters the absorber vessel. This cyclical process will continue as long as the sealed system has a heat source sufficient to percolate the gaseous ammonia from the strong ammonia water solution. *(See Figure 2 as an example of an absorption refrigerator.)*

FIGURE 2—Rearview of a recalled Dometic RM 2852 absorption refrigerator.

Flammable Components

The ammonia and hydrogen which are contained within this sealed system of the cooling unit are flammable under certain conditions. Hydrogen has an auto ignition temperature around 1040° F (560° C) with flammability limits in air of 7-75 percent[3]. Ammonia has an auto ignition temperature around 1204° F (651° C) with flammability limits of 15-28 percent[4]. Of note, ammonia starts to dissociate into hydrogen at temperatures above 600° F (316° C)[4]. If either the hydrogen or ammonia contained within the sealed system is released within a flammable range in the presence of a competent ignition source, a fire event can occur.

Failure Mode

The recalls for these absorption refrigerators identifies a crack in the cooling unit at the boiler region as the instigation for fire failures. Variables such as boiler mode (electric or gas), boiler temperature, release rate, release direction and available air must be within an appropriate level to produce a fire failure mode. It should be noted that although a boiler failure may initially result in a non-fire event, the reduction in pressure in the system can allow for variables such as release rate to decrease. This is important to understand that in the transient, the pressure decreases, liquid solution is lost and the crack is exposed to thermal expansion and contraction. Therefore, an initial non-fire event failure can produce a fire event as fuel to air ratios change.

The boiler region, as seen in Figure 2, is surrounded by fiberglass insulation and galvanized steel sheet metal. This enclosure most often prevents a visual inspection of the subject area. It is recommended that proper notification, in accordance with ASTM E 860 *Examining And Preparing Items That Are Or May Become Involved In Criminal or Civil Litigation*[5], be sent to potential parties before this inspection is performed.

The Investigation/Inspection

Care should be taken during the investigation of fire related losses to conduct the investigation in accordance with applicable codes and industry standards. Although not a standard, NFPA 921 *Guide for Fire and Explosion Investigations 2004 Edition*[6] has been recognized by most certifying agencies and courts as being the standard of care for the investigation of fire and explosion related losses.

Witness Statements

It is important to interview witnesses as soon as possible. If an absorption refrigerator is determined to be the point of fire origin, a detailed interview should be conducted prior to the witness being bombarded by questions from other interested parties. It is important to establish the facts about the condition and operation of the RV prior to the fire event. Important information includes:

1) Maintenance and repair history
2) Which electrical appliances were 'ON' prior to the fire?
3) Which gas appliances were 'ON' prior to the fire?
4) Was electricity being supplied to the RV, and how?
5) Did the witness smell ammonia?
6) Was the refrigerator cooling properly?
7) Was the refrigerator in automatic or gas mode?

Indicators

There are several indicators that can assist in identifying if an absorption refrigerator cooling unit has been compromised. Many of the indicators can be a result of either a pre or post fire failure, thus it is important to examine all the observed indicators for a particular unit before determining whether the unit is the source of a fire, or conversely, the failure is the result of an ensuing fire.

✱ Presence of Ammonia

Depending on the level of damage to the refrigerator being inspected, an odor of ammonia may be present. The odor can be trapped in the refrigerator or freezer compartments. It is recommended that a wafting motion with the hand be used to check for the presence of ammonia. This should be done cautiously as a high concentration of ammonia may have accumulated and would be a health hazard. Appropriate personal protection equipment should be utilized when working around areas suspected of being contaminated with ammonia.

✱ Presence of Sodium Chromate

Another indicator of a refrigerant leak is the presence of sodium chromate on the exterior of the sealed system. Sodium chromate is a yellow crystalline compound which is very soluble in water. While water and ammonia are normally colorless, the sodium chromate imparts a yellow tint to the water solution. Evidence of yellow residue in the area of the boiler region of the cooling unit before or after a fire event indicates a loss of refrigerant as well as partial de-pressurization of the system. Figure 3 shows the presence of sodium chromate on a recalled Dometic RM 2662.

FIGURE 3—Rear view of a refrigerator in an RV after the refrigerator access panel was removed. Note the yellow residue on the galvanized steel sheet metal and below the incoming propane gas line.

Care must be taken while looking for sodium chromate, as it can be blown and/or wicked away from the original leak site. It has been suggested during some inspections that the yellow residue at the back of the refrigerator could be from other sources, such as a fire extinguisher. At some point in the investigation it may be necessary to have the residue tested for the presence of sodium chromate.

Sodium chromate on the exterior of the cooling unit indicates a release of liquid water and sodium chromate solution from the unit. At some point the source of the leak must be identified and analyzed to determine its relevance in the investigation.

✱ Thermal Stress

Evidence of isolated thermal stress to the galvanized steel sheet metal in the area of the boiler indicates an abnormal thermal event. Closer examination of the heat affected area normally reveals a radial heat pattern. See Figure 4 for an example of localized zinc discoloration.

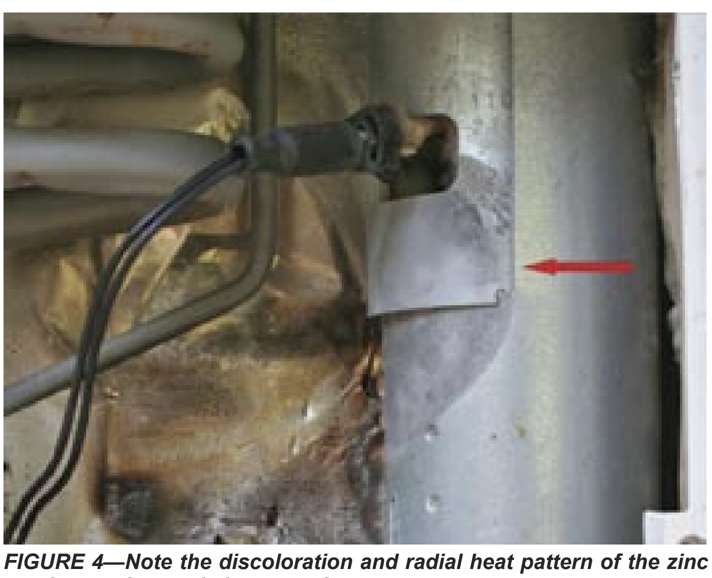


FIGURE 4—Note the discoloration and radial heat pattern of the zinc coating on the steel sheet metal.

✱ Cooling Unit Ruptures

If the cooling unit exhibits a rupture at a location where it does not have a known heat source, this indicates an external fire was the cause of that damage. Importantly, the entire cooling unit is under the same pressure: however, metals lose yield strength with increasing temperature. A rupture that occurs at a site without a known heat source indicates an external fire caused the steel in that location of the cooling unit to rise in temperature and weaken until the pressure inside the cooling unit exceeded its wall strength. Figure 5 shows a rupture in the upper portion of a Dometic cooling unit which was caused by an external fire.

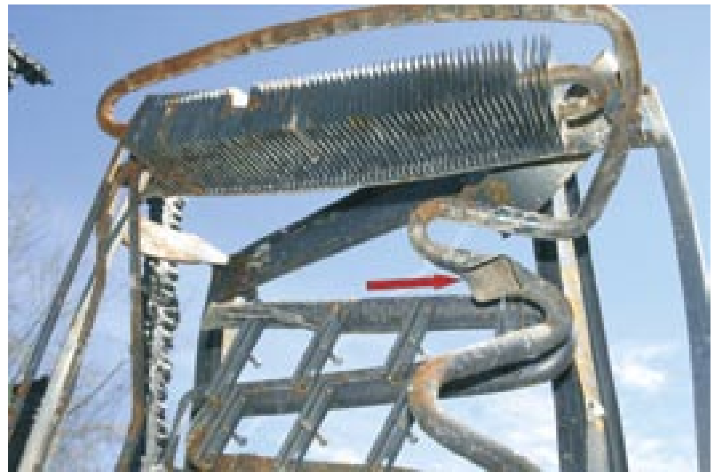


FIGURE 5—Rupture of the cooling unit involved in a complete RV burn. This unit had maintained pressure up until the point where a fire weakened an area of the cooling unit sufficiently to yield catastrophic failure.

✱ Dissolution of Steel into Molten Aluminum

Molten aluminum in contact with steel at elevated temperatures will cause the iron to dissolve, with what appears to be a melting pattern. Interestingly, the aluminum-iron mixture can stay molten below the melting point of both pure aluminum and pure iron, because of the eutectic in the equilibrium phase diagram. Some fire investigators familiar with the phenomenon call it “the eutectic reaction”, which is technically incorrect terminology. It is better to refer to this as dissolution of iron into molten aluminum.

It is common to see the dissolution of steel components when molten aluminum falls on the steel surfaces. The steel surfaces must be at temperatures in the range of the molten aluminum for the dissolution process to occur. This has been observed many times on the condenser fins and coil of cooling units as seen in Figure 6. This can occur with or without pressure in the system reducing its helpfulness

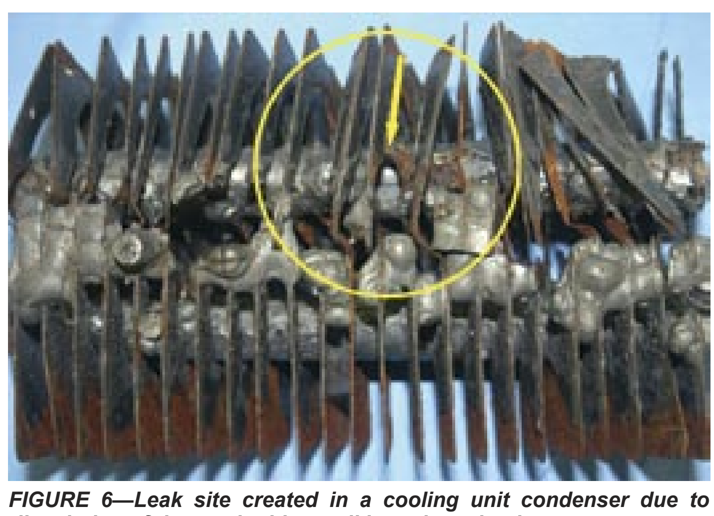


FIGURE 6—Leak site created in a cooling unit condenser due to dissolution of the steel tubing wall in molten aluminum.

in determining whether the refrigerator caused the fire. It can, however, be misleading to a fire investigator unfamiliar with this interaction.

✱ Over Temperature Relief Plug

Absorption refrigerators have a built-in temperature relief plug made of a tin-bismuth alloy. The purpose of this plug is to blow out if exposed to abnormally high temperatures, causing the cooling unit to depressurize instead of undergoing a catastrophic rupture in an unknown area. This particular alloy is used because it has a low melting temperature, with a eutectic temperature of 281° F (138° C)[7]. On Dometic units, this plug is located on the absorber vessel and oriented away from the boiler region of the cooling unit, as in Figure 7. Figure 8 shows the Norcold unit design, and the plug is located higher up on the absorber coils and is also oriented away from the boiler region of the cooling unit. If the plug is observed to be "blown out", with little heat/fire damage in the area of the plug, then it was likely exposed to temperatures higher than normal operating temperatures produced by an attacking fire. Fire patterns must be analyzed to determine how an attacking fire reached the blow plug.

FIGURE 7—Shows the relief plug on the absorber vessel of a Dometic RM 3862 refrigerator unit which has been "blown out."

FIGURE 8—Shown is the still intact relief plug of a Norcold N621 refrigerator unit which is located at the top of the absorber coils.

Additional Testing and Analysis

Additional testing and analysis of the refrigerator requiring disas- sembly may need to be performed at an appropriate testing facility. If litigation is anticipated it is strongly recommended that appropriate notification be given to potential parties prior to conducting the following inspections.

✱ Field Pressure/Leak Test

Many times a field pressure test of the cooling unit can be performed to identify if a leak is present. This test should only be performed in the presence of all interested parties. In some cases multiple leak sites may be identified in different areas of the cooling unit. Each penetration must be examined to determine when it occurred *(i.e. pre or post fire)*. It has been observed on a few occasions that during the field pressure test, some boilers do not leak in the area of the cracks due to thermal contraction and clogging after a fire event. In some cases, these units will maintain positive pressure after a failure event. Further pressure/leak testing requiring the removal and isolation of sections of the cooling unit may need to be performed.

✱ Examination and Testing of the Propane System

If the refrigeration unit is connected to a propane supply, attention should be given to the gas delivery system of the RV. A regulated pressure as well as a leak test should be performed prior to the removal of the refrigeration unit when possible. It may be necessary to isolate areas of the gas system due to damage prior to testing. An inspection of the refrigerator's flare connection at the control valve and visible burner assembly should be performed in the field. Additional inspection of the gas system requiring disassembly of the burner components such as the orifice, burner jet and valve may also need to be performed.

✱ Materials Examination

In many cases a single indicator may not be enough to conclusively identify a particular failure mode. Further metallurgical analysis may be necessary to identify the exact mode of failure. This is especially true when damage to the unit is inconsistent with the recall.

SUMMARY

Due to the large number of recalled RV absorption refrigerators, if it has been identified that the area of fire origin is consistent with originating at the RV refrigerator, due care should be taken to handle the investigation in a manner that will maintain the integrity of the fire scene until appropriate notification has been made to all parties potentially involved ASTM E860[5]. Evidence of sodium chromate and isolated thermal stress in the area of the boiler would suggest that subsequent forensic inspections be conducted with all parties involved in the manufacturing, installation and maintenance of the unit present. Due to the economics involved in pursuing a product defect it is important that the preliminary investigation and subsequent inspections be performed in a manner that does not compromise the integrity of the case. ●

REFERENCES

[1] Keenan, Joseph H., and Keyes, Frederick G., *Thermodynamic Properties of Steam*. New York: John Wiley & Sons, Inc., 1936.

[2] Department of Commerce. Circular of the Bureau of Standards No. 142. *Tables of Thermodynamic Properties of Ammonia*. Washington: Government Printing Office, 1923.

[3] Babrauskes, Vytenis. *Ignition Handbook*. Issaquah: Fire Science Publishers, 2003.

[4] International Institute of Ammonia Refrigeration, *Ammonia Data Book*, Arlington, Virginia 1993.

[5] ASTM E 860 – 97 (Reapproved 2006) *Examining And Preparing Items That Are Or May Become Involved In Criminal or Civil Litigation*

[6] *NFPA 921 Guide for Fire and Explosion Investigations* 2004 Edition

[7] *Binary Alloy Phase Diagrams*. Ed. T.B. Massalski, Materials Park: ASM International, 1986, 540.

ABOUT THE AUTHORS

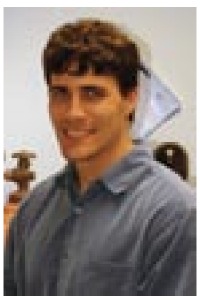
ORION P. KEIFER, P.E.

Mr. Keifer is a principal mechanical engineer at Applications Engineering Group, Inc. (AEGI) since its founding in 1994. He graduated from the US Naval Academy with a Bachelor of Science in Mechanical Engineering in 1973, from the Naval Postgraduate School with a Masters of Science in Mechanical Engineering in 1984 and from Lynn University with a Masters of Science in Biomechanical Trauma in 2000. He completed 21 years of active commissioned service in the US Navy, specializing in Naval Nuclear Power retiring in 1994. His expertise includes an extensive background in thermodynamics, heat transfer, materials, mechanics and collision physics. He is a professional engineer, registered in California, Florida, Georgia and Alabama.

PETER DAVIS LAYSON

Mr. Layson is a principal staff scientist at Applications Engineering Group, Inc. (AEGI) since 2000. He holds a Bachelor of Science in Applied Physics along with a Minor in Mathematics from Jacksonville University, Jacksonville, Florida. During this time he has examined and analyzed over a thousand cases involving electrical and gas related issues. Along with his normal case load, Mr. Layson finds himself actively involved in research and testing at AEGI, as well as with other private and public agencies. His specializations include causation and contributing factor determination of electrical and gas systems.

Professional Societies and Certificates: International Association of Arson Investigators (IAAI); Evidence Photographer International Council (EPIC); Florida Advisory Committee on Arson Prevention (FACAP), Director; National Fire Protection Association (NFPA); American Boat and Yacht Council (ABYC), Certified Marine Electrical Technician; National Association of Fire Investigators (NAFI), Certified Fire and Explosion Investigator



CHARLES A. WENSLEY, E.I.T.

Mr. Wensley is a staff materials engineer at Applications Engineering Group, Inc. (AEGI). He graduated from Clemson University with a Bachelor of Science in Ceramic Engineering in 2003, and from Virginia Tech in 2005 with a Masters of Science in Materials Science and Engineering. His areas of expertise include thermodynamics, heat transfer, material properties, material failure modes, corrosion, amorphous metals and composite properties and design.