

# Fluid Solutions

A Heat Transfer Fluid Magazine

Edition 1, December 2015

Inaugural  
Edition

The History of **Refrigeration**

See the next page to know  
more about the cover

Common Types of **Corrosion**  
in Heat Transfer Fluid Systems

Maintaining Low Electrical Conductivity  
of Coolants for **Electronics Cooling**

**DYNALENE**  
Tomorrow's Solutions Flow Through Us

# Commentary

## Why A Heat Transfer Fluid Magazine?

Heat transfer fluids are important components of many industrial processes. We, here at Dyalene, have long been thinking about having a magazine dedicated to these fluids. There is no academic curriculum that teaches the science and engineering of heat transfer fluids. Therefore, we have decided to cover topics that are relevant to a heat transfer system using a fluid, but not covered in a typical Heat Transfer or Fluid Mechanics course in an undergraduate engineering curriculum.



We have named the magazine “Fluid Solutions” and this is the inaugural edition. At this moment, we are only planning to publish once a year in December. However, in the future, depending on the availability of topics, authors and research work in our labs, we may increase the frequency to twice a year, with a summer edition in June.

In this inaugural edition, you will find three review articles, a research paper, and a section called “Ask the Experts”, where we have covered several questions that are frequently asked by our customers. Throughout the magazine, we have tried to incorporate certain “Fun Facts” related to the topics covered. We hope that the readers will enjoy reading these facts.

The articles in this edition cover topics related to cooling and low temperature heat transfer fluids. There is a review article discussing the history of refrigeration, and how the world has arrived at the current primary and secondary refrigerants (low temperature heat transfer fluids). Another review article discusses different types of corrosion that are common in a heat transfer fluid system and ways to control the corrosion before it ruins the system. The pros and cons of nano-fluids are discussed in another short review article that may throw some light on the future of heat transfer fluid technology. The research paper on liquid coolants for electronics cooling discusses experimental results pertaining to maintaining low electrical conductivity of a water-based coolant using ion-exchange cartridges.

Please enjoy reading the articles and have a wonderful holiday and a prosperous new year 2016.

Sincerely,

A handwritten signature in black ink, appearing to read 'S. Mohapatra'.

Dr. Satish Mohapatra, President & CEO, Dyalene

## About The Cover



Tardigrades, also known as water bears, are tiny 1.5 mm invertebrates that live in aquatic and semi-aquatic habitats which mostly feed by sucking the juices from moss, lichens and algae. They are perhaps the most durable of known organisms as they are able to survive extreme conditions. They can withstand temperature ranges from  $-458^{\circ}\text{F}$  ( $-272^{\circ}\text{C}$ ) to  $300^{\circ}\text{F}$  ( $149^{\circ}\text{C}$ ), pressures about six times greater than those found in the deepest ocean trenches, ionizing radiation at doses hundreds of times higher than the lethal dose for a human, and the vacuum of outer space. They can go without food or water for more than 10 years, drying out to the point where there is less than 3% water in their body.

These tardigrades were attached to a satellite and blasted into space in 2007. Scientists found that many of the tardigrades had survived the harsh condition after the satellites returned to the earth. In fact, some of the females had even laid eggs in space, and the newly-hatched young were healthy. Over 900 different tardigrade species have been discovered and fossils of them are dated to the Cambrian period over 500 million years ago, when the first complex animals were evolving. Ever since they were discovered in 1773, it has been clear that they are special.

*Image credits: Eye of Science / Science Source*

*Source: <http://www.bbc.com/earth/story/20150313-the-toughest-animals-on-earth>*



# Fluid Solutions

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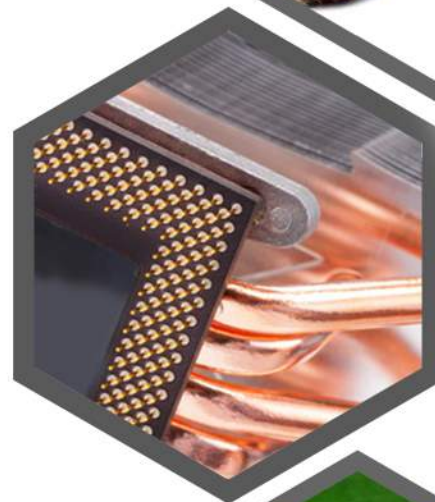
Numerous questions from our customers are answered by our experts everyday. Here are a few.



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## Review

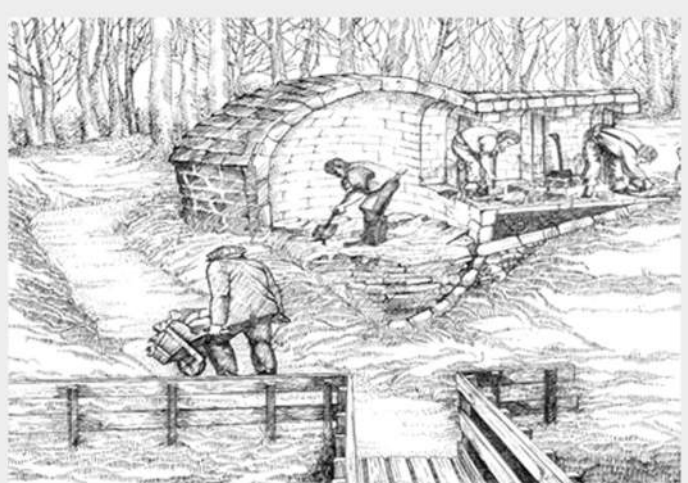
# The History of Refrigeration

by Kevin Coscia, Research Engineer, Dynalene

## The Ice Trade

Prior to the invention of mechanical refrigeration, just being able to enjoy a cold beverage or preserving food for several days was challenging. The Ancient Egyptians would cool water by putting earthen jars filled with water on their roofs at night. Periodically they would moisten the outside of the jars, and as the water on the outside evaporated, the water inside the jar would cool. The Persians mastered the technique of preserving ice in the desert summer by storing the ice in large chambers called Yakhchals, utilizing insulation and clever wind traps to keep the ice cold. During the winter, they would channel water from the mountains along a wall aligned from east to west, keeping the water in the shade of the wall so it would cool faster and be nearly frozen by the time it reached the Yakhchals.

Sometimes an “icehouse” was just a hole dug a few feet in the ground, lined with woodchips or hay, and filled with snow or chunks of ice. If you lived in a northern climate where you readily had access to snow or frozen ice atop a pond, you could harvest it to continually replenish your ice supply. But for others in warmer climates, ice had to be shipped down from New England or New York, which was expensive.



*An artist's rendition of an ice house.*

Frederic Tudor, dubbed the so-called “Ice King,” was the first to commercialize and pioneer the ice trade in the early 1800s. Food storage and icehouses became much more prevalent as the United States began to expand and people moved farther away. Daily trips to the butcher or market were not as practical, and people needed ways of storing meat and perishables for several days before they would spoil. Tudor thought that he could capitalize on this growing market, with dreams of shipping ice to the southern states and even the Caribbean. His first venture

in 1799 was a costly learning experience after attempting to ship ice from New York to South Carolina, as almost all of the ice melted by the time it arrived [1].

To prevent the ice from melting, Tudor experimented with different insulating techniques and established several icehouses in South Carolina, Virginia, and even the Cuban port town of Havana. He was able to cut his melting losses from 66% to a remarkable 8%. Tudor also partnered up with Nathaniel Wyeth who invented a horse-drawn ice cutter in 1825, replacing handheld pickaxes and saws and increasing ice harvesting productivity. These advances allowed the ice industry to flourish, and ice was soon seen as a commodity rather than a luxury. In the early 1830s the price of ice dropped from 6 cents per pound to half of a cent per pound. In the northeast, regions such as New York City and Boston saw their ice consumption increase almost ten fold over the next few decades [2].

With the rapid expansion of the ice trade however, complications would arise. Ice that was scraped from clean ponds and rivers was being consumed so quickly that ice harvesters had to look in areas that were less than sanitary. By the 1870s pollution and sewage began to creep into fresh bodies of water, and with the rise of germ theory health concerns started to sweep the country over tainted ice.

The beer brewing industry, the largest user of ice, was the first industry to be severely affected. With the arrival of German lager in the 1840s, Americans started to prefer the taste of lager brought over from German immigrants over the taste of American Ale. The boom in the beer industry led to massive consumption of tainted ice and media outlets began to release articles linking the ice to the spread of typhoid fever. Ice harvesting was deemed illegal in some parts of the US by the early 1900s, which significantly increased the demand for clean ice production by mechanical refrigeration. [1]

## The Birth of Mechanical Refrigeration

The earliest work of mechanical refrigeration originated from work in the 1750s by William Cullen, a Scottish physician and chemist. In 1755, Cullen created a small refrigerating machine by creating a partial vacuum over a container of diethyl ether. As the pump reduced the pressure in the container, the diethyl ether boiled, absorbing heat from the surrounding air and creating ice on the outside of the container. Unfortunately for Cullen, his machine had no commercial applications at the time. [3]

By 1758, Benjamin Franklin and John Hadley, a chemistry professor, worked on a project to investigate the principle of refrigeration at Cambridge University in England. They





**A horse-drawn ice cutter scraping ice off a river in Toronto, Canada, circa 1890.**

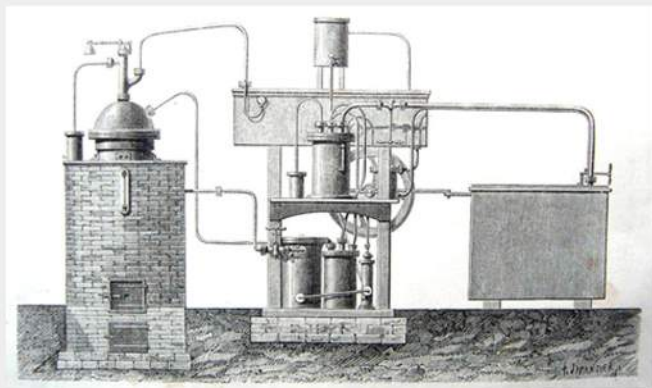
experimented by evaporating ether using bellows to quicken the process and successfully reduced the temperature of a mercury bulb down to 8°F when the outside air was 70°F. As the temperature dropped to 32°F, they noticed a thin film of ice forming around the outside of the mercury bulb, and when the experiment was finished they had achieved a layer of ice almost one quarter inch thick [4].

In 1805, American inventor Oliver Evans designed the very first vapor-compression refrigeration machine. His design focused on first compressing a gas and cooling it through coils, and then expanding the gas to absorb heat from the surrounding environment. Research on refrigeration was also conducted by English scientist Michael Faraday in the 1820s, as he was the first to liquefy ammonia using high pressures and low temperatures. His work would eventually lead to the adoption of the gas absorption refrigeration system using gaseous ammonia dissolved in water [5].

In 1842, American physician John Gorrie built a similar working prototype of a vapor-compression refrigeration machine to cool down ill patients from tropical heat which he believed led to the spread of disease and malaria. Gorrie's machine was capable of cooling air and water to produce ice, but was a commercial failure. Ferdinand Carré of France expanded on Gorrie's work and would develop the first water-ammonia refrigeration machine in 1859, patenting it in 1860 [6]. Carré's machine was used to

produce ice for New Orleans during the Civil War as southern states could no longer get ice from the ice trade up North.

Carl von Linde, an engineer and professor at the Technological University of Munich in Germany, primarily specialized in steam locomotives but took an interest in refrigeration in the 1860s. His goal was to provide year-round refrigeration for the production of lager, and by 1876 he patented an improved method of liquefying gases such as ammonia, sulfur dioxide, and methyl chloride. These gases, otherwise known as refrigerants, would be widely used for the next several decades. In 1879, Linde founded Gesellschaft für Lindes Eismaschinen Aktiengesellschaft ("Linde's Ice Machine Company"), now Linde AG, in Wiesbaden, Germany, and by 1890 he had sold 747 refrigeration machines. His machines were found in breweries, slaughterhouses, and cold storage facilities throughout Europe. By 1892, Linde would receive an order from the Guinness brewery in Dublin for a carbon dioxide liquefaction plant, vaulting Linde into the field of low-temperature refrigeration. This would eventually lead to the development of a process for the liquefaction of air and fractional distillation to obtain pure oxygen and nitrogen. [7]



**Ferdinand Carré's ice machine.**

Because of the advances in mechanical refrigeration, breweries could continuously create large quantities of lager year round. One of the first breweries to use a mechanical refrigeration system was S. Liebmann's Sons Brewing Company in Brooklyn, New York in 1870. Over the next few decades almost every brewery would be using a mechanical refrigeration machine. Refrigeration was then adopted to service the meat packing industry by freezing meat supplies and providing cold storage locations.

## DID YOU KNOW?



Within cold storage warehousing, specialized techniques can be employed. For example, Chelan Fruit Cooperative in Washington houses millions of pounds of apples far beyond the harvest date. The apples are harvested and before they are boxed, they can stay in a sealed room for months. This technique is called controlled atmosphere storage and the oxygen in the room is replaced with nitrogen. By keeping the room at a chilly 34°F, it halts the apple's ripening process almost completely. This allows fresh apples to be available throughout the year.

Source: <http://www.southwestvault.com/9-fascinating-things-you-didnt-know-about-cold-storage/>



Packing plants in Chicago were some of the first to use the new refrigeration technology, with almost all of the plants using ammonia refrigeration systems. By 1914, the refrigeration machines were placed on train cars to keep meats cool during transportation to different regions of the US. Fruits, vegetables, perishable food, and other temperature sensitive chemicals were also shipped using these refrigerated trains [8].

### The Rise and Fall of CFCs

There were some significant hazards associated with these mechanical refrigerators. Older versions of mechanical refrigerators used toxic gases like ammonia, methyl chloride, and sulfur dioxide. There were many deaths due to leaked gases since the advent of mechanical refrigeration, including machines that used methyl chloride. Methyl chloride is an extremely flammable gas with a very mild sweet odor that can be difficult to detect until toxic levels are reached. Some of these refrigerants were also very flammable which would leak and cause explosions and fires. To be safe for home use, the refrigerant technology had to be improved.

In the 1890s, Frédéric Swarts was the very first to synthesize chlorofluorocarbons. The compound was nonflammable and generally non-toxic. By the 1920s a research team led by Charles Kettering was formed in General Motors to create a safer refrigerant alternative [9]. After devising a refrigerating system that used the new CFC gas, a patent was issued to Frigidaire, which at the time was a subsidiary of General Motors. During this time the only household refrigerator that was being used was the Monitor Top, developed by GE. The Monitor Top, so-called because of the resemblance to the gun turret aboard the ironclad warship USS Monitor, used either sulfur dioxide or methyl formate refrigerants, which were either irritating to the eyes or very flammable [10]. The new development of CFCs by Swarts and Kettering would usher in a new era of safer refrigerators for home use.

By 1930 GE soon had a competitor for the household refrigeration market. General Motors collaborated with DuPont to create Freon, otherwise known as dichlorofluoromethane. With the arrival of Freon, smaller, cheaper, and safer refrigerators could be produced for household use. By the early 1930s the average price of a refrigerator dropped from \$275 to \$150 after the invention of Freon. More than half the households in the US would have a refrigerator by 1935.

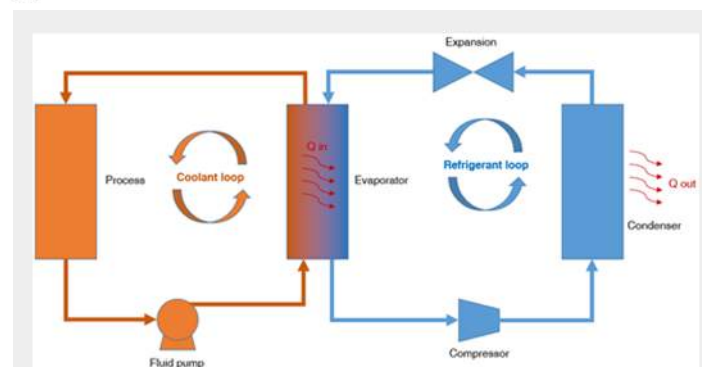
After World War II, separate freezer units, popularly known

at the time as “deep freeze” units, went into production and began to include units like automatic ice makers and defrosters. A few decades later the efficiency of these units would drastically improve, however the use of Freon and its detrimental impact on depleting the ozone layer became known [2].

The ozone layer plays a vital role in protecting the earth’s surface from harmful ultraviolet radiation, and these CFCs were found to react with atmospheric ozone. By 1989, The Montreal Protocol on Substances that Deplete the Ozone Layer was enforced, banning any compounds that are responsible for ozone depletion. Other refrigerant compounds based off fluorocarbon chemistries have since been devised that are not as harmful to the ozone layer, but all are under strict control under the Kyoto protocol.

### Refrigeration and Secondary Coolants

Refrigeration and secondary coolant systems are widely used in conjunction with each other in industrial applications because they allow for efficient heat transfer at low temperatures. Today, the most widespread use of refrigerating machines is in air conditioning and refrigerating food. Residential refrigeration generally only involves the cooling of air – such as the air that enters your refrigerator or is used in HVAC systems. For large-scale industrial processes that deal with great amounts of heat transfer, a liquid must be used to control the process temperature. One common example of this is an ethylene glycol-water mixture used to freeze water in an ice rink.



**A typical refrigerant loop coupled with a secondary coolant loop. Heat from the secondary coolant is transferred into the refrigerant in the evaporator.**

Ethylene glycol is one of the most widely used heat transfer coolants because it delivers efficient heat transfer and provides antifreeze-like properties in solution, allowing the coolant to be circulated at very cold temperatures. It was first prepared by the French chemist Charles-Adolphe Wurtz in 1859 for use as a coolant and an ingredient in explosives, and widespread industrial production began after World War I. Wurtz originally synthesized ethylene glycol by reacting ethylene iodide with silver acetate, and then treated the reaction product with potassium hydroxide. He named the product ethylene glycol as it was midway between ethanol and glycerin [11]. The introduction of ethylene glycol around this period was revolutionary in



advancing aircraft design because the ethylene glycol-water solutions allowed for smaller radiators aboard planes. An ethylene glycol-water mixture has a higher boiling point than water alone, and this allowed the coolant to operate at higher temperatures which reduced the radiator's required surface area and weight. Using a smaller coolant system allowed for an increase in the plane's fuel efficiency and reduced the coolant system's exposure to gunfire.

Larger-scale industrial processes may also use glycols or more efficient salt-brine solutions, like calcium chloride or potassium formate, to control low-temperature processes. Brines are generally more efficient compared to glycol-based fluids because they have more desirable properties such as low viscosity, high thermal conductivity, and high specific heat. These three properties are very important in fluid heat transfer. A fluid with a low viscosity has many benefits when operating at cold temperatures, such as improved heat transfer and easier pumping during cold starts.

Secondary coolants with refrigeration systems are widely used throughout various industries to offer excellent heat transfer for low temperature applications. Coolant technology has changed significantly from prior decades, with new coolants offering safe, non-toxic, and non-flammable heat transfer. In the past, toxic and flammable chemicals such as methyl chloride resulted in many health and fire hazards during leaks and spills, but now many of these systems have been retrofitted to allow for safer, water-based coolants that mitigate these hazards.

## Past to Present

In Henry David Thoreau's classic *Walden Pond*, he remarked, "it appears that the sweltering inhabitants of Charleston and New Orleans, of Madras and Bombay, and Calcutta, drink at my well." What he implied is that the very same ice scraped and chiseled from Walden Pond would travel to the far reaches of the earth out of Boston Harbor

to chill drinks. [12] Refrigeration has come quite a long way since the days of Frederic Tudor shipping ice from the icy barrens of New York and New England, and Cullen and Franklin and Hadley watching ice grow on the outside of a thermometer bulb. The refrigerator has spent the past century keeping meat fresh and milk from spoiling and giving people a break from summer heat, and that makes the refrigerator one pretty cool invention.

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## HOW LONG DOES YOUR FOOD LAST IN A REFRIGERATOR?

Product	Refrigerator 40 °F (4.4 °C)	Freezer 0 °F (-17.7 °C)
Eggs, fresh, in shell	3 to 5 weeks	Do not freeze
Eggs, raw yolks & whites	2 to 4 days	1 year
Eggs, hard cooked	1 week	Does not freeze well
Mayonnaise, refrigerate after opening	2 months	Do not freeze
Frozen dinners & entrees. Keep frozen until ready to heat	—	3 to 4 months
Hot dogs, opened package	1 week	1 to 2 months
Hot dogs, unopened package	2 weeks	1 to 2 months
Bacon	7 days	1 month

Product	Refrigerator 40 °F (4.4 °C)	Freezer 0 °F (-17.7 °C)
Sausage, raw — from chicken, turkey, pork, beef	1 to 2 days	1 to 2 months
Fresh poultry, chicken or turkey, whole	1 to 2 days	1 year
Fresh poultry, giblets	1 to 2 days	3 to 4 months
Cooked meat & meat casseroles	3 to 4 days	2 to 3 months
Gravy & meat broth	3 to 4 days	2 to 3 months
Fried chicken	3 to 4 days	4 months
Chicken nuggets, patties	3 to 4 days	1 to 3 months
Pizza, cooked	3 to 4 days	1 to 2 months

Source: <http://www.fsis.usda.gov/>



## Research Spotlight

# Maintaining Low Electrical Conductivity of Liquid Coolants for Electronics Cooling

by

Bojana Shantheyanda, Research Engineer, Dynalene

Sreya Dutta, Material Scientist, Dynalene

Kevin Coscia, Research Engineer, Dynalene

David Schiemer, Engineer, Phoenix Electric Corporation

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## 1.0 Background

Electronics are involved in practically every aspect of modern life. The introduction of the integrated circuit (IC), where several components such as diodes, transistors, resistors, and capacitors are placed on a single chip, revolutionized the electronic industry. The number of components packed in a single chip has increased steadily to Giga-Scale Integration (GSI) today with over a billion components per chip [1]. With a decrease in size of electronic components, there has been a dramatic increase in the amount of heat generated per unit volume, jeopardizing the safety and reliability of the electronic equipment. The failure rate of electronic components is doubled for every 10°C increase in operating temperature. Therefore, thermal control has become increasingly important in the design and operation of electronic equipment [2].

Air cooling has been the preferred cooling technique for electronics packages for decades. Combinations of natural, forced and mixed convection air cooling methods are still popular in most applications due to their simple design, low cost, easy maintenance, and high reliability [3]. However, air cooling is less effective compared to liquid cooling due to its low thermal conductivity and ineffective convective cooling. Additionally, air has a low density and low specific heat compared to liquids. This diminishes its thermal capacitance and hence, lessens its ability to store thermal energy without incurring unacceptable temperature rise [4].

A combination of fan and dedicated heat sink for CPU cooling is expected to accommodate a heat flux of about 50 W/cm<sup>2</sup> [5].

## 1.1 Liquid cooling

Liquid cooling is used in applications involving power densities that are too high for safe dissipation by air

cooling. With much higher thermal conductivity and specific heat than gases, liquids have much higher heat transfer coefficients [1]. Using high velocities and high pressures, liquid cooling can be used to remove heat up to 200 kW/cm<sup>2</sup> [5]. Liquid cooling can be classified into different techniques. Some of the techniques are:

## 1.2 Single and two phase liquid cooling

A single phase cooling loop usually consists of a pump, a heat exchanger (cold plate/mini or micro-channels), and a heat sink (radiator with a fan or a liquid to liquid heat exchanger with chilled water cooling) [6]. In two phase cooling, a phase change of the working coolant is used to absorb thermal energy from the electronic circuit [7]. Some two phase cooling applications are heat pipes, thermosyphons, vapor chambers, sub-cooled boiling, spray cooling, and direct immersion systems [7, 8, 9].

## 1.3 Active and passive liquid cooling

In passive cooling, external energy is not applied to remove heat from the electronics. Examples of these systems are heat sinks with fins, phase change systems, high conductivity chassis and heat pipes. In an active cooling system, external energy is used to remove heat from the electronics. This system can help maintain the chip junction temperature independently of the ambient air temperature. Examples of these systems are pumped liquid cooling, pumped phase change systems and vapor compression systems.

## 1.4 Indirect and direct liquid cooling

Liquid cooling, which can be achieved using indirect or direct means, is utilized in electronics applications having thermal power densities that may exceed safe dissipation through air cooling. Indirect liquid cooling is where heat dissipating electronic components are physically separated from the liquid, whereas in the case of direct cooling, the components are in direct contact with the liquid coolant [4]. Most desirable liquid coolants for electronics cooling applications have good thermophysical properties, high flash points and auto ignition temperatures, compatibility with the materials of construction, good chemical and thermal stability, are inexpensive and nontoxic and have a long shelf life. Good thermophysical properties for liquid coolants are required in order to obtain higher convective heat transfer coefficients and reduce pumping power [10]. Deionized water is a good example of a widely used electronic coolant for indirect cooling applications. Other popular non-dielectric coolant chemistries used in indirect cooling applications are propylene glycol, ethylene glycol, ethanol/water, calcium chloride solution, potassium formate/acetate solution and liquid metals such as an alloy of gallium, indium and tin (Ga-In-Sn) [10].

## 1.5 Electrical conductivity in indirect, single phase active liquid cooling

The electrical conductivity of a liquid coolant becomes important in a direct cooling application because of the



direct contact between the coolant and the electronics [11]. In indirect cooling applications, electrical conductivity can be important if there are leaks and/or spillage of the fluids onto the electronics. In indirect cooling applications where water based fluids with corrosion inhibitors are generally used, the electrical conductivity of the liquid coolant mainly depends on the ion concentration in the fluid stream. The higher the ionic concentration, the larger the electrical conductivity of the fluid. The increase in the ion concentration of a closed loop fluid stream may occur due to ion leaching from metal and nonmetal components that the coolant is in contact with. During operation, the electrical conductivity of the fluid may increase to a level which could be harmful for the cooling system. Ion exchange resin can be used to remove the ionic substances that raise the electrical conductivity of the coolant in an electronics cooling application. These resins are polymer beads that are capable of exchanging their own ions with the ions in the coolant fluid.

In the present work, ion leaching tests were performed with various metals and polymers in both ultrapure deionized (DI) water (water which is treated to the highest levels of purity) and a low electrical conductivity ethylene glycol/water mixture, with the measured change in conductivity reported over time. Additionally, changes in the electrical conductivity of ultrapure DI water in an indirect, single phase, active cooling loop, with and without ion exchange resin, are characterized with the findings reported. Finally, recommendations for design and estimation of the longevity of the ion exchange resin cartridge in an electronics cooling loop are discussed.

## 2.0 Experimentation

In this section, the experimental setup for measuring coolant electrical conductivity in both the ion leaching and closed loop indirect cooling experiments is described.

### 2.1 Long-term ion leaching experiment

The experimental setup used for the long-term ion leaching analysis is shown in Figure 1. The experiment was performed using aluminum (AL3003), brass (B5665), stainless steel (304L), high-density polyethylene (HDPE), polypropylene, nylon, polyvinyl chloride (PVC), nitrile rubber (Buna-N), polyurethane and silicone samples immersed in:



**Figure 1.** Long-term ion leaching experimental setup.

- 1) Ultra-pure distilled water (UP-H<sub>2</sub>O) with an electrical conductivity of 0.5 μS/cm, and
- 2) Premade mixture of 50:50 ethylene glycol and UP-H<sub>2</sub>O, and nonionic inhibitors ( EG-LC).

The fluid and test sample were placed in a polytetrafluoroethylene (PTFE) container which was cleaned with distilled water, alcohol and UP-H<sub>2</sub>O and dried in ambient atmosphere. PTFE containers were chosen over borosilicate glass because they contain strong, compact bonds which are excellent at maintaining their original crystallinity, therefore exhibiting less ion leaching into the base fluid. The containers were charged with either UP-H<sub>2</sub>O or EG-LC. Metal and polymer coupons were rinsed with distilled water, alcohol and UP-H<sub>2</sub>O and polished to remove excess surface debris. The materials were placed in the containers and sealed with PTFE thread tape and PTFE lids. The samples were allowed to equilibrate at room temperature for two days before recording the initial electrical conductivity. In all tests, fluid electrical conductivity was measured to an accuracy of ±1% using Oakton® CON 510/CON 6 Series meter which was calibrated prior to each measurement. A furnace was preheated to 80°C in ambient atmosphere and verified for heating uniformity to ±1°C at different locations, i.e. from the wall heating coils to the center of the furnace. The PTFE sample containers were placed in the furnace when steady state temperature was reached. The test setup was removed from the furnace every 168 hours (seven days), cooled to room temperature, and the electrical conductivity of the fluid was measured. The time for the samples to cool, be measured, and placed back in the oven was generally less than four hours. The electrical conductivity of each fluid sample was monitored for a total of 5000 hours (~208 days).



## DID YOU KNOW?

An average human being dissipates 350 kJ of energy per hour, which is equivalent to a 100 Watt light bulb. There is a common myth that the majority of our body heat is released through our head. But the fact is the head only represents about 10% of the body's total surface area. So if the head were to lose even 75% of the body's heat, it would have to lose about 40 times as much heat per square inch as every other part of your body, which is unlikely. The real reason we lose heat through our head is because most of the time when we're outside in the cold, we're clothed.

Source: <http://www.physlink.com/>, <http://www.webmd.com/>



## 2.2 Closed loop, indirect cooling experimental set-up

A schematic of the experimental setup is shown in Figure 2. Table 1 lists the components used with which the coolant made direct contact. Before commencing each experiment, the test setup was rinsed with UP-H<sub>2</sub>O several times to remove any contaminants. The system was loaded with 230 ml of UP-H<sub>2</sub>O and was allowed to equilibrate at room temperature for an hour before recording the initial electrical conductivity, which was 1.72 μS/cm. Fluid electrical conductivity was measured to an accuracy of ±1%. After the initial measurements, the copper cooling block was placed on a hot plate operated at 80°C. During operation the fluid reservoir temperature was maintained at 34°C. The change in fluid electrical conductivity was monitored for 136 hours. The fluid from the system was collected and stored.

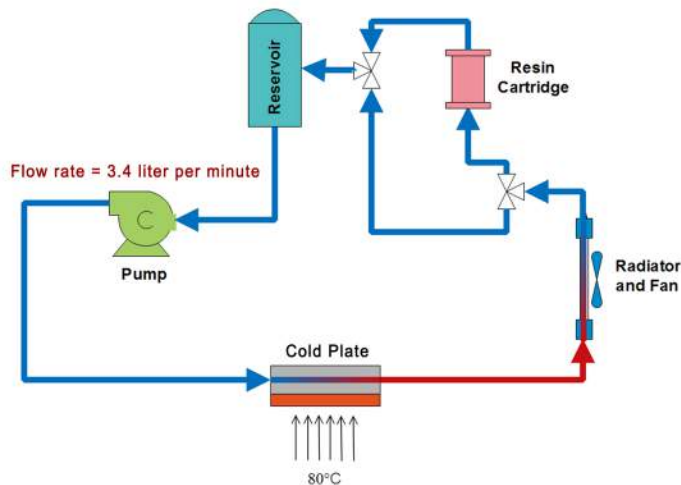


Figure 2. Schematic of the indirect closed loop cooling experiment set-up.

Similarly, the closed loop test with ion exchange resin was carried out and the same cleaning procedures were employed. The initial electrical conductivity of the 230 ml UP-H<sub>2</sub>O in the system measured 1.84 μS/cm. An ion exchange resin cartridge (diameter = 38.1 mm, height = 50.8 mm) containing 20 g of Dowex mixed bed resin was installed in the fluid loop. Table 2 shows the test matrix that was used for both the ion leaching and closed loop indirect cooling experiments.

The change in electrical conductivity of the fluid samples when stirred with Dowex mixed bed ion exchange resin was tested. The fluid samples that were used for the testing are:

- 1) Water from the closed loop, indirect cooling experiment that did not use a resin cartridge and
  - 2) NaCl solution with the electrical conductivity 11.82 μS/cm
- 0.1 g of Dowex resin was added to 100 g of each fluid sample in separate containers. The mixture was stirred and the change in electrical conductivity at room temperature was measured every hour.

Table 1. Components used in the indirect closed loop cooling experiment that fluid gets in contact with.

Components	Construction Material
Reservoir	Acrylic and chrome plated aluminum
Tubing	Silicone
Cooling block	Copper
Tube connectors	Nylon and PVC
Radiator	Aluminum
Swiftech MCP655-B Pump	Polypropylene
Sealant tape	PTFE
Ion exchange resin cartridge	Acrylic

Table 2. The test matrix for both ion leaching and indirect closed loop cooling experiments.

Parameter	Long-term ion leaching	Closed loop indirect cooling
Test fluid	(1)UP-H <sub>2</sub> O* (2) EG-LC**	UP-H <sub>2</sub> O
Test samples	<ul style="list-style-type: none"> <li>• 3003 Aluminum</li> <li>• B5665 brass</li> <li>• 304 stainless steel</li> <li>• High-density polyethylene (HDPE)</li> <li>• Polypropylene</li> <li>• Nylon</li> <li>• Polyvinyl chloride (PVC),</li> <li>• Nitrile rubber (Buna-N),</li> <li>• Polyurethane</li> <li>• Silicone</li> </ul>	<ul style="list-style-type: none"> <li>• Acrylic</li> <li>• Chrome plated aluminum</li> <li>• Silicone</li> <li>• Copper</li> <li>• Nylon</li> <li>• PVC</li> <li>• Aluminum</li> <li>• Polypropylene</li> <li>• PTFE</li> </ul>
Temperature	80°C	Hot plate = 80°C, fluid reservoir =34°C
Flow rate	Stationary	3.4 liters per minute
Duration of the experiment	5000 hours	136 hours
Ion exchange resin	None	Both with and without ion exchange resin
*Ultra-pure distilled water with electrical conductivity of 0.5 μS/cm (UP-H <sub>2</sub> O)		
**Premade mixture of 50:50 ethylene glycol and UP-H <sub>2</sub> O, and nonionic inhibitors (EG-LC)		

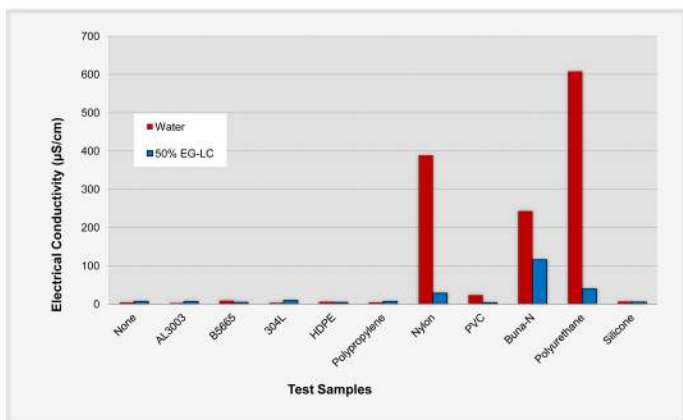
## 2. Results and Discussion

### 2.1 Long-term ion leaching experiment

The measured change in electrical conductivity of the UP-H<sub>2</sub>O and EG-LC test fluids containing polymer or metal when immersed for 5,000 hours at 80°C is shown Figure 3. To place in context the measurement results, the electrical conductivity of drinking water is typically less than 500 μS/cm, river water between 50 to 1500 μS/cm, industrial water less than 10,000μS/cm, and seawater less than 50,000 μS/cm [12].

The results indicate that metals contributed fewer ions to





**Figure 3.** Ion leaching experiment: Measured change in electrical conductivity of water and EG-LC coolants containing either polymer or metal samples when immersed for 5,000 hours at 80°C.

the fluids than plastics in both the UP-H<sub>2</sub>O and EG-LC based coolants. This could be due to a thin metal oxide layer which may act as a barrier to ion leaching and cationic diffusion. Both UP-H<sub>2</sub>O and EG-LC fluid containing polypropylene and HDPE test samples exhibited the lowest electrical conductivity changes. This could be due to the short, rigid, linear chains which are less likely to contribute ions than longer branched chains with weaker intermolecular forces. Silicone also performed well in both test fluids, as polysiloxanes are generally chemically inert due to the high bond energy of the silicon-oxygen bond which would prevent degradation of the material into the fluid. It was observed that materials containing nitrogen groups, such as Buna-N rubber, polyurethane, and nylon had the largest electrical conductivity increases. It would be expected that PVC would produce similar results to those of PTFE and HDPE based on the rather similar chemical structures of the materials, however there may be other impurities present in the PVC, such as plasticizers, that may affect the electrical conductivity of the fluid. Additionally, chloride groups in PVC can also leach into the test fluid and can cause an increase in electrical conductivity.

Figure 4 shows the before and after sample images of 5,000 hour testing of the metal and polymer samples used in the ion leaching experiment. Buna-N rubber and polyurethane showed signs of degradation and thermal decomposition which suggests that their possible utility as a gasket or adhesive material at higher temperatures could lead to application issues. Polyurethane completely disintegrated into the test fluid by the end of the 5000 hour test.

## 2.2 Closed loop, indirect cooling experiment

The measured change in electrical conductivity of the UP-H<sub>2</sub>O over 136 hours, with and without ion exchange resin in the loop, is shown in Figure 5. The electrical conductivity of the UP-H<sub>2</sub>O in a loop without a resin cartridge increased by a factor of seven, from 1.72 µS/cm to 11.77 µS/cm by the end of 136 hours of testing, an

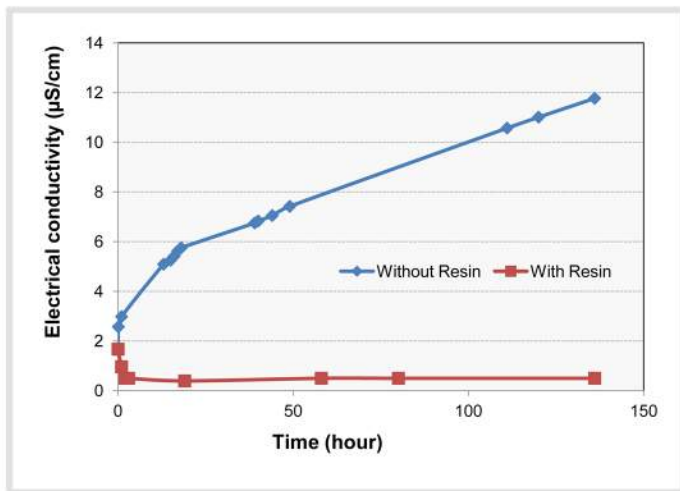
Test Sample	Before	After testing with UP-H <sub>2</sub> O at 80°C	After testing with LC-EG at 80°C
Aluminum			
Brass			
Stainless Steel			
HDPE			
Polypropylene			
Nylon			
PVC			
Buna-N			
Silicone			

**Figure 4.** Before and after images of metal and polymer samples immersed for 5,000 hours at 80°C in the ion leaching experiment.

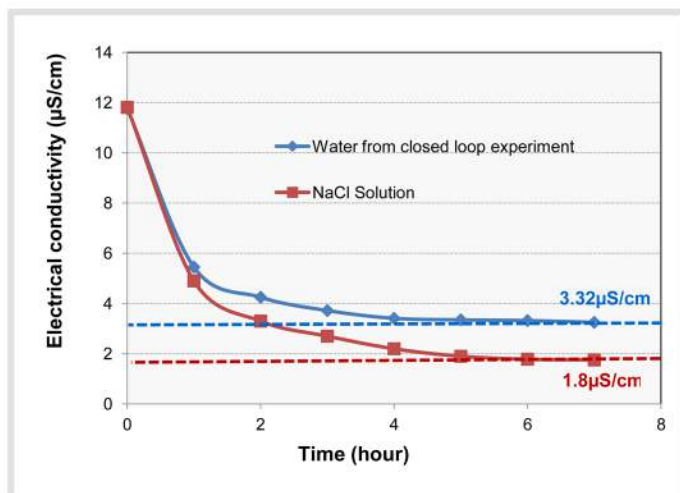
increase of approximately 1.77 µS/cm per day. This indicates that, during the course of the experiment, a constant ion leaching occurred when the fluid was in contact with the components in the system. The electrical conductivity of the UP-H<sub>2</sub>O in the loop containing the ion exchange resin cartridge consistently remained below 0.5 µS/cm, indicating that the ion exchange resin was able to remove the ions that leached into the fluid stream, maintaining the low electrical conductivity of the fluid for the duration of the experiment.

Figure 6 shows the change in the measured electrical conductivity of the fluid samples when stirred with the resin sample. The conductivity of the water sample from the closed loop experiment reduced by approximately 70%, from 11.77 µS/cm to 3.32 µS/cm in six hours. The electrical





**Figure 5.** Measured change in the electrical conductivity of UP-H<sub>2</sub>O coolant as a function of time with and without resin cartridge, in the closed indirect cooling loop experiment.



**Figure 6.** Measured change in electrical conductivity of fluid samples as a function of time when stirred with the resin sample in the closed indirect cooling loop experiment.

conductivity of the NaCl solution reduced by approximately 85%, from 11.82 µS/cm to 1.8 µS/cm in six hours.

These results indicate that the capacity of the resin depends on the test fluid used for the experiment. Therefore, calculating the ion exchange resin capacity with a fluid sample from the actual cooling loop is important. In order to accurately calculate the longevity of the resin cartridge used in the cooling loop experiment, the resin capacity with the water sample from the closed loop experiment was taken into consideration. An ion exchange resin cartridge containing 20 g of Dowex mixed bed resin may take on the order of 938 days to saturate. In other words, to maintain a low electrical conductivity, a resin cartridge with the same dimension and weight specification as that of the resin cartridge used in the experiment, needs to be changed every 30 months for the cooling system that was used in the experiment.

### 3. Conclusions

The long term ion leaching experiment showed that an increase in the electrical conductivity of the coolant fluid is affected by ion leaching of both metals and polymers that are used in the closed loop cooling system. By determining the rate of increase in the electrical conductivity and the ion exchange capacity of the resin with the ions in the fluid used in the cooling system, the estimation of the longevity of the resin cartridge in an electronics cooling loop can be calculated.

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# FLUID FOCUS

## What will chloride ions do to your system?

Water-based heat transfer fluids (i.e. glycols) can be contaminated with aggressive chloride ions if tap/city water is used for on-site dilution. A chloride concentration of higher than 25 ppm in the fluid can cause pitting corrosion of metal components. For dilution purposes, deionized (DI) or distilled water should be used.



Chloride ions can be monitored in a glycol fluid by:

- Sending a sample to Dynalene
- Sending a sample to an outside lab
- On-site testing using a chloride strip such as the one shown in the picture



If your fluid is contaminated with chloride ion in excess of 25 ppm then contact the glycol experts at Dynalene for an action plan.

## DO YOU FILTER YOUR HEAT TRANSFER FLUID?

Heat transfer fluids such as glycols, brines, thermal oils and silicones are important components of many heating and cooling processes. Maintaining the health of these fluids is very important for increasing the service life of the system. Particulates in the fluid can cause severe system problems as discussed below. Filters are recommended to be used in heat transfer fluid loops to mitigate these issues.



PIPE BLOCKAGE DUE TO EROSION AND CORROSION



SEIZING OF PUMP DUE TO RUST BUILD UP

- Clogging of the heat exchangers
- Erosion of the piping and other components
- Seizing of pumps
- Increase of viscosity, therefore requiring higher pumping power
- Localized corrosion due to debris deposit
- Foaming



## GLYCOL REFRACTOMETER Do's and Don'ts

A quick and accurate way to measure the glycol concentration in a HVAC or mechanical system is through a hand-held refractometer. Here are a few do's and don'ts for the proper use of this instrument.



- Be sure the instrument is clean and dry before use
- Use enough fluid to cover the entire measuring prism
- Point the instrument at a light source when taking the reading
- Read from the appropriate side of the scale (ethylene or propylene glycol)
- Clean the instrument after each use



- Do not touch the measurement prism or bottom of the sample cover
- Do not get fluid on the eyepiece of the instrument
- Do not open the sample cover when taking a reading
- Do not test a sample that is too hot or too cold (between 70°F and 85°F is best)
- Do not drop the instrument or subject it to hard knocks



# ASK THE EXPERTS

## Q. What is the difference between propylene glycol (PG) and ethylene glycol (EG)?

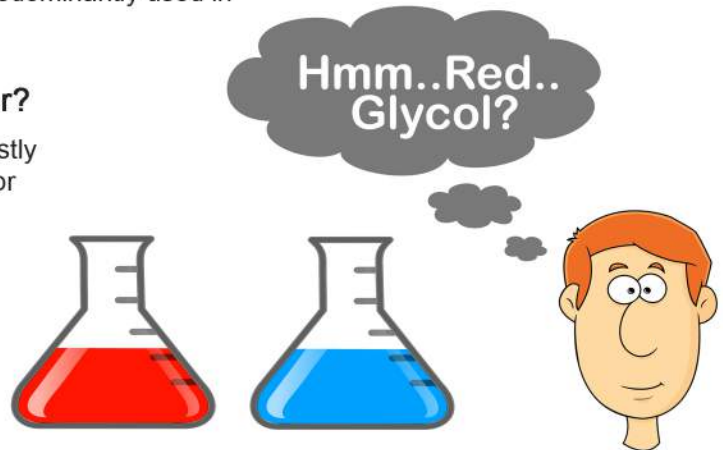
A. The main difference between the two glycols is that ethylene glycol (EG) is toxic while propylene glycol (PG) is non-toxic and can be purchased in a food grade version in addition to the technical/industrial grade. Another difference is that PG has higher viscosity than EG, which means PG could be less efficient than EG, especially at lower temperatures. PG is also more expensive than EG. PG is mainly used in Heating, Ventilation and Air Conditioning (HVAC) as well as food and pharmaceutical process cooling applications, whereas EG is predominantly used in automotive antifreeze/coolant formulations.

## Q. Can I tell what type of glycol I have by the color?

A. No. When glycols are manufactured they are clear and mostly colorless. The color in a glycol is added for leak detection. Color does not indicate the type of product in the system. The other issue with color is that over time the glycol will change color to darker brown, so the original color may not be apparent.

## Q. Should I use the glycol straight or mix it with water?

A. In most cases you should mix glycol with water. The goal should be to minimize the amount of glycol in the fluid mixture, while maintaining the needed freeze protection and corrosion inhibitor content. For example, if the freeze protection needed is -20°F then the minimum amount of propylene glycol needed is 46% by volume (47% by wt.). You can consult the glycol technical data sheets provided by the manufacturer to determine the percentage of glycol for the freeze protection needed.



## Q. What are inhibitors and do I need them?

A. Inhibitors or corrosion inhibitors have multiple functions in a water-based fluid. The main purpose of the inhibitor is to stop the metallic parts in a system from corroding. The second function of the inhibitor is to extend the life of the coolant itself. Glycol based coolants will degrade over time to acids. The presence of the inhibitors helps to slow that degradation. Even if you have a stainless steel or non-metallic system you should consider using an inhibitor to protect the fluid. The only time Dynalene recommends not using an inhibitor is when there is galvanized (zinc coated) piping or parts in the coolant loop and when zinc coating is in contact with the fluid.

## Q. How long will the glycol last in my system?

A. This is a difficult question to answer because of the range of different variables that determine the longevity of the coolant. Temperature range, materials of construction, and fluid maintenance are all factors. Dynalene's customers have systems where the glycol has lasted for more than 15 years. In certain very high temp systems (> 300°F), the glycol may last only a few years. The pH and the inhibitor concentration or reserve alkalinity must be maintained for a glycol to have a prolonged life.

## Q. How can I tell if I need to adjust or change the glycol in my system?

A. The easiest way to determine if something needs to be done with the glycol is to check the pH of the fluid. Normally the pH should be above 8.0, but if it drops below that you should have it tested professionally and adjusted, or change the fluid completely. In addition, if you observe severe corrosion (particulates in the fluid) in the interior of the cooling loop then a thorough testing of the fluid is necessary. The glycol manufacturer can recommend any adjustment or change-out of the fluid.



### Q. How do I know what heat transfer fluid will work in my system?

A. The answer to this question depends on a number of factors including the temperature range, materials of construction, whether the system is open or closed, and if it is pressurized. These questions are the basis of choosing a fluid because they dictate if you should use a thermal oil (hydrocarbon), a brine (salt solution), a glycol or another chemistry. Once the chemistry is figured out we can move on to other properties like viscosity, thermal conductivity, toxicity, flammability, cost and durability. The best way to pick a fluid for your specific system is to speak with an expert.

### Q. What is the difference between an open and a closed system and why are the recommended temperature ranges different?

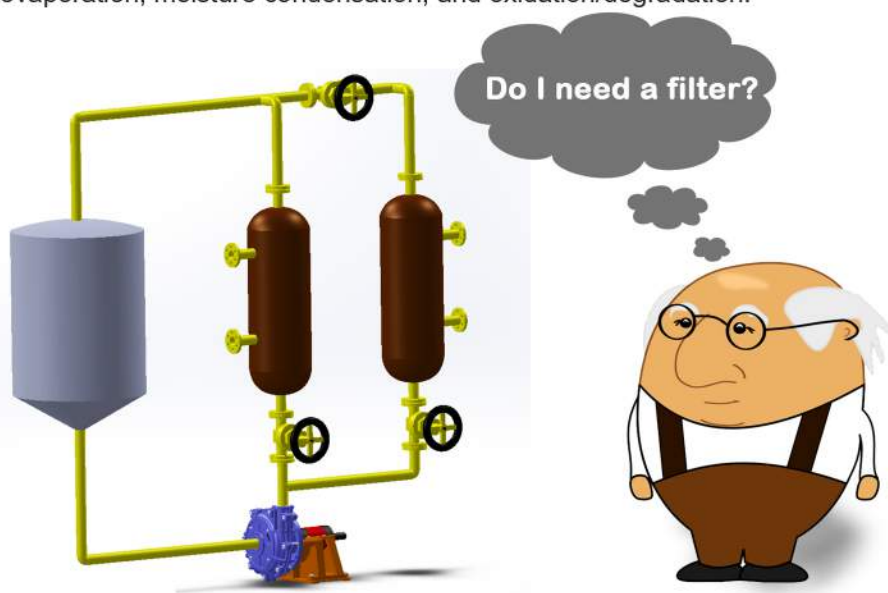
A. Actually, it is not straightforward to call a system open or closed. A truly open system would be a bath that is completely open to atmosphere. A truly closed system would be an air-tight system completely purged of air with no way for it to get in or out. There are a number of different types of systems in between. There are covered baths, which limit the amount of air that comes in contact with the fluid. There are systems with reservoirs that have an air filled head space or a bladder attached to the head space for expansion/contraction. The reason the recommended temperature range varies from open system to closed system is based on vapor pressure (boiling)/evaporation, moisture condensation, and oxidation/degradation.

### Q. How do heat transfer fluids affect aluminum?

A. Aluminum is a great material to use in a heat transfer fluid system; however, typical corrosion inhibitors may not be good enough to protect the product. The pH of typical glycol-based heat transfer fluids is too high (> 9.0). Aluminum behaves well at a pH of 4.5 to 8.5. You can either adjust the pH of your fluid or add an aluminum corrosion inhibitor.

### Q. Do I need to filter my heat transfer fluid?

A. It is always good to have a filtration system (in-line or slip-stream) in the heat transfer fluid circulating loop. Fluids over time accumulate debris, corrosion products, and precipitates due to contamination, system corrosion or fluid degradation. If the fluid is not filtered then it may lead to system clogging, reduction in heat transfer rate, and excessive corrosion.



### Q. Can I use a glycol at 300 or 350°F?

A. You can use properly inhibited glycols at high temperatures up to 350°F. Regular inhibited glycols are generally rated up to 250°F. At temperatures higher than 250°F, glycols degrade severely forming acid molecules. However, with proper buffering and corrosion inhibitors a glycol can be used at high temperatures.

### Q. How do I check the condition of my heat transfer fluid?

A. It depends on the type/chemistry of the heat transfer fluid. If your fluid is a glycol then you can check the pH and the concentration of the glycol onsite. A hand-held pH meter and a refractometer can be used for this purpose. However, for the determination of inhibitor concentration, a sample must be sent to the glycol supplier. For hydrocarbon and silicone heat transfer fluids, moisture content by Karl Fisher method and composition analysis by Gas Chromatography can be performed in a laboratory equipped with these instruments.

### Q. I have a low temperature silicone oil in the system and it has a lot of moisture that is creating freezing issues. What can I do?

A. Moisture is a common problem in non-aqueous (hydrocarbon, silicone) heat transfer fluids. To remove moisture, a desiccation system using molecular sieves can be installed in-line or as a slip-stream.



## Review

# Common Types of Corrosion in Heat Transfer Fluid Systems

by

Sreya Dutta, Ph.D, Material Scientist, Dynalene

## What is Corrosion?

Corrosion can be defined as the degradation of a material due to its interaction with the environment. In addition to corrosion of metals, polymers can disintegrate, swell and crack under certain conditions. Even ceramics can undergo degradation by selective dissolution. A study conducted in 1998 unveiled that the direct cost of metal corrosion in the US was \$276 billion, which was 3.1% of the GDP for that year [1, 2]. Due to this staggering cost, fundamental understanding of different types of corrosion and their prevention is of utmost importance.

In the following section, different types of metal corrosion found in water-based heat transfer fluid systems are discussed with examples and control strategies.

## Uniform or General Corrosion Attack [3-9]

When a large metal surface is attacked by a chemical/acid, the metal piece slowly etches and thins out leading to ultimate failure of the system. Though uniform corrosion causes a huge mass loss yearly, it is predictable and measures can be taken to prevent ultimate failure. Examples of this type of corrosion are atmospheric corrosion leading to tarnishing of copper, weathering or rusting of steel, and rusting of iron pipes exposed to hot and humid weather. Aluminum heat exchangers with uninhibited glycol may exhibit surface oxidation that can lead to breakdown of the coating and thinning of metals.

Control: Protective coating, inhibitor to prevent corrosion, cathodic protection

## Galvanic Corrosion [3-9]

Galvanic or bimetallic corrosion occurs when two dissimilar metals are in an electrolytic media. The metal that is more noble than the other (based on ionization potential chart) acts as the cathode while the less noble metal undergoes rapid dissolution in presence of an electrolyte. For galvanic corrosion to happen, it requires:

- Two dissimilar metals

- Electrical contact or direct contact between the metals
- Electrolytic media

The driving force for this corrosion mechanism is the potential difference between the two metals in addition to a smaller ratio of anode to cathode surface, the presence of joints or rivets of dissimilar metals, and ionic electrolyte.



Figure 2: Galvanic corrosion of stainless steel screw in cadmium plated steel [13]

Examples of this type of corrosion can be found in steel plates with copper rivets in seawater and in the cast iron frame supporting the copper Statue of Liberty. Presence of joints of dissimilar metals in pipes carrying any ionic salt water based coolant can lead to galvanic corrosion and failure of the joints.

Prevention: The following steps are recommended to avoid galvanic corrosion:

- Select metals close to each other in the galvanic chart
- Large anode to cathode surface area ratio
- Insulating layer separating the metals
- Protective coating on the joints, rivets and piping

## Crevice Corrosion [3-9]

This is a form of localized corrosion that happens at the area of contact between 2 metals or metal and a non-metal. Crevice corrosion is initiated due to a difference in concentration of chemical constituents like oxygen, inhibitor inside and outside of the crevices. Small amounts of stagnant solutions under crevices, washers, threads, coatings, joints, etc. cause an extremely corrosive environment, setting up differential concentration cells inside (anode) and outside (cathode) of the crevices. Lower pH, oxygen content and presence of chloride further worsen the condition. Factors that affect crevice corrosion are:

- Type of metal and non-metals involved
- Microstructure of the crevices
- Environmental factors: pH, oxygen and chloride concentration, etc.

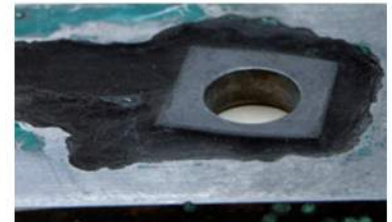


Figure 3: Crevice corrosion in seawater [13]

## Pitting Corrosion [3-10]

This is a localized form of corrosion which causes the formation of pits or holes in metal. Pitting corrosion is autocatalytic and a very aggressive form of corrosion which is very difficult to predict and prevent. As the corrosion products cover the pits, the pits are not detected easily. It is commonly seen in metals which form passive oxide films like aluminum and stainless steel. Pits that form do not

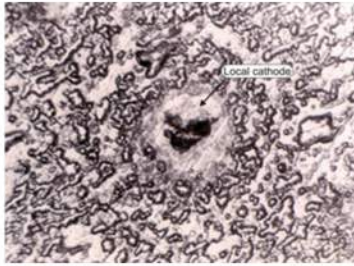


Figure 1: Bolted post showing uniform corrosion [13]



passivate but grow with time. Factors that affect pitting corrosion are:

- Mechanically or chemically damaged film on a metal
- Presence of chloride ions, low dissolved oxygen and acidic nature of the surrounding environment
- Presence of surface defect or inclusions



**Figure 4: Pitting corrosion in unclad 2024 Aluminum alloy [13]**

Like crevice corrosion, differential aeration cells are formed, where the cavity or the pit becomes increasingly anodic and the surrounding well-aerated areas are more cathodic in nature. There is localized mass loss in the corrosion pits but more notably these pits act as stress points.

Examples: Deformities in the bore due to pitting corrosion affects the accuracy of firearms. Rust bubbles with higher concentration of chloride can lead to severe pitting corrosion. Uninhibited calcium chloride used for freeze protection and other applications can cause severe corrosion in cast iron, carbon steel and even stainless steel.

Prevention: The following methods can be applied to prevent pitting corrosion:

- Use of inhibitors to coat the metal surface and prevent corrosion
- Use of pit resistant alloying elements in the metals like Cr, Mo etc.
- Control of pH, chloride concentration and temperature
- Use of Cathodic or Anodic Protection

### Intergranular Corrosion [3-10]

Grain boundaries in metals that separate grains from each other are susceptible to intergranular corrosion in which different grains act as anodic and cathodic regions.



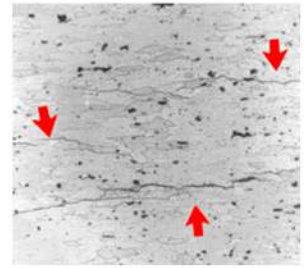
## DID YOU KNOW?

The Statue of Liberty that was unveiled in 1886 might seem almost unrecognizable to people today. Instead of the familiar green skin, Lady Liberty shone like a brand new copper penny. That is because the skin of the statue is actually made of a copper sheet no more than 2.4 millimeters thick. The statue that was made with an exterior of untreated copper, slowly turned green over time through oxidation. This shiny pale green outer layer called patina actually protects the copper below the surface from further corrosion. In fact, the weathering and oxidation of the Statue of Liberty's copper skin has amounted to just .005 of an inch over the last century, according to the Copper Development Association.

Source: "Facts About the Statue of Liberty", USA Today

Thompson Andrea , "Why Does Copper Turn Green?", Live Science February 09, 2013

This type of corrosion is driven by segregation of chemical species or precipitation of phases along or near the grain boundaries. Such preferential attack of the grain boundary causes the corrosion to proceed along a narrow path near the grain boundary and if left undetected can completely dislodge the grain. The mechanical properties of the metal are seriously affected as it loses its corrosion resistance near the grain boundaries.



**Figure 5: Intergranular corrosion of a failed aircraft component made up of 7075-T6 alloy [13]**

Examples: Sensitization in stainless steel or weld decay where the chromium carbide precipitates out at the grain boundary, making the grain boundary weak and a preferential path for corrosion. Hot corrosion in molten salt based heat transfer fluids can lead to dechromatization and weakening of the grain boundaries.

Prevention: Intergranular corrosion can be prevented by following some of these steps:

- Use of low carbon (<0.05%) stainless steel
- Use of Ti and Nb in stainless steel as stabilizers
- Use post weld reheating for diffusion to occur



**Figure 6: Exfoliation in Al alloy based aircraft component [13]**

### Exfoliation or Lamellar Corrosion [5-11]

This is a type of intergranular corrosion that proceeds laterally from the point of initiation along a plane parallel to the surface, generally along a grain boundary just below the surface. The expanding corrosion product takes the metal grains out of the metal body giving the surface a lamellar look. Exfoliation can cause a large mass of internal oxide growth which puts stress on the structure of the metal system. Thermal coefficient mismatch also contributes to this type of corrosion as the mass of the corrosion product is much larger than the mass of the

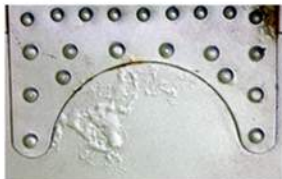


metal, leading the metal to delaminate.

Examples: Exfoliation corrosion is mostly seen in extruded high strength aluminum alloys, where corrosion product exerts pressure under the elongated grains and lifts up the grain. Iron and steel alloys shows exfoliation corrosion due to internal oxide growth which damages metal structures like turbines at very high temperatures.

Prevention: The following methods can prevent corrosion:

- Use coatings
- Use exfoliation corrosion resistant aluminum alloys
- Use heat treatments to control precipitation



**Figure 7: Filiform corrosion crawling under paint [13]**

### Filiform Corrosion [5-10]

A special type of crevice corrosion which happens under a thin coating or paint in threadlike filament form. The filaments originate from a microscopic defect and propagate in different directions under a bulged or cracked coating. Lacquers and quick dry paints where moisture permeates through the coating are more susceptible to this type of corrosion.

Examples: This form of corrosion is found on the surface of aluminum, magnesium, coated steel within coatings of gold, silver, enamel, lacquer etc.

Prevention: This form of corrosion can be avoided by using a coating with excellent adhesion and low moisture transmission properties.

### Pack Rust [5, 7-10]

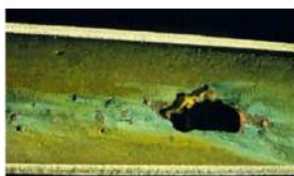
A type of corrosion where the corrosion product forms between plates, joints etc., developing crevices exposed to atmospheric conditions. It is an electrochemical reaction, leading to formation of rust. Pack rust specifically causes bulging and distortion between steel plates leading to structural deformities and failure.



**Figure 8: Pack Rust between steel plates [13]**

Examples: Pack rust between steel plates in road and railway bridges can lead to untimely failure of the structure

Prevention: To prevent pack rust steel components should be treated with anti-rust coatings during assembly.



**Figure 9: Erosion corrosion causes pits in the tube [13]**

### Erosion Corrosion [4-10]

This is a type of a velocity-assisted corrosion which causes accelerated corrosion attack due to the relative motion of corrosive fluid against the metal surface. Erosion and wear occur due to turbulent flow of a fluid containing solid

particles. Erosion corrosion increases pitting tendency. This corrosion etches away the protective coating on the metal and chemically attacks the bare metal leading to accelerated metal loss. This corrosion is generally observed in softer metals.

Examples: This type of corrosion is observed at high flow rates in tube inlets, pump impellers. In off-shore well-systems, where the components come in contact with sand-bearing liquid. Circulating brine solutions for cooling at high speed can cause erosion corrosion at the pump impellers and deposition of the corrosion product on the iron pipes.

Prevention: To prevent erosion corrosion and material loss, the following steps can be taken:

- Reduction of flow velocity and abrupt change in direction of fluid
- Promote laminar flow of the fluid
- Use a filter to remove the abrasive particles
- Add corrosion inhibitors to coat metal walls
- Use cathodic protection to prevent erosion corrosion



**Figure 10: Cavitation causes bubbles and gas pockets on the surface [13]**

### Cavitation [7-9]

Cavitation corrosion is a special type of erosion corrosion where water bubbles collapse at the joints where the fluid turbulence is higher. Pressure differential within and outside of gas pockets and bubbles causes them to burst in an explosive manner. Collapsing gas bubbles destroy the protective scales on the metal leading to pit formation.

Examples: This corrosion is observed in marine rudders and propellers. Cavitation can corrode volutes and pump impellers in systems circulating heat transfer fluids.

Prevention: Steps similar to erosion corrosion prevention can eliminate cavitation. Along with these, hydrodynamic pressure gradients should be reduced to avoid pressure drops.

### Environmental Cracking (EC) [6-8]

This type of corrosion occurs as a brittle fracture of a ductile metal due to the corrosive effect of the environment. Environmental cracking occurs due to the combined action of (i) tensile stress (ii) corrosive medium and (iii) a susceptible metal. EC can be divided into the following categories:

#### Stress Corrosion Cracking (SCC) [7-10, 12]:

This is induced by applied or residual tensile stresses in the presence of a corrosive environment. Cold deformation, welding, heat-treatment, machining, and grinding generate residual tensile stresses in the metal body. Also, corrosion product build-up within the cracks and spaces creates



significant stresses. SCC shows a branched pattern of fine cracks which are generally sub-surface and initially very hard to detect. The cracks propagate within the metal body and can ultimately lead to catastrophic failure of the structure. The cracks can be intergranular or intra-granular.

Examples: Caustic SCC happens in stainless steel steam generator tubing in pressure water reactors due to high concentrations of NaOH or KOH, and the conditions become more corrosive at high temperature.

Chloride SCC is seen in stainless steel used for nuclear applications where the Cr precipitates out in the grain boundary, making the grains more susceptible to SCC.

Prevention: SCC can be avoided by following the steps below:

- Choice of correct metal
- Proper designs to reduce mechanical stresses at notches and corners
- Remove high concentration of corrosive species like hydroxide, oxygen and chloride
- Avoid stagnant areas and crevices in heat exchangers where corrosive species can accumulate.

#### Corrosion Fatigue [5-9]

This type of corrosion causes premature failure of metal due to a synergistic action of alternating/cyclic stresses and a corrosive environment. Due to the presence of a



**Figure 11:**  
*Intergranular SCC in Inconel heat exchanger tube [13]*

corrosive environment, the failure occurs at a much lower load and in a shorter time. Corrosion Fatigue causes fracture of the protective layer and the fracture is brittle and transgranular but not branched like SCC.

Examples: Fatigue strength in aluminum structure in aircrafts in mildly corrosive environment shows a reduction in strength by 25 to 75%.

Prevention: Corrosion Fatigue can be controlled by

- Lowering cyclic stresses
- Reducing stress concentrations
- Decreasing vibrations and pressure fluctuations
- Use of coatings and inhibitors to delay onset of cracks.

#### **Microbiologically Influenced Corrosion (MIC) [9, 2, 4]**

MIC is a biological corrosion that happens due to metabolic activity of micro-organisms present in water. MIC is associated with formation of a biofilm on the metal which collects corrosive species and creates an extremely corrosive environment. Biofilm significantly enhance the chances of pitting and crevice corrosion. Bacteria alters the local chemistry of water and sea-water, creating a corrosive environment. Factors that further promote MIC include micro-organism content in the water, pH, and temperature of the water, and whether or not the fluid is stagnant (which further worsens corrosion conditions). The organisms can be aerobic (iron and manganese oxidizing bacteria) or anaerobic (sulfate reducing bacteria-SRB).

Examples: MIC can affect (i) pipes, tanks, various components of chemical industries when they are hydrotested with well or river water; (ii) underground pipelines in soil due to the presence of SRB; (iii) sewage handling and treatment; (iv) heat exchangers in water treatment and (v) marine industries among various others.

Prevention: The following steps are recommended to control MIC:



**Figure 12:** *Corrosion Fatigue leading to failure of aircraft [14]*



## **DID YOU KNOW?**

The iron pillar located at the center of the Quwwat-ul-Islam Masjid in Delhi, India, continues to confound tourists, puzzled at how such a piece of ancient craftsmanship has stayed rust-free for more than 1600 years. This 23 ft tall pillar which weighs 6.5 tons was erected in about the fourth century AD by Gupta monarchs. In spite of its large size and old age, the pillar remains free of rust blemishes. The Delhi Iron Pillar is a classical example of massive production of high class iron and is the biggest hand-forged block of iron from antiquity. It is a demonstration of the high degree of accomplishment in the art of iron making by ancient Indian iron and steel makers. It has been said that the Indians were the only non-European people who manufactured heavy forged pieces of iron and the pieces were of a size that European smiths did not learn to make until more than one thousand years later.

Source: "Delhi Iron Pillar", *Corrosion Doctor*, 2015

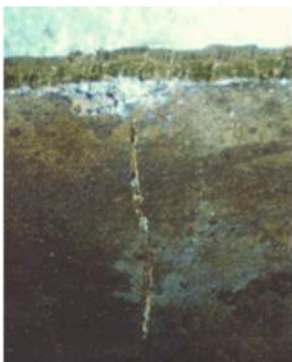
Image Credits: Mark A. Wilson, Department of Geology, The College of Wooster



- Mechanical cleaning and scrubbing of components if possible
- Use a flushing fluid with biocide to control bacteria growth
- To prevent stagnant water, when not in use, drain system completely, air dry, shrink wrap and store

### Dealloying [5, 7, 8]

Dealloying is a comparatively rare type of corrosion where one or more components of the metal solid solution selectively leaches out. Common types of dealloying are dezincification, decarburizing, and graphitic corrosion. A potential difference between different elements in an alloy in an electrolytic medium is the driving force for preferential attack of the active elements, leaving behind a porous sponge like structure with low strength and microstructure.



**Figure 13:** Dezincification leaches Zn out of brass [13]

Examples: In dezincification, zinc leaches out of unstable brass leaving behind a porous and brittle copper structure. In graphitic corrosion of cast iron, metal leaches out or gets converted to corrosion product leaving behind the graphitic network.

Prevention: Dealloying can be stopped by the following steps:

- Corrosion resistant or inhibited metal alloys
- Use of sacrificial cathode or anode

### Fretting Corrosion [5, 7, 8]

Fretting corrosion occurs at the interface of contacting surfaces under high load and in the presence of surface movements like vibrations. Corrosion occurs at the asperities of contact surface due to vibrations caused, for example, during transportation. Damage occurs due to rubbing of the surfaces which breaks the protective film and exposes the fresh surface. Pits and oxide corrosion products are seen at the damaged spots.

Examples: Fretting corrosion can occur in the bearing

surfaces of machinery, in bolted assemblies, etc.

Prevention: Fretting corrosion can be prevented by regularly inspecting and lubricating the surfaces.



**Figure 14:** Fretting corrosion at highly loaded surfaces [14]

**Acknowledgement:** The author would like to express her gratitude to NACE International and NASA Corrosion Technology Laboratory for their permission to reprint images for this article.

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## DID YOU KNOW?

It was reported in 2011 that the US Navy has discovered "aggressive" corrosion around the USS Independence vessel which is considered to be the workhorse of tomorrow's Navy. The problem is so bad that the barely year-old ship will have to be laid up in a San Diego drydock so that the workers can replace whole chunks of her hull. This is not an isolated problem. It is estimated that corrosion is a \$23-billion per year problem in the equipment-heavy U.S. military.

Source: Axe, David, "Builder Blames Navy as Brand-New Warship Disintegrates" Wired, May, 2011.



## Review

# Future Fluids - Nano-fluids

by

Abhinav S, Research Assistant, Lehigh University

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## Nano-Revolution a “giga”ntic leap

As the advancement of technology took a leap with the development of microchips, we moved on from a computer occupying an entire room to a tablet that fits into the palm of your hand. Over the last few decades the birth of nanotechnology has revolutionized numerous branches of science and engineering. Nanotechnology deals with the study of materials which are on the order of one billionth of a meter ( $10^{-9}$  m). To give you an idea of how incredibly small this is, the size of an individual atom is in the range of  $10^{-11}$  to  $10^{-10}$  m. This means on average, there are only tens to a few thousand atoms in a nano-particle. A nano-meter is approximately the same length as the growth of your fingernail in 1 second [1]. The diameter of a human hair is about 50,000 to 100,000 nm. Introducing nanotechnology is not only about reducing the system size, but also increasing the speed and efficiency of systems.



Nano-materials are not new and were very much present in nature around us for a long time. For example, ash produced by volcanic eruptions are nano-sized particles. The splendid colors of some butterflies are due to the

fine nano-scales present on the wings which bend and scatter reflected light [2]. The ability of a gecko to climb a vertical wall is due to the presence of nano sized hair-like structures on its feet [3]. The diameter of human DNA is in the order of 2 to 5 nm in size.

The most fascinating property of nanomaterials is that they tend to behave differently compared to when they are much larger. For instance, gold is considered very stable as a bulk material and cannot be used as catalyst, but at nanolevel, it can act as catalyst in a chemical reaction [4]. We have carbon nanotubes that are single layers of graphite and are just a few nanometers thick. While graphite is weak in its bulk form, its strength as a nanotube increases so much that researchers see the possibility of building a space elevator using this nanomaterial. Imagine a permanent cable fixed on earth and extended into space carrying an elevator just like our regular elevator transporting us back and forth between earth and space. If this turns into reality one day, it would avoid millions of dollars spent on current space vehicles which use immense amounts of energy to propel themselves beyond our atmosphere.

## Nano-fluids our Next Stop

According to Gordon Moore, it is predicted that the speed of computers will double about every 2 years [5]. A consequence of this increasing computing power is that heat generation from the microprocessor also increases. Removing this heat is vital to maintaining the computing efficiency and preserving the long-term life of the computer. Besides electronic equipment, heat is also the byproduct of many other mechanical and power generating systems, and designing compact yet efficient heat exchangers can pose significant challenges to engineers. In the quest to find an effective heat transfer fluid to circulate inside these heat exchangers, scientists have developed new fluids called nano-fluids, which are fluids that contain colloidal substances of the nano-scale size. While the importance of colloidal fluids for heat transfer applications was recognized in the early 20th century, the settling of particles deterred its use in commercial applications. More than ten decades after this field was discovered, Stephen Choi, a researcher from the Argonne National laboratory, came up with a new approach of preparing stable colloidal fluids. He effectively replaced micron level colloidal particles with nano-particles and termed them “nano-fluids”. At the nano level the viscous forces and Brownian motion of the particles are very prominent which helps in counteracting gravitational effects. Even though these fluids display better stability than micron level particles, the stability level is still not sufficient to be used for commercial purposes. This is because nano-particles tend to have greater attraction forces that result in agglomeration, forming larger particles which eventually settle out of the fluid.

With over two decades of research in this field, many new techniques have been introduced to address the dispersion and agglomeration issues. Approaches varied from techniques such as stirring, ultra-sonication, chemical modification by functionalizing the particle surface, and adding surfactants. From past research, it was observed that chemical modification gave better results in improving the stability of the nano-fluid when stored over long periods of time. Chemical modification primarily results in the formation of charged ion layers surrounding the nano-particles and helps in repelling two particles when they come too close to each other. Since settling is the direct consequence of density difference between the nano particle and the base fluid, researchers are now altering the density of the particle to match up with the density of the base fluid. One such approach is by making hollow nano-particles. Even though there are some methods to produce hollow nanoparticles, precisely controlling the size of the particle cavity is necessary for uniform distribution. Any excess deviation in cavity size would result in particles floating or settling.

Interest in nano-fluids grew as these fluids claimed to have enhanced thermal properties when compared to the base fluid. The thermal conductivity of most solid materials is generally 100 times larger than the thermal conductivity of fluids, so one might expect a fluid containing nano-particles



to have a higher thermal conductivity than the base fluid. While many studies showed that there is a significant improvement in effective thermal conductivity, some works indicated that there is no significant enhancement. These discrepancies in the experimental results were also observed when similar types of nano-fluids were tested by two different research groups. This could be because effective thermal conductivity of a nano-fluid is dependent on many factors, including preparation method, additives, distribution pattern of particles, particle size, and particle shapes.

Many theories have surfaced to explain the anomalous increase in the effective thermal conductivity of nano-fluids. Brownian motion of particles, formation of highly conductive layers at the particle and liquid interface, and nano-convection due to the motion of particles are some of the possible reasons for enhanced thermal conductivity of nano-fluids [6]. Numerous theoretical models were formulated which incorporated the above mechanisms to predict the thermal conductivity of nano-fluids. These models are broadly divided into static and dynamic models [7]. While static models are very basic models where Brownian motion of particles is ignored, dynamic models include motion of particles in the base fluid. Most of these models could not accurately predict the thermal conductivity values obtained from experimental work [7]. Forced convection property which is primarily based on the heat transfer coefficient of the fluid was also expected to increase in these nano-fluids. Researchers also suggest that the disturbances caused in boundary layers by particle motion could be the factor contributing to the enhancement of the heat transfer coefficient of nano-fluids. In addition to the issues related to settling of the nano particles, an increase in viscosity of the fluids with the addition of nano particles poses a different kind of challenge. Higher viscosity results in increased pumping power, and in many cases a marginal increase in heat transfer coefficient will not be sufficient to justify the use of nano-fluids.

Nano-fluids can be used in a variety of fields, including aerospace, automobile, electronics, nuclear applications, biotechnology, defense, tribology, etc. In areas such as nuclear power generation, nano-fluids could play a vital role for pressurized water reactors (PWR) where critical heat flux (CHF) limits the amount of steam that can be generated. Some studies have concluded that the use of

nanofluids would increase the CHF and thereby improve the productivity of PWR nuclear power plants.

After almost two decades of extensive research in this field, the scientific community is still working to engineer very stable nano-fluids for heat transfer applications with improved thermal properties. High viscosity coupled with stability issues are the primary concerns that are hindering the growth of nano-fluids into full-fledged commercial products. Though the enhancement of heat transfer properties for some nano-fluids tends to be satisfactory, the overall effectiveness is hindered due to poor rheological properties. The other aspect that researchers are trying to achieve is a cost-effective production technique to produce these nano-particles. Though there have been great advancements with nano-fluid technology in the past decade, many more challenges are yet to be addressed to make these fluids commercially viable and compete with traditional heat transfer fluids.

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Image Source: <https://pixabay.com/>

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## DID YOU KNOW?



A new smart-fabric derived from the properties of pinecones has been developed by the UK based Centre for Biomimetic and Natural Technologies. The fabric adapts to changing temperatures by opening up when warm and shutting tight when cold, just like a pinecone's scales do in nature, and is just one of the emerging developments in the burgeoning field of "biomimetics". The "breathing" fabric is designed to stop the wearer getting hot or cold by adjusting itself to both internal and external temperatures. The textile is made up of a layer of thin spikes of wool, or another water-absorbent material, that opens up when it's made wet by the wearer's sweat. When the layer dries out, the spikes automatically close up again.

Source: <http://www.gizmag.com/go/3515/>

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# Dynalene News

## Dynalene opens new western US Location



Dynalene Inc. is pleased to announce the opening of its 3rd manufacturing and distribution facility in Salt Lake City, Utah. This new location will be equipped with multiple large scale blending tanks as well as more than 40,000 gallons of bulk fluid storage for propylene glycol, ethylene glycol and Dynalene HC.

The plant will produce and ship the entire line of Dynalene heat transfer fluids. The Salt Lake City facility was added to service our customers in the western states including Utah, Wyoming, Colorado, California, Nevada, New Mexico, Oregon, Washington, Idaho, and Montana. This new location will result in reduced shipping costs by as much as 60% and cut transit times in half for customers in these states. By adding this facility Dynalene is in a position to deliver products to our customers throughout the United States in a short period of time while maintaining high quality standards (ISO 9001), excellent customer service and flexibility.

## Dynalene now offers filtration equipment



FILTRATION SOLUTION THAT IS COMPATIBLE WITH MOST OF THE HEAT TRANSFER FLUIDS

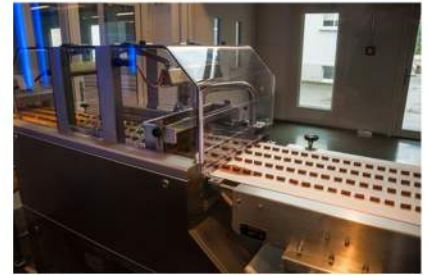
Dynalene now offers a comprehensive filtration solution that is compatible with most heat transfer fluids. Our product line includes standard and custom design equipment that can be tailored to your needs. The filtration product line consists of filter vessels and bag filters that are compatible with our fluid chemistries. They are available in different materials of construction, fluid handling capacity and flow rate. The

bag filters are compatible for use with standard filter housing.

Additionally, Dynalene also offers basic testing devices that can be used for fluid property measurements to help monitor the health of your fluids.

## Dynalene HC now has a NSF HT-1 rating

Dynalene HC chemistry, one of the leading products in the Dynalene fluid lineup, is now available in a "food safe" formula. We are proud to present Dynalene HC-FG.



This formulation has an NSF HT-1 rating for incidental food contact and maintains the identical heat transfer efficiency as the original formula. With two formulations of Dynalene HC (the original and the FG) to choose from, process engineers and designers of HTF systems around the world now have a "go to" fluid for food and non-food plant applications. Visit Dynalene's website to know more about the Dynalene HC-FG product or contact us today at 1.877.244.5525.

## Dynalene nominated for Governor's Impact Award 2015



Dynalene has been nominated for the Governor's Impact Award in the category of Export Impact Category for the year 2015.

The Governor's ImpAct Awards are designed to celebrate the companies and individuals who are investing in Pennsylvania and creating jobs.

In the recent past, Dynalene was nominated in the category of Entrepreneur Impact for the years 2013 and 2014.

## Ion exchange resin cartridge for low conductivity applications

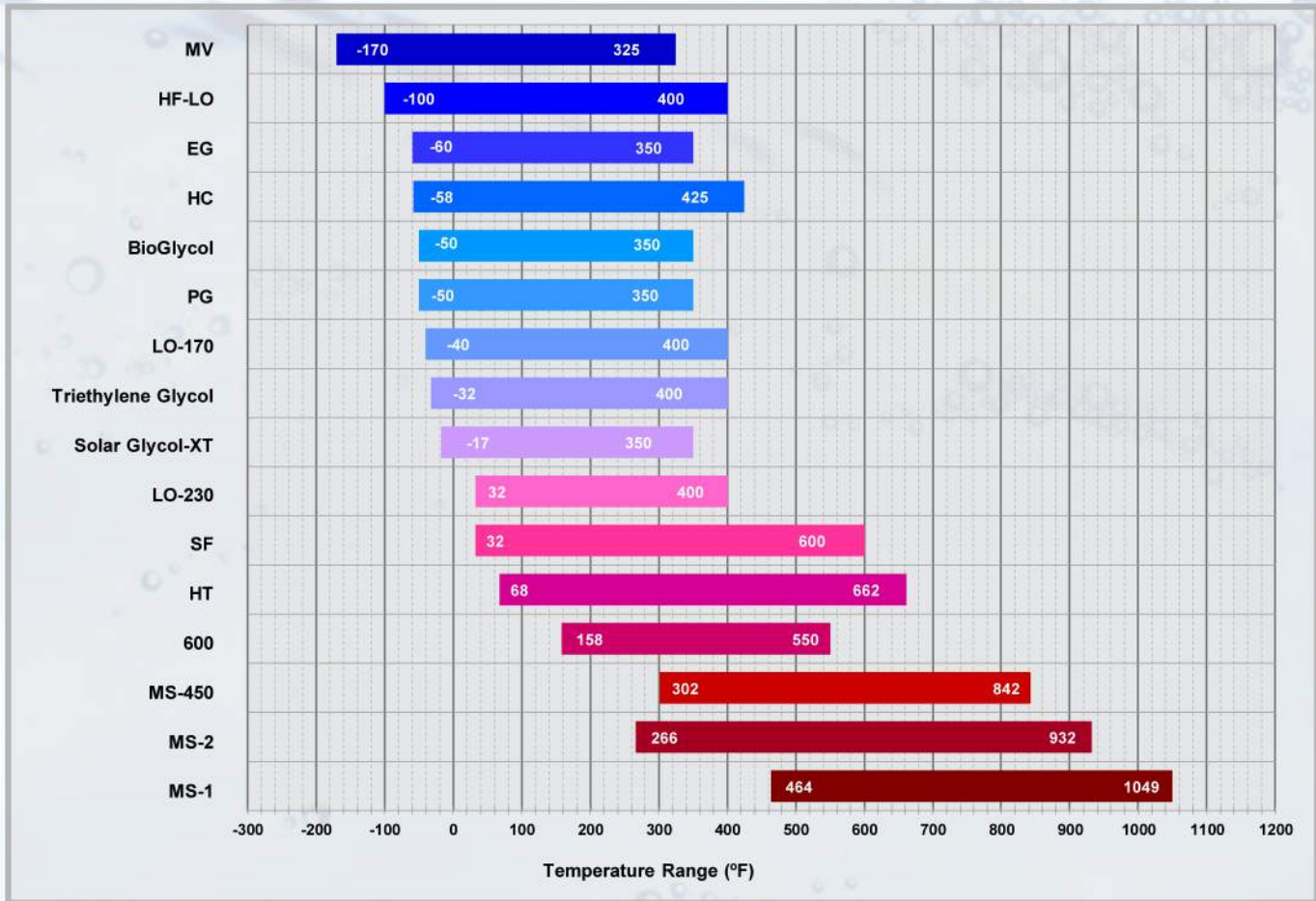
Dynalene's new ion exchange resin product line includes resin cartridges that can help maintain low conductivity in the coolant loop.

These IC Series ion exchange resin cartridges are designed and tested extensively for greater ion removal and can be installed in a system operating at 200°F (93°C). These cartridges are currently used in low conductivity cooling applications such as fuel cell and battery cooling and can be custom designed for any cooling system.





## Temperature range reference chart for Dynalene heat transfer fluids



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**Dynalene is an ISO-9001 certified leading manufacturer and supplier of heat transfer fluids. For the past 20 years, Dynalene quality products have been used in a variety of applications by thousands of customers worldwide.**

