MOJAVE

Preventing Carryover in Liquid Desiccant A/C systems

Executive Summary

Liquid Desiccant Air Conditioning systems (LDAC) are a superior choice for energy efficiency in comparison with conventional packaged Heating, Ventilation, and Air Conditioning (HVAC) systems, yet LDAC systems must prove there is negligible risk of unintentionally introducing desiccant into the airstream (a phenomenon called "carryover"). Carryover can cause operational issues to the AC unit and damage building materials as many desiccants accelerate the corrosion of metals.

At Mojave, understanding and preventing carryover is the number one priority in all our units. Mojave has designed an LDAC system that exhibits carryover of less than 1 particle per billion with over 99.99% confidence resulting in airflows that are non-corrosive with 99.999% confidence.

We tested for carryover using a suite of three tests:

1) Desiccant mass accumulation over time

2) Direct detection of corrosion using advanced sensors

3) Field corrosion testing

Through these tests, we demonstrated that customers can deploy our LDAC system without being concerned with potentially adverse effects of carryover. This paper summarizes Mojave's extensive testing and robust results, which conclusively show the reliability of our design.

Introduction

Liquid desiccant air conditioning (LDAC) offers the potential for massive energy savings in many applications. The naturally low effective vapor pressure of liquid desiccants will extract water from air with a higher partial pressure of water, a process that reduces the humidity of air supplied to buildings and industrial process equipment. For example, by combining a liquid desiccant (LD) system with a vapor compression (VC) system, one can pass air pre-cooled by the VC system to the LD system to provide air at desirable conditions such as 68°F dry bulb and 50°F dew point: the desired output for many Dedicated Outdoor Air Systems (DOAS). A conventional DOAS using a VC system alone will require approximately double the energy of a LD-DOAS with equivalent capacity. Accordingly, LD-DOAS systems offer building owners an opportunity to reduce their energy costs by thousands of dollars per year; at scale LD-DOAS can create billions of dollars of economic value while reducing the climate impact of A/C by over 100 million metric tons CO_{2e} annually.

Designing such a system, however, requires careful engineering to develop a system that meets customer expectations for performance and reliability. One such expectation is that there is negligible risk of the desiccant being pulled into the air stream that provides conditioned air to the customer space, a phenomenon known as "carryover". While LDAC systems offer building owners an opportunity to reduce their energy costs by thousands of dollars per year, carryover must be addressed as it can cause problems within the unit operation and could also corrode metals in customers spaces. In this whitepaper, you'll learn how Mojave has designed a system without carryover through extensive engineering and robust testing so you can deploy our LDAC system with no concern for the adverse effects of carryover.

Carryover arises through the interaction of the airstream to be conditioned with the liquid desiccant. The design of this interaction directly impacts how effectively the system transfers heat and moisture from the airstream to the desiccant to achieve the desired dehumidification. There are three established methods for interacting the desiccant with the air stream, each with challenges and advantages:

- Spraying the desiccant into the airstream followed by mist elimination. This has the advantage of presenting excellent surface area and moisture transfer rates. However, no mist eliminator has demonstrated sufficient effectiveness to reduce carryover to acceptably low levels. Accordingly, we eliminated this option from consideration.
- Using membranes between the airstream and the desiccant. This method reduces the effectiveness of heat and mass transfer significantly while increasing the cost of the unit. Further, membranes are difficult to seal and can be easily damaged: leaks or damage will lead to very significant carryover. The drawbacks of this method led us to avoid it as well.
- Directing the desiccant onto a hydrophilic surface. This method is used in conventional cooling towers. Using a surface such as a media bed and passing the air over can provide excellent contact area and thus effectiveness; with sufficient engineering and design this approach can assure carryover well below acceptable levels.

Naturally we decided to pursue the third method and have developed a system that exhibits carryover of less than 1 particle per billion with over 99.99% confidence resulting in airflows that are non-corrosive (i.e., ISO corrosivity index of C1) with 99.999% confidence.

Testing Methodology and Results

We developed and applied three specific tests that could accurately measure carryover within the airstream in full-scale and small-scale settings. The tests developed are listed below:

- Test 1 - Direct observation of desiccant mass accumulation
- Test 2 - Direct measurement of corrosion rates
- Test 3 - Field tests of the airstream corrosivity as per ASTM rating.

This section details the methodology and results for each test .

Test #1 – Desiccant Mass

The goal of this test was to detect all droplets and aerosolized particles released through carryover into the process and regeneration airstreams. We were unable to identify a sensor that could directly detect particles in the airstream with the sensitivity we required, so we opted to capture particles with a high efficiency filter to then weigh the cumulative mass change of filters. This allowed for rapid, accurate, and sensitive detection of carryover after several hundred hours of testing. The filters used were MERV 13 filters which can capture particles down to 1µm with >90% efficiency.

The test consisted of multiple measurements of the filters' weight during 650 hours of run time. Each filter was weighed on a 10mg sensitive electronic mass scale three times for each weight measurement to account for measurement variance. Desiccant flow rate, air flow rate, and uniformity were set to match the most aggressive performance targets for the duration of the test.

Figure 1: Mass accumulation test equipment

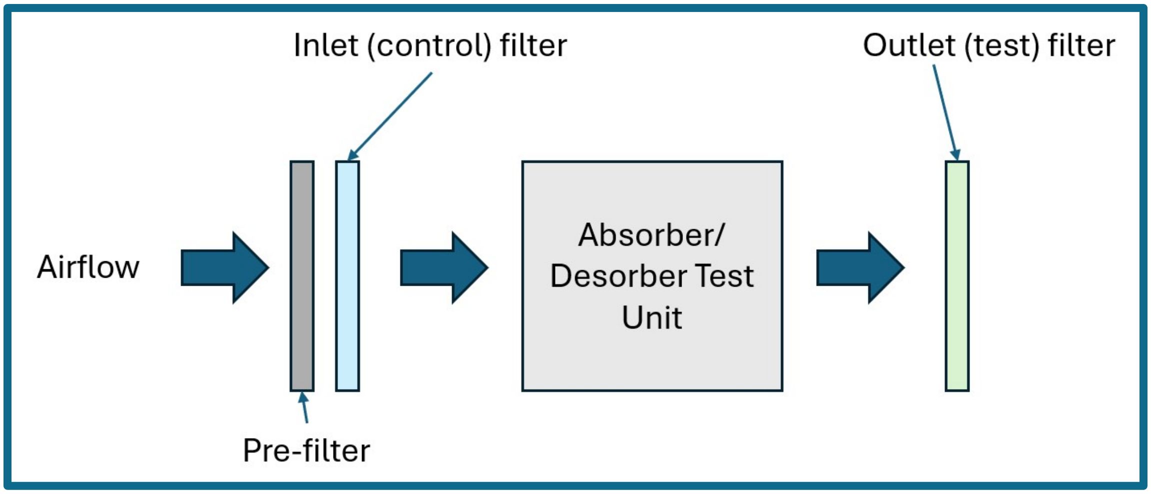

Figure 2: Mass accumulation airflow diagram

To replicate a full-scale setting, we tested the supply and regeneration airflow configurations used in the commercial product. The test apparatus, shown in Figure 1 and detailed in Figure 2, comprised an inlet filter housing that contained a pre-filter and a control-filter, the absorber/desorber being tested, and an outlet filter housing containing the test filter. The pre-filters remove any naturally occurring particles, such as dust or pollen, initially present in the inlet air. The control filters account for changes in filter mass that arise from changes in humidity in the testing environment. The filters capture all particles exiting the unit. Our test comprises weighing the test and control filters after running a known quantity of air through the test setup. Accordingly, carryover will manifest as a difference in the change of mass between the test and control filters, termed Dm. For example, if changes in humidity result in a 4 mg decrease in mass of the control filter, and the combination of humidity change and carryover result in a 1 mg decrease in mass of the test filter, we would recognize (-1 mg test) – (-4mg control) = 3 mg of carryover in the system.

Prior to gathering all the data, the absorber and desorber used in the test were put through a representative shipping protocol. This protocol replicates the potential vibration and shock stresses the units would undergo during transportation. This test involved loading the absorber and desorber into a standard truck which subsequently drove for 90 minutes.

Following the shipment simulation, the filters are occasionally removed from the assembly and weighed on a scale with 10 mg sensitivity; the mass difference Δm is converted to Parts Per Billion (PPB) of lithium chloride (LiCl) based on air flow rate and total run time assuming that any mass increase arises entirely from accumulation of 40% desiccant solution droplets and aerosols. This assumption would be considered conservative as any dust, debris or additional water in low concentration desiccant would be counted as LiCl.

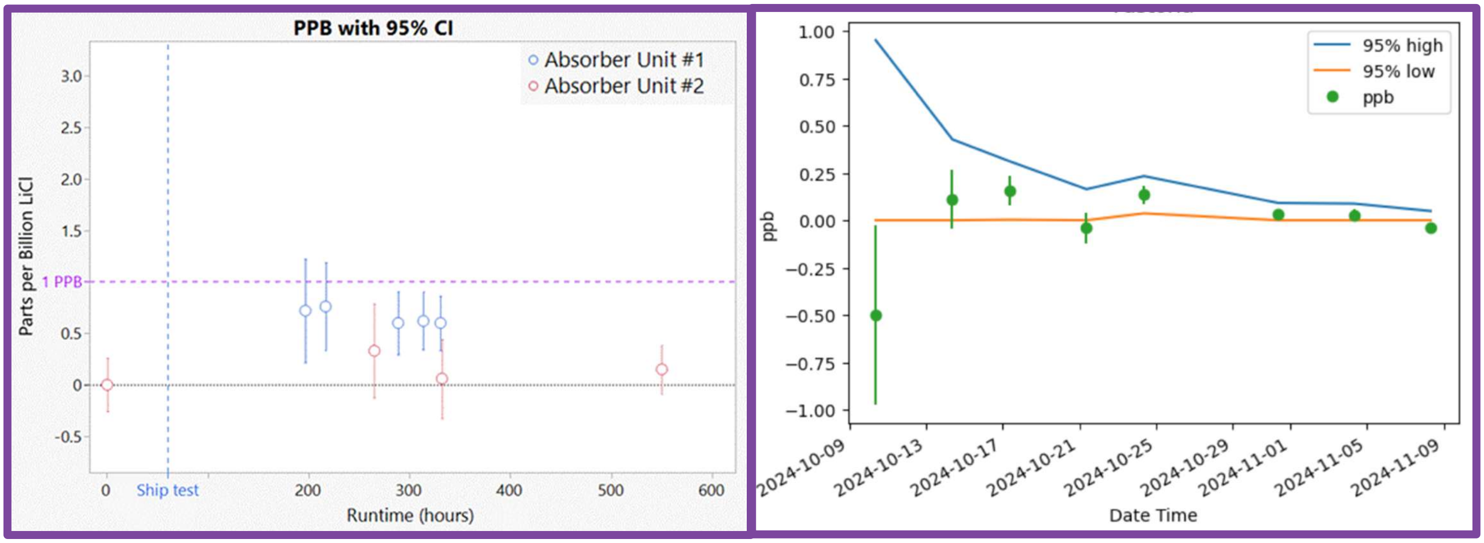

Figure 3a: Absorber mass accumulation limit data initial (left) test demonstrated 1 ppb limit, long term absorber test (right) shows 95% confidence limit of under 80 parts per trillion

The concentrations of LiCl in the outlet airstream of the absorber and desorber were plotted with 95% confidence intervals in Figures 3a and 3b. **Both the absorber and desorber test units exhibited <1 PPB accumulation rate with 99.99% confidence**. The actual concentration of desiccant in the air stream is likely lower, given the conservative assumptions in converting filter mass change to PPB outlined above. The absorber test was repeated for an extended time; we reached our systematic detection limit and demonstrated an upper limit of 80 parts per trillion.

Accordingly, we can conclude that a negligible quantity of desiccant escapes the system during unit operation. This assures us that the desiccant initially loaded into the system will last the full 15-year life of the unit and that desiccant will not exit the unit or enter the building.

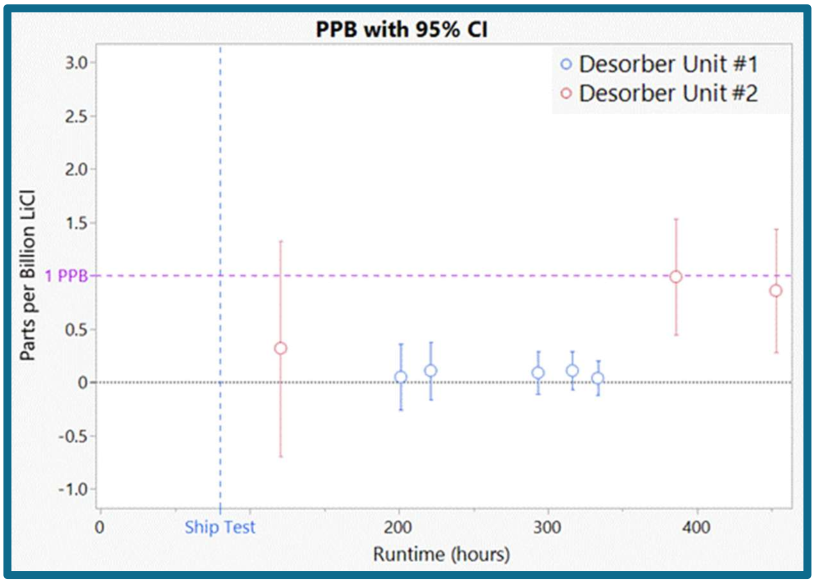

Figure 3b: Desorber mass accumulation limit data

Test #2 – Corrosion Rate

The objective of test #2 was to further evaluate the corrosive impact of the delivered air, measured at <1 PPB of LiCl, since limited research exists directly tying concentration of LiCl in air to corrosion rates. We acquired a set of advanced sensors to directly measure the corrosion rate of a sensitive metal surface: a technology used in thin film corrosion sensors. This test serves as a direct measurement of corrosion rate that can be compared against ASTM standards for atmospheric corrosivity. This allows us to directly reference an established standard that can be used to determine potential corrosion rates.

The sensor used was manufactured by iButtonLink™: it uses a current detection algorithm to measure the thickness of two thin films, one copper and the other silver, with nanometer precision. These types of sensors have been used by IBM and other companies to monitor atmospheric corrosion in data centers and similar sensitive environments to high precision and are extremely sensitive to corrosive chemicals such as a LiCl solution.

We built a sub-scale absorber test apparatus, to approximately 1:5 scale, using the same construction materials as the commercial absorber. We placed the test sensor within the airstream exiting this sub-scale absorber, approximately 1 foot downstream from the absorber outlet. A second sensor, serving as a control, was placed in ambient conditions in the same laboratory as the sub-scale absorber. (Note that this sub-scale absorber was validated using a variety of desiccant detection methods including the filter mass accumulation used in the mass accumulation test in Test #1 and an ASTM G4-95 copper coupon used in Test #3 below)

The test consisted of taking thickness measurements before and after exposing the sensor to operating conditions with nominal air flow and desiccant flow rates over a period of 1500 hours of run time.

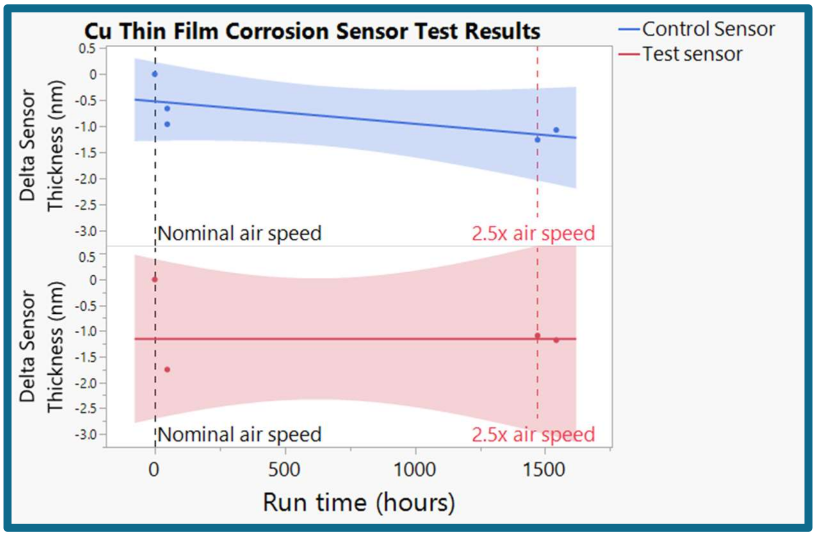

Figure 4: Corrosion sensor test data

As shown in Figure 4, no significant change in thin film thickness was detected over the course of the test. Using the 95% confidence intervals we can bound our thickness loss to less than 25nm per year. Accordingly, **we can conclude with 99.999% confidence that the corrosion rate is below the threshold of 100nm/year for ISO corrosivity index C1.** This is the lowest ISO category, allowing us to conclude that our supplied air is non-corrosive.

Test #3 – ASTM Field Test

While laboratory testing provides strong evidence that our systems show negligible carryover in a controlled environment, further evidence from a field deployed unit confirms our system robustness in the "real world" and serves as a final confirmation of our carryover testing under uncontrolled field conditions.

Shipping and installing a unit creates stresses and allows for settling within the unit. It is difficult to accurately reproduce these effects in laboratory tests, even with simulated shipping conditions. Furthermore, any accelerated rate of corrosion in the field is what ultimately is most important to customers.

For this test we placed bare, uncoated copper coupons in the supply side air stream of our engineering test units deployed at field test sites. The units were shipped from California to Tampa, Florida, U.S.A. and ran continuously at a normal load for 3400 hours. Six copper coupons were placed in the ducting immediately on the exit from the unit covering the lower half of the duct. Additional control coupons were installed inside the unit, in a place where no process air supply would contact the coupons allowing us to account for any ambient environmental reactions with air moisture or other sources.

All coupons were weighed and measured as per ASTM G4-95 standards prior to installation to then be photographed and installed after unit commissioning. After 3400 hours of continuous run time, the coupons were inspected and photographed once again in site.

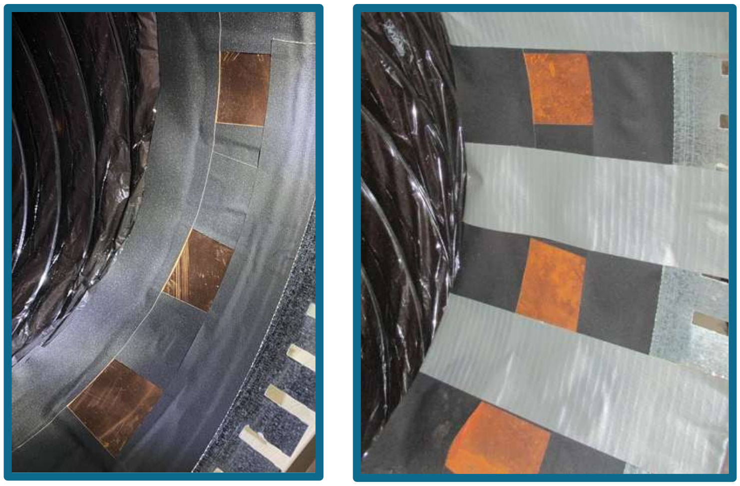
Figure 5a: Coupons in air stream before (left) & after (right) 3,400 hours of run time

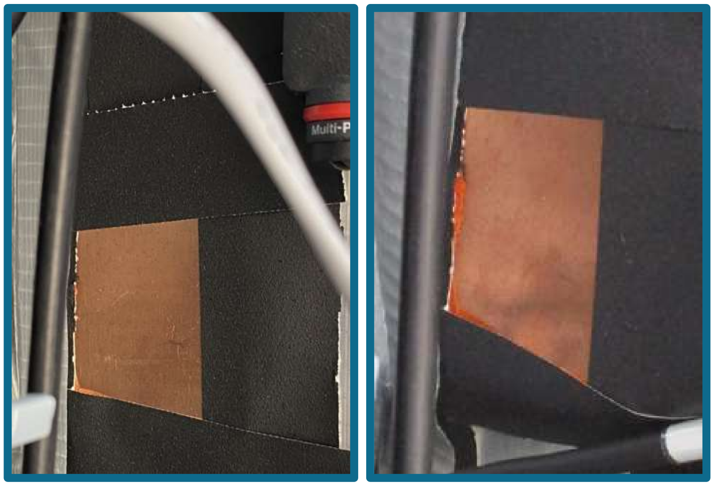

Figure 5b: Ambient coupons before (left) & after (right) 3,400 hours of run time

No corrosion was observed on the test coupons, moreover the control and test coupons exhibited the same general surface dulling due to atmospheric moisture as seen in Figures 5a and 5b. For comparison, we exposed a 2nd testing coupon to LiCl for a short period of time, as you may see in Figure 6. This coupon showed a rapid and visually obvious green copper oxide/chloride reaction.

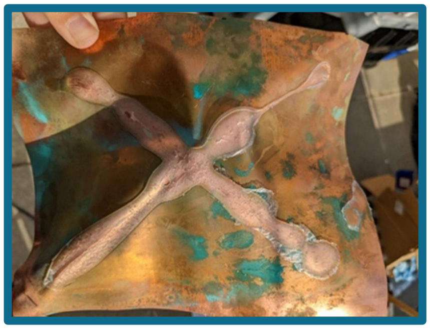
Figure 6: Coupon exposed to LiCl

Conclusions

The tests performed confirm that through our extensive engineering and research we have develop a product that demonstrates:

- A negligible amount (<1 PPB) of desiccant mass being carried out of the system into either the regeneration or process airstreams
- The supply air presents a non-corrosive environment, specifically below an ISO C1 environment with 99.999% confidence
- A robust design that even after field installation and operation in an uncontrolled environment shows no corrosion after 3500 hours of operation.

Full-scale lab testing, small-scale lab testing, and sustained field operation have all shown little to no presence of desiccant in the air stream using multiple sensitive detection methodologies. We are confident that we have designed a system that reduces the risk of carryover to a negligible level thus eliminating any concern for the use of liquid desiccant in our DOAS.

Several of these tests, including the mass accumulation test and field coupon exposure tests, continue through the present day. Mojave remains focused on producing a reliable and robust product; we will continue and expand on these results with more aggressive testing to enhance our understanding of our safety margins.

We are very excited to bring our technology to every corner of the world as our Liquid Desiccant Dedicated Outdoor Air System, ArctiDry DX, can create billions of dollars of economic value while reducing the climate impact of the AC industry by over 100 million metric tons CO2e annually.

Mojave produces novel liquid desiccant systems designed to change the nature of air conditioning by dramatically increasing energy efficiency and reducing the climate impact of AC. Mojave's patented technology cools and dehumidifies the air, enabling the independent control of dew point and dry bulb. By focusing on dehumidification, lowering energy consumption, reducing refrigerant use, and improving indoor air quality for commercial buildings, Mojave’s ArctiDry DX product is an ideal solution for Dedicated Outdoor Air Systems (DOAS). When compared to other alternatives on the market, ArctiDry DX offers a highly reliable, lowest-cost-of-ownership product that reduces energy use by 40 to 60%. Mojave, founded in 2022 to commercialize a decade-long, Palo Alto Research Center (PARC) R&D project, has received seed funding from At One Ventures, Fifth Wall, Xerox Ventures, and others.