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<u>Final Report</u>

LIQUID DESICCANT SYSTEM FOR COMBINED HUMIDITY AND CHLORIDE CONTROL

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14. ABSTRACT

A more efficient, lower cost means for reducing indoor humidity is an important part of any plan to reduce the Air Force's $4.5 billion annual cost for aircraft maintenance related to corrosion. A novel, high latent air conditioner that integrates a liquid-desiccant circuit into a conventional compressor-based DX air conditioner (LDDX) was studied as a Corrosion Mitigation System (CMS)that could efficiently maintain an aircraft shelter at a relative humidity below 40%. A 5-ton, 2,000 cfm LDDX CMS was designed, fabricated and lab tested. Based on the laboratory tests, the prototype is projected to almost triple the latent cooling provided by a conventional DX air conditioner, i.e., with both units operating under very hot, humid ambient conditions (110/87 F DB/WB) the LDDX CMS prototype provides 34.2 lb/h of moisture removal at a moisture removal efficiency (MRE) of 7.37 lb/kWh versus 11.9 lb/h and 2.6 lb/kWh for the conventional air conditioner. Although operating hours were limited (i.e., on the order of 100 hours), the LDDX-AD CMS prototype operated with no detectable carryover of liquid desiccant droplets in the supply air.

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Executive Summary

The Air Force spends $4.5 billion annually on aircraft maintenance related to corrosion. The source of this corrosion is frequently airborne chlorides that, after settling on metal parts of stored material, absorb moisture to create an electrolyte that promotes galvanic corrosion.

A comprehensive approach to protecting stored material from corrosion must both limit the ambient relative humidity and filter chloride particles from the air. Humidity control alone in storage is not sufficient since once chloride particles have settled on the material, corrosion will proceed when the material is moved from the low-rh storage into a high-rh environment and the settled chloride particles absorb moisture.

Work was performed in this project in two phases. The Phase I work performed the following principal tasks:

- The conceptual design of a mobile Corrosion Mitigation System (CMS) that can supply 1,000 scfm (75 lb/min) of deeply dried, high pressure air directly to the interior of parked aircrafts.
- The conceptual design of a CMS that can maintain an aircraft shelter at less than 40% relative humidity by supplying the shelter with upward of 2,000 scfm of ventilation air that has been dried to a dewpoint below 50^{o}F.
- The assessment of a liquid-desiccant conditioner that simultaneously dries the air and scrubs out chloride particles.
- The determination of safety margins that will insure the operation of a liquid-desiccant CMS with zero carryover of desiccant droplets
- The execution of preliminary proof-of-concept tests for a low-cost means to monitor the deposition rate of chloride particles
- The assessment of a membrane-based liquid-desiccant conditioner as part of a CMS.

Work was more focused in Phase II and performed the following principal tasks:

- The detailed design of a 2,000 cfm, 5-ton mobile CMS prototype for shelters
- The fabrication of the CMS prototype
- The laboratory verification of the CMS prototype's performance
- The preparation of a preliminary Safety Hazard Analysis for the CMS prototype

Conceptual Design of a Mobile Liquid Desiccant CMS for the Delivery of Deeply Dried, High Pressure Air

A key requirement for a CMS that delivers deeply dried, high pressure air directly to the interior of parked aircraft is that the CMS's refrigeration system can supply air with a dewpoint below 32^{o}F without ice accumulating on its evaporator. This requirement can be met by applying AILR's wicking-fin technology to the CMS's evaporator.

In a wicking-fin evaporator the aluminum fins of a conventional plate-fin evaporator are replaced with thin, wicking surfaces.that are continuously wetted by a cooled flow of liquid desiccant. The process air is cooled and dried as it flows over the desiccant-wetted surfaces. The desiccant, which absorbs sensible and latent energy from the process air, is maintained at a low temperature as it repeatedly flows over the evaporator's refrigerant tubes.

Since the water vapor removed from the process air is absorbed by the desiccant, a wicking-fin evaporator can operate with refrigerant tube temperatures as low as -40°F without ice accumulating on its surfaces.

In Phase I, a 1,000 scfm (75 lb/min) liquid-desiccant CMS that uses wicking-fin technology was designed to have the following characteristics:

- At ambient conditions typical of a summer design-day in southeastern U.S., the LDDX CMS with wicking-fin technology (LDDX-WF) delivers 32.5°F dewpoint air at 77.6°F.
- In applications where supply pressures are low, the LDDX-WF CMS power requirements are 7.07 lb/kWh (147 watt-hours per pint). (When supplying air at the same dewpoint, the power requirements for a commercial off-the-shelf solid-desiccant system is 1.73 times higher at 4.09 lb/kWh, or 254 watt-hours per pint.)
- The LDDX-WF CMS operates in a regime where the air velocity through the liquid-desiccant heat exchangers is too low to entrain desiccant droplets, i.e., air velocities would have to be more than twice the design values before droplet entrainment became a problem.
- The particle capture efficiencies of the desiccant-wetted surfaces of the LDDX-WF are too low to act at the unit's final filter. Consequently, the LDDX-WF CMS includes a HEPA filter that removes at least 99.97% of 0.1 micron particles and higher percentage of both larger and smaller particles. The HEPA filter also provides a back-up defense against the carryover of desiccant droplets in the delivered air.
- The LDDX-WF CMS has additional roughing filters upstream of the liquid-desiccant heat exchangers.

The Conceptual Design of a Liquid Desiccant CMS for Shelters

The requirements for an LDDX CMS that maintains a dry, chloride-free environment within a shelter for aircraft and aerospace ground equipment (AGE) will be very different than those for the mobile system that supplies deeply dried air directly to parked aircraft. In general, the shelter requires that a larger volume of air be treated, but the supply dewpoint will not be as low.

The Phase I conceptual design of the CMS for shelters maintains a 20,000 square foot facility at 78°F and 38% rh. The indoor dewpoint and absolute humidity at these conditions are 50.4°F and 0.007733 lb/lb. We assume that positive pressure sufficient to prevent significant infiltration can be maintained by introducing 0.1 cfm/ft^2 of treated outdoor air into the shelter. For design-day conditions representative of a southeastern U.S. location, the CMS for shelters must then treat 2,000 cfm of ambient air initially at 86°F and 0.0188 lb/lb (78°F wetbulb temperature) and dried to a humidity less than 0.007733 lb/lb.

The LDDX CMS for shelters is a packaged cooling system that exploits the fact that the amount of water absorbed by a desiccant depends almost exclusively on the relative humidity of its environment—the higher the relatively humidity the more water absorbed by the desiccant. For a conventional DX air conditioner, the process air leaving the evaporator is close to 100% rh. The relative humidity of the cooling air leaving the condenser will depend on its initial humidity and its temperature rise as it gains heat from the condenser. Since the relative humidity of air decreases by about a factor of two for every 20°F increase in temperature and the temperature rise for the cooling air through the condenser is on the order of 20°F, the relative humidity of the air leaving the condenser is almost always less than 50%, and often closer to 35%. Under these conditions, a desiccant that circulates between the process air and the cooling air will passively "pump" moisture from the process air to the cooling air. The rate at which moisture is pumped can be high, more than doubling the amount of latent cooling provided by the air conditioner under many operating conditions.

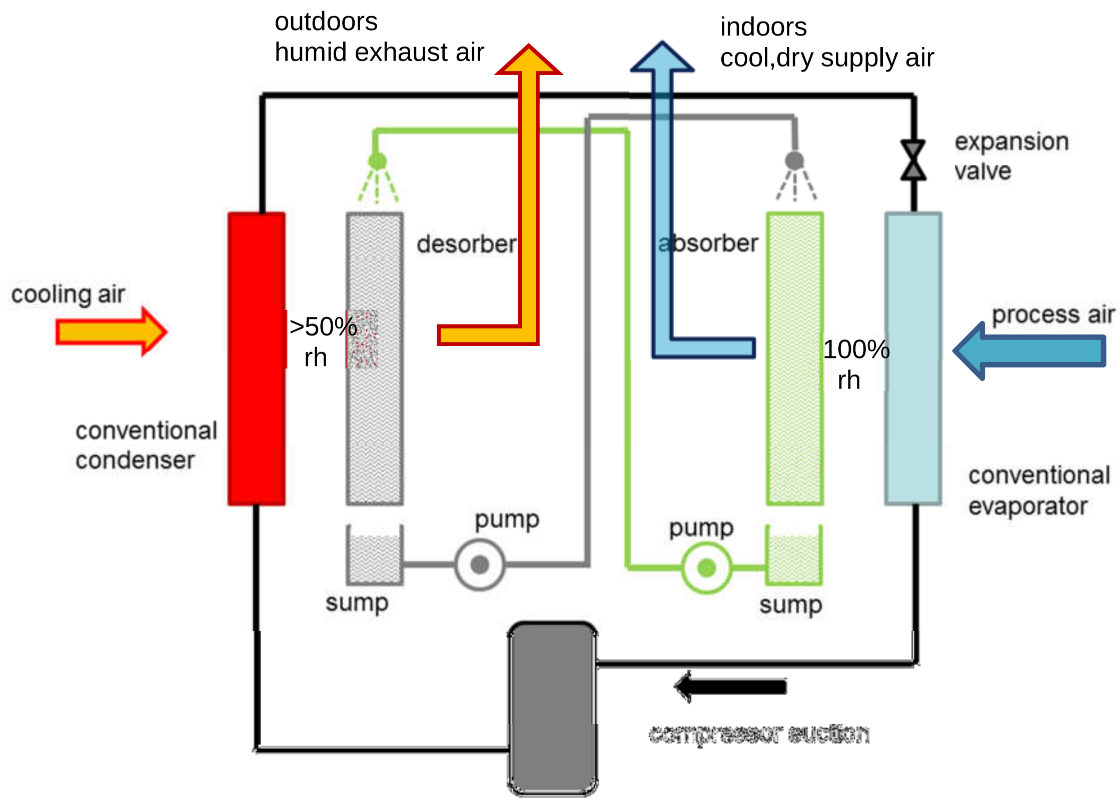


Figure E.1 – Integrated Liquid-Desiccant DX Corrosion Mitigation System (CMS LDDX) For Aircraft Shelter Applications

As shown in the functional schematic that appears in Figure E.1, the proposed LDDX CMS for shelters implements this humidity pump by recirculating a liquid desiccant between two desiccant-wetted, adiabatic porous pads—the high relative humidity air leaving the evaporator of the DX air conditioner flowing through one bed and the low relative humidity air leaving its condenser flowing through the other. Additional features of this LDDX with adiabatic pads (LDDX-AD) are:

- The compressor-based refrigeration circuit for the LDDX-AD is essentially identical to that used in a conventional DX air conditioner.
- The desiccant desorber and absorber are simple pads of corrugated, fiberglass contact media with no internal cooling (i.e., they operate adiabatically).

- When ambient conditions are naturally dry, the desiccant flow can be turned off and the LDDX-AD reverts to a conventional DX air conditioner that supplies mostly sensible cooling.

To illustrate the potential energy savings for the shelter LDDX-AD CMS, its performance was compared to a commercial off-the-shelf DX air conditioner that uses a combination of a deep evaporator and low evaporator temperature to deliver 2,000 scfm of ventilation air at the same dewpoint as the LDDX-AD CMS, i.e., 49.4°F dewpoint for the delivered air which will maintain the shelter at 78°F and 38% rh.

The most significant different between the LDDX-AD CMS and the commercial off-the-shelf alternative is the operating temperatures of their evaporators. The LDDX-AD CMS achieves the required 49.4°F supply dewpoint by first cooling the air to saturated conditions at 59.7°F and then passively pumping moisture from this saturated air to reduce its dewpoint to the required level. The evaporator for the LDDX operates at 53.3°F.

In contrast to this relatively high evaporator temperature, the commercial off-the-shelf system operates with a 43.0°F evaporator temperature. Keeping the same assumption for fan power and condenser temperature for the two systems, the LDDX-AD CMS has a power requirement for water removal of 9.93 lb/kWh (104.7 watt-hour/pint) versus 6.22 lb/kWh (167.1 watt-hour/pint) for the commercial off-the-shelf alternative—a savings of 39%.

A HEPA filter at the supply air discharge from the LDDX-AD CMS will ensure the delivery of air with no airborne chloride particles.

Commercial Viability of the LDDX CMSs

Both the shelter and mobile LDDX CMSs are modified DX air conditioners. Much of the tooling and manufacturing procedures needed to produce them are familiar to the HVAC industry. Although not as common in the HVAC industry, the corrugated fiberglass contact media used in both LDDX CMSs is commercially available. With no expensive capital investments for specialized tooling, the first cost premium for the LDDX CMSs should be modest and payback periods based on energy savings, relatively short.

Capture of Airborne Chloride Particles by the LDDX CMS

All liquid-desiccant dehumidifiers that bring the liquid desiccant in direct contact with the process air will act as wet scrubbers. However, Phase I laboratory tests showed that the filter efficiency cannot match that of a standard HEPA filter, i.e., at an air velocity representative of nominal operation, the LDDX capture efficiency was 89.6% at 10 microns and decreased to 5.4% at 0.5 microns. These capture efficiencies are far below the +99.9% that can be achieved with a HEPA filter.

Operation of the LDDX CMS with Zero Carryover of Desiccant Droplets

The Phase I measurement of particle capture efficiency were made on a wicking-fin LDDX. These tests confirmed that desiccant droplets were not entrained in the process air: i.e., in no size range do more particles leave the LDDX than enter. As confirmed in the Phase II work, this zero-carryover operation applies to the operation of both the mobile (i.e., wicking-fin) and shelter (i.e., adiabatic pad) LDDX CMSs (assuming that the air velocities at the face of desiccant-wetted media are no higher than those at which the particle measurements were made). Furthermore, the LDDX CMSs will operate with a very comfortable safety margin protecting against desiccant droplet entrainment, since the desiccant-wetted media that they will use—GLASdek ™ manufactured by the Munters Corporation—can operate at face velocities that are almost twice those at which the particle measurements were made without droplet entrainment (based on performance data in the manufacturer's engineering manual).

A Low-Cost Instrument for Monitoring Chloride Deposition Rates

A comprehensive Corrosion Mitigation System must both control indoor relative humidity and suppress airborne chloride particles. Whereas relatively inexpensive, reliable instrumentation is available to measure relative humidity, the same is not true for instrumentation that would measure chloride particles. Furthermore, since the corrosion induced by chloride particles only occurs after the particles have settled onto a sensitive surface, the required instrumentation should measure chloride deposition rates and not airborne concentrations.

The feasibility of a simple means to monitor chloride deposition rates was studied in the Phase I work. This simple means involved monitoring the chloride concentration of a known volume of water that is exposed to ambient. Commercially available instrumentation could then be used to measure the chloride concentration of the water. In the cursory feasibility test, the procedure measured a chloride deposition rate of 34 mg/m^2-day at a site 0.25 mi from the Atlantic Ocean—a value that is consistent with deposition rates reported for ocean locations—and a deposition rate of zero at an indoor location.

The Detailed Design of a 2,000 cfm, 5-ton Mobile CMS for Shelters

An LDDX CMS for shelters will be most effective if it uses adiabatic, desiccant-wetted pads as configured in Figure E.1. Following this design approach allowed us to build on our experience with the 5-ton LDDX-AD that was tested at Fort Belvoir under the ESTCP program.

Engineering drawings of the CMS prototype appear in Figure E.2. At operating conditions at which the American Refrigeration Institute (ARI) rates roof-top air conditioners (i.e., the ARI A rating conditions with entering process air at 80/67 F DB/WB and ambient air for cooling at 95/75 F DB/WB), the CMS is projected to have the following performance:

Supply Air Temperature	2,000 cfm
Supply Air Humidity Ratio	3,400 cfm
Supply Air Relative Humidity	48.3%
Total Cooling	65,820 Btu/h
Latent Cooling	43,718 Btu/h
Sensible Heat Ratio (SHR) for Process	0.336
Moisture Removal Efficiency (compressor-based)	9.96 lb/kWh

The Fabrication of the CMS Prototype

Fabrication of the CMS prototype was a nine-month effort that began in January 2017 and ended in September 2017. The completed CMS prototype is shown in Figure E.3.

As built, the prototype has the following physical characteristic:

Height	60 in
Width	62 in
Length	87 in
Weight	TBD

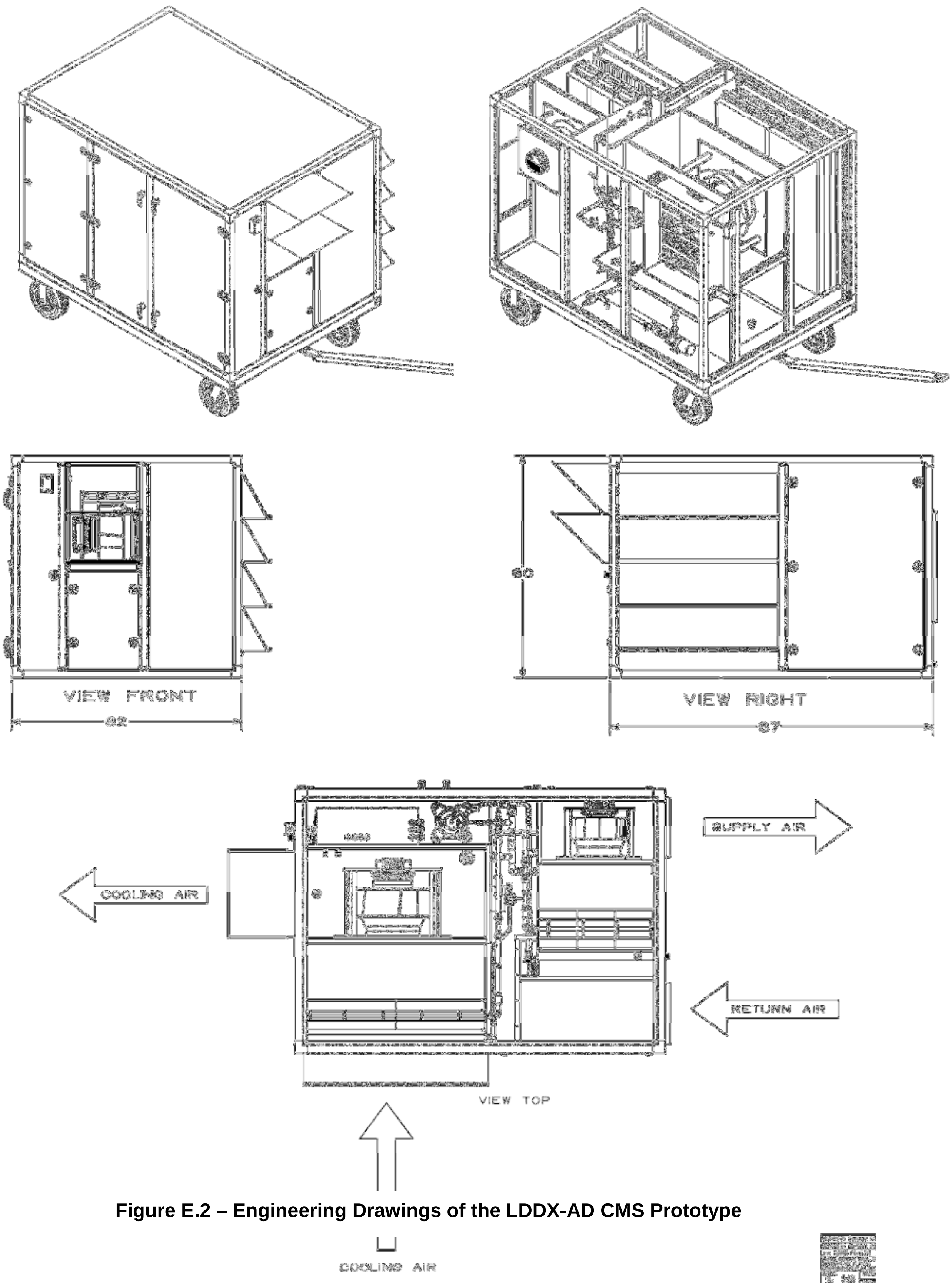


Figure E.2 – Engineering Drawings of the LDDX-AD CMS Prototype

Figure E.3 –The Completed LDDX-AD CMS Prototype

The Laboratory Verification of the CMS Prototype's Performance

Laboratory testing of the CMS prototype fully charged with liquid desiccant commenced in February 2018. Initial tests in February and March identified several instrumentation problems and one aspect of the design that required modification: the frame for the filter for the process air was reinforced to prevent air leakage around the filter during operation.

On May 4, 2018 the CMS prototype was operated in our shop for approximately four hours under near steady conditions. Humidity in the shop was sufficiently high to permit operation without exchanging air between the prototype's condenser and the evaporator (i.e., shop air was drawn directly into the evaporator.) In order to reproduce operation at a high ambient temperature and humidity, the condenser air was recirculated, and the air-to-air heat exchanger in this recirculated loop was modulated to adjust air temperature. All condensate draining off the evaporator was discharged to a sewer line.

The measured performance of the CMS prototype on May 4 at 15:35 is shown on a psychrometric chart in Figure E.4. The state points on this chart are:

1 – entering process air (drawn from shop)
2 – air leaving evaporator
3 – exiting process air (delivered to shop)
4 – entering cooling air (recirculated air after cooled in AAHX)
5 – air leaving condenser
6 – exiting cooling air (recirculated air before cooled in AAHX)

A detailed description of the CMS prototype's performance on May 4 at 15:35 appears in Table E.1.

During the four hours of operation on May 4, the concentration of desiccant slowly increased. This unsteadiness in operation slightly penalized the CMS prototype's performance because the desorber was rejecting more water than was absorbed from the process air (i.e., in addition to the water load from the absorber, the desorber was removing water from the desiccant stored in the sump).

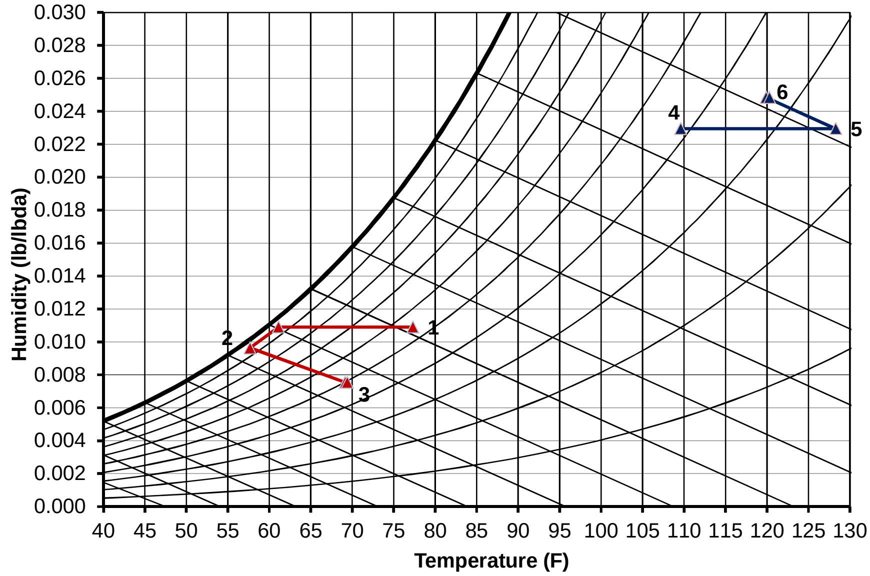


Figure E.4 – Psychrometric Performance of the LDDX-AD on May 4

A computer projection of steady-state performance at the operating conditions shown in Table E.1 predicts a higher desiccant concentration (0.308 versus 0.297 when expressed as equivalent LiCl) and a 10% increase in latent cooling (34.21 kg/h versus 31.35). This simulated performance appears in Table E.1 in the column labeled "projected steady".

The primary effect of the desiccant circuit is to almost triple the water removal of the DX air conditioner from 11.86 kg/h to 34.21 kg/h. The desiccant-wetted pads do increase fan power, but the pressure drops across these pads are projected to be small—0.10 in w.c. for the absorber and 0.05 w.c. for the desorber—and so in the increase in fan power will not be significant. The 3% loss in total cooling caused by the supply of warm desiccant to the absorber is then the most significant cost to be paid for almost tripling the air conditioner's latent cooling.

Table E.1 – Detailed Performance of CMS Prototype on May 4

	T	w	rh
	F	lb/lb	%
process air entering CMS	77.3	0.0111	55.4
process air leaving evaportor	57.7	0.0096	95.0
process air exiting CMS	69.4	0.0078	51.0
cooling air entering CMS	109.6	0.0229	41.4
cooling air leaving condenser	128.3	0.0229	24.6
cooling air exiting CMS	120.3	0.0248	33.0

	measured unsteady	projected steady	
process air flow rate	2,097		cfm
cooling air flow rate	3,919		cfm
desiccant flow to absorber	0.35		gpm
desiccant flow to desorber	0.52		gpm
T desiccant supply	80.2		F
C desiccant supply (as LiCl)	0.297	0.308	
pump power	115		W
fan power	3,466		W
compressor power	4,639		W
total power	8,220		W
condenser Q rejection	72,380		Btu/h
evaporator Q absorption	57,719		Btu/h
net total cooling	52,856	55,877	Btu/h
evaporator moisture removal	11.86		lb/h
total moisture removal	31.35	34.21	lb/h
desorber moisture rejection	31.37		lb/h
EER (compressor-based)	11.4	12.0	
moisture removal efficiency (MRE) (compressor-based)	6.76	7.37	lb/kWh

1.0 Introduction

The Air Force spends $4.5 billion annually on aircraft maintenance related to corrosion. The source of this corrosion is frequently airborne chlorides that, after settling on stored material, absorb moisture from the air to create an electrolyte that promotes galvanic corrosion.

A comprehensive approach to protecting stored material from corrosion must both limit the ambient relative humidity and filter chloride particles from the air. Humidity control alone in storage is not sufficient since once chloride particles have settled on the material, corrosion will proceed when the material is moved from the low-RH storage into a high-RH environment and the settled chloride particles absorb moisture.

Liquid desiccants provide a unique opportunity to minimize corrosion of stored material both by reducing ambient relative humidity and filtering particulates from the air. Desiccants—both liquid and solid—have long been used to control humidity in archival and storage facilities. Cargocaire (now a part of the Munters Corporation, the global leader in dehumidification) derived its name from the function its solid desiccant dehumidifiers played in protecting stored cargo from damage caused by humidity.

The overall objective of the Phase I work was to determine the most promising configuration for a liquid-desiccant, corrosion mitigation system (CMS) for aircraft shelters that both controls ambient relative humidity to less than 50% while removing chloride-salt particles from the ambient air. Specific objectives identified in the proposal for the Phase I included:

- Define the performance requirements for a liquid-desiccant CMS for aircraft shelter
- Understand the design and operation of liquid-desiccant CMSs that use the alternative approaches of (1) directly contacting the desiccant with the process air, and (2) separating the desiccant and the process air with a membrane
- Determine whether the functions of humidity control and particle removal can be combined in a single component.
- Define the viability of solar energy as the primary energy input to a CMS
- Define O&M requirements for each type of CMS
- Confirm that a CMS that uses liquid desiccants will be more attractive to the Air Force than available alternatives that might use solid desiccants or conventional dehumidifiers.

Early discussions with personnel at Robins AFB identified the need to include smaller, mobile systems that serve individual aircraft and AGE. The definition of performance requirements for these smaller systems was added as a Phase I objective.

Phase II work focused on the design, fabrication and testing of a prototypical liquid-desiccant CMS for aircraft shelters. Specific objectives for the Phase II work included:

- Design a mobile, liquid-desiccant CMS prototype that supplies 2,000 cfm of deeply dried air to an aircraft shelter
- Build and laboratory test the CMS prototype
- Identify technology transfer opportunities into government and civilian market
- Identify potential safety and hazard concerns for liquid-desiccant CMS

2.0 Liquid Desiccant Technology Applied to Particle Filtration

All liquid-desiccant dehumidifiers that bring the liquid desiccant in direct contact with the process air will act as wet scrubbers. Furthermore, since the liquid desiccant most commonly used in dehumidifiers—solutions of lithium chloride—is a strong biocide, manufacturers of liquid desiccant systems often highlight the air cleaning that occurs when their equipment captures and kills pathogen-laden particles.

The value of a liquid-desiccant CMS will be enhanced if chloride particles are captured as part of the air drying process. However, since there are very effective traditional methods for air filtration (i.e., HEPA filter), a liquid-desiccant CMS that filters air only provides value if it can match the extremely high capture rates of HEPA filters while introducing lower air-side pressure drops.

Particle filtration tests were conducted in Phase I using the corrugated media shown in Figure 2.1. As described in Sections 3.0 and 4.0, this media is used in the LDDX CMSs that are proposed for both mobile and shelter applications.

Particle filtration tests were conducted with 1.5 gpm of 30% lithium chloride solution delivered to the top of a wicking-fin evaporator that uses corrugated, fiberglass media (GLASdek 5090 media). The air velocity at the face of the corrugated media was 1.8 m/s (360 fpm). (The evaporator, which is shown in Figure 2.2, is part of a high latent air conditioner for HVAC applications that AILR developed for the Department of Defense in a parallel ESTCP project.)

An Airnet II (model 501-4) manufactured by Particle Measuring Systems was used to measure the concentration of particles in the air entering and leaving the desiccant-wetted media. Particle counts were summed over one second intervals in four size bins: 0.5 micron, 1.0 micron, 5.0 micron and 10.0 micron.

Sampling was alternated between the entering and leaving air streams. Two samples of between 4 and 6 minutes were collected at both locations.

The raw data is shown in Figure 2.3. This data, converted to “particles per cubic foot” and averaged over the sampling period, is shown in Table 2.1.

Figure 2.1 – Fiberglass Corrugated Media within a Wicking-Fin Evaporator

Figure 2.2 – A Wicking-Fin Evaporator with Corrugated Media

As shown in Table 2.1, the desiccant-wetted corrugated media is a moderately good particle filter for larger particles (89.6% capture at 10 microns), but it is a poor filter for small particles (5.4% capture at 0.5 microns). Airborne salt droplets will typically be 1 micron or greater. Although a significant number can be captured, the desiccant-wetted media alone will not be sufficient to insure that the CMS delivers chloride-free air when the air velocity at the face of the media is 1.8 m/s or lower.

Although it may be possible to increase particle capture by increasing the air velocity (and thereby increasing the inertial forces that drive particles towards the media) it was judged unlikely that particle captures rates that match a HEPA filter (i.e., >99.9%) could be reached without unacceptably high pressure drops and potential desiccant droplet entrainment by the high velocity air. Consequently, the mobile and shelter LDDX CMSs presented in Sections 3.0 and 4.0 do not rely on filtration by the liquid desiccant; both include a HEPA filter to suppress air-borne chloride particles.

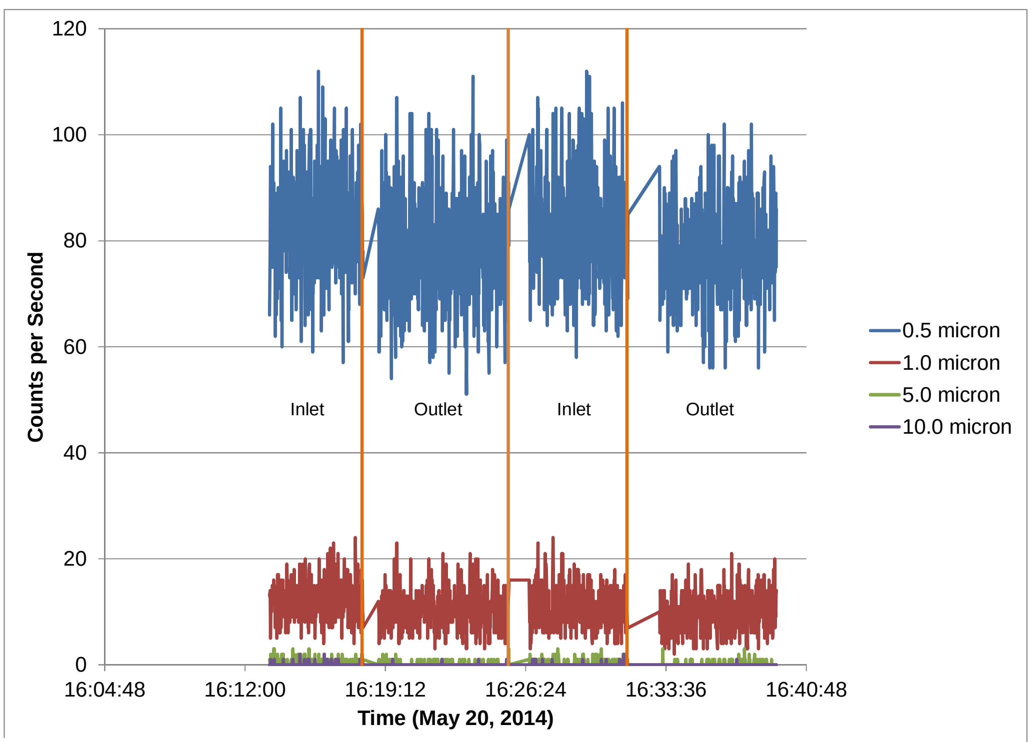


Figure 2.3 – Raw Data from Particle Capture Experiment

Table 2.1 Results of Phase I Particle Capture Experiment

Particles per Cubic Foot

	0.5 micron	1.0 micron	5.0 micron	10 micron
Inlet	49,675	7,235	245	45.7
Outlet	47,044	6,197	91	6.0
Inlet	49,647	6,606	195	27.5
Outlet	46,956	6,000	91	1.7
Pct Capture	5.4%	11.9%	58.6%	89.6%

It is important to note that the data in Table 2.1 implies that air flows through the corrugated media at 1.8 m/s in direct contact with the liquid desiccant without entraining droplets of lithium chloride: i.e., in no size range do more particles leave the corrugated media than enter. This zero-carryover operation should apply to the operation of both the mobile and shelter LDDX CMSs where the velocities at the face of the corrugated media are in the range of 1.3 to 1.7 m/s. (The LDDX CMSs will operate with a very comfortable safety margin protecting against desiccant droplet entrainment, since the corrugated media that they will use—GLASdek manufactured by the Munters Corporation—can operate at face velocities as high as 3.5 m/s without droplet entrainment.)

Table 3.1

Desicair Model Number MDU-300-PPC
Nominal Performance with First Stage DX AC

Supply Air Volume	300	scfm
Design-Day Ambient Air Conditions		
Temperature	85	F
Humidity	153.6	gr/lb
Relative Humidity	84.0%	
First-Stage DX Air Conditioner		
Supply Conditions to Solid Desiccant Rotor		
Temperature	55	F
Humidity	64.0	gr/lb
Total Cooling	2.41	tons
Supply Conditions to Aircraft		
Temperature	103	F
Humidity	12.4	gr/lb
Dewpoint	13.6	F
Water Removal		
First-Stage DX	17.3	lb/h
Second-Stage Solid Desiccant	10.0	lb/h
Total	27.2	lb/h
Net Cooling	2.01	tons
Power Requirements		
Reactivation Heater	6,092	W
DX Compressor	1,515	W
Fan	TBD	
Supply Pressure	18.2	in w.c.
Efficiency	291	Wh/pint
(based on compressor and reactivation power only)		

3.0 Liquid Desiccant Technology Applied to a Mobile System

3.1 State of Practice

Working with Logis-Tech (LTi), a service company that maintains dehumidified storage facilities for military and industrial customers, AILR identified the critical operating characteristics for a commercial off-the-shelf mobile Corrosion Mitigation System (CMS) representative of the systems now used by LTi.

Table 3.1 presents the nominal operation of the Desicair MDU-300 offered by Logis-Tech. The MDU-300 is designed to deeply dry the saturated air that leaves a first-stage cooling coil. In Table 3.1, the first-stage coil is the evaporator of an air-cooled compressor-based air conditioner that delivers saturated air at 55^{o}F. The second-stage solid-desiccant rotor, which is reactivated with 270^{o}F air, dries the 55^{o}F saturated air to a dewpoint of 13.6^{o}F.

As part of the drying process, the solid-desiccant rotor will "dump" heat into the supply air as the 270^{o}F regeneration section rotates into the supply air. Whereas the first-stage direct-expansion (DX) air conditioner delivers 2.4 tons of cooling, the "heat dump" negates about 0.4 tons of this cooling. The final result is that the dry supply air that leaves the solid-desiccant rotor is quite hot—for the design-day operation shown in Table 3.1 it is 104^{o}F. Post cooling can be used to lower the temperature of the delivered air.

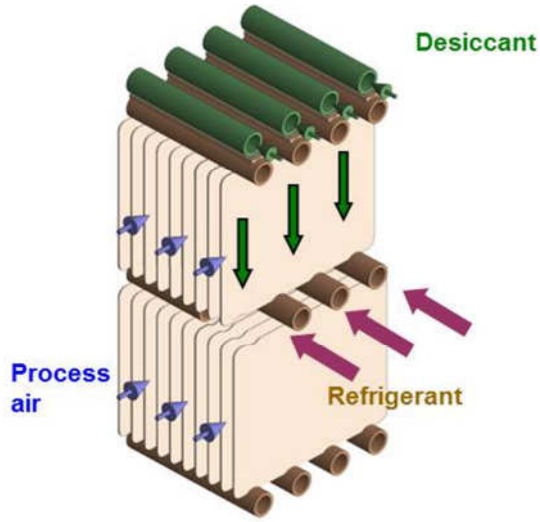


Figure 3.1 – Wicking-Fin Heat and Mass Exchanger

3.2 An Integrated Liquid-Desiccant Wicking-Fin DX (LDDX-WF) Mobile CMS

A compressor-based DX air conditioner that applies a liquid desiccant to increase latent cooling can meet the demands of the mobile CMS much more efficiently than a commercial off-the-shelf solid-desiccant system. This application of a liquid desiccant has two important consequences: (1) the air conditioner can deliver air with a dewpoint that is lower than the suction temperature of the evaporator, and (2) the air conditioner can deliver air with a dewpoint that is below 32°F without ice accumulating on its evaporator.

As shown in Figure 3.1, the technology that enables the integrated liquid-desiccant DX air conditioner uses a heat and mass exchanger (HMX) that has refrigerant tubes embedded between stacks of non-metallic wicking fins. This wicking-fin liquid-desiccant DX air conditioner will be referred to as an LDDX-WF.

Low flows of liquid desiccant are delivered to the top of the wicking-fin HMX. If the HMX is an evaporator, the liquid desiccant (green arrows in Figure 3.2) is cooled as it flows over the uppermost refrigerant tubes (brown). The cool desiccant then flows from the tubes onto the first row of fins. The wicking surfaces of the fins uniformly spread the desiccant. The process air that flows horizontally between the fins is simultaneously cooled and dried as it comes in contact with the desiccant-wetted surfaces. Heat is released as the desiccant absorbs water and its temperature rises. However, the fin length is designed so that the desiccant's temperature rises only a few degrees before it flows onto the next lower row of cooling tubes. When properly designed, the convective heat transfer of the desiccant on the fin is an effective substitute for the conductive heat transfer of the aluminum fins used in a conventional finned-tube heat exchanger.

Figure 3.2 – Wicking Fins Implemented with Corrugated Media

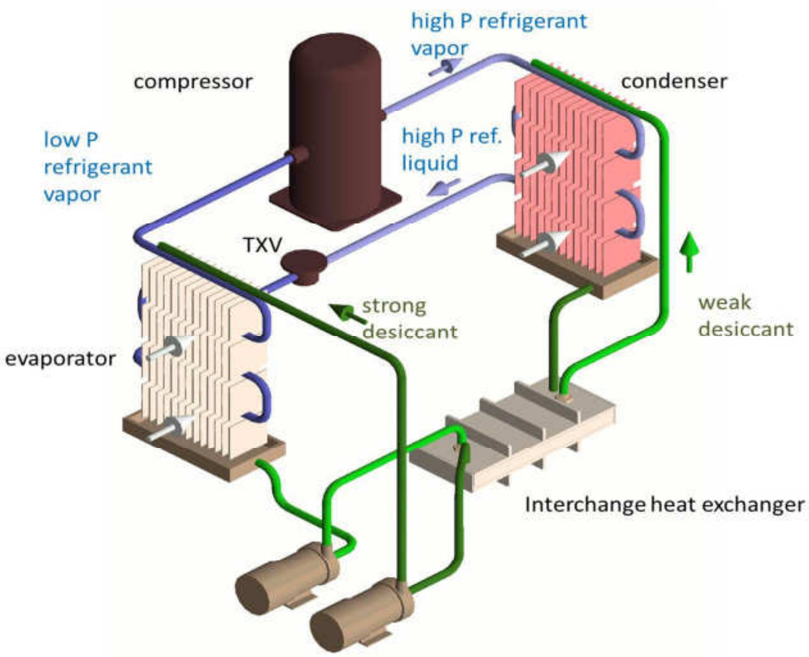


Figure 3.3 – Refrigerant and Desiccant Circuits for the LDDX

In the latest version of the LDDX-WF the corrugated fiberglass media shown in Figure 3.2 replaces the flat plastic fins shown in Figure 3.1. This corrugated media, which is manufactured and sold by the Munters Corporation under the trade name GLASdek ™, provides better heat and mass transfer between the air and the desiccant than flat fins.

The refrigerant circuit for the LDDX-WF functions identically to that of a conventional DX AC. However, as shown in Figure 3.3, the aluminum-finned heat exchangers commonly used as the evaporator and condenser of a conventional AC are replaced by the wicking-fin HMXs.

The high affinity of a liquid desiccant for water vapor allows a wicking-fin evaporator to dry air to a dewpoint that can be 10°F to 30°F lower than the suction temperature of the evaporator. Furthermore, since the water vapor that is removed from the process air is absorbed by the liquid desiccant, which can have a freeze point as low as -75°F, the LDDX can deliver air with dewpoints well below 32°F without ice accumulating on the evaporator.

As shown in Figure 3.3, the water absorbed by the liquid desiccant in the evaporator is rejected to ambient in the LDDX-WF's condenser. This coil is again a wicking-fin HMX. However, in the condenser, the liquid desiccant is heated as it flows over the refrigerant tubes. The desiccant releases water as its temperature rises. The cooling air that flows through the condenser carries the released water, as well as the heat rejected by the condenser, out to ambient.

As shown in Figure 3.3, the LDDX-WF may use an interchange heat exchanger (IHX) to precool the warm, concentrated desiccant flowing from the condenser to the evaporator using the cool, weak desiccant flowing in the opposite direction. This heat exchange increases the LDDX-WF's efficiency by reducing the heat dumped onto the evaporator by the desiccant.

A mobile LDDX-WF CMS that supplies 75 lb/min (1,000 scfm) of deeply dried air will be similar to the 3-ton HVAC LDDX shown in Figure 3.4. For the CMS application, this LDDX is modified to include a first-stage conventional DX air conditioner so that a conventional aluminum-fin evaporator is located immediately upstream of the wicking-fin evaporator and a conventional aluminum-fin condenser is located immediately upstream of the wicking-fin condenser.

The following description is the projected performance of a mobile LDDX-WF CMS that supplies 1,000 scfm of deeply dried, highly filtered air to one or more aircraft:

- The LDDX-WF CMS delivers 32.5^{o}F dewpoint air at 77.6^{o}F (assuming the design-day conditions shown in Table 3.1). Although this dewpoint is significantly higher than the 13.6^{o}F supply-air dewpoint for the solid-desiccant commercial off-the-shelf system described in Table 3.1, it is sufficiently dry to meet the needs of the mobile CMS. At the supply dry-bulb temperature, the delivered air has a 19.3% relative humidity, which is well below the 40% target relative humidity below which corrosion is effectively suppressed. Incidental sensible heat gain that will occur on the design day (85^{o}F ambient) will increase the delivered air's dry-bulb temperature and further decrease relative humidity.
- Ignoring the power for the supply fan (which could be large if the CMS must supply high pressure air at several pounds-per-square-inch), the LDDX-WF CMS dehumidifies air on the design day at an efficiency equal to 147 watt-hours/pint. This value is less than half the 291 watt-hours/pint required by the compressor and reactivation heater of the commercial off-the-shelf solid-desiccant system shown in Table 3.1. (The commercial off-the-shelf system is delivering drier air than the LDDX-WF CMS, but allowing for a lower reactivation temperature so that air is delivered at a 32.5^{o}F dewpoint only increases the efficiency of the commercial off-the-shelf system to 254 Wh/pint.)
- As discussed in Section 2.0, the corrugated media wetted with liquid desiccant (see Figure 3.2) that is the heat and mass transfer surface in the LDDX-WF acts as a moderately efficient particle filter. However, particle capture efficiencies of the corrugated media are too low for it to be the LDDX-WF's final filter. Consequently, the LDDX-WF CMS includes a HEPA filter that removes at least 99.97% of 0.1 micron particles (which are the size particle that are most difficult to capture) and higher percentage of both larger and smaller particles.
- The LDDX-WF CMS also has roughing filters upstream of the liquid-desiccant heat exchangers.
- The LDDX-WF CMS operates in a regime where the air velocity through the corrugated wicking fins is much too low to strip desiccant droplets from the fins. The product manual for the Munters corrugated media lists a face velocity limit of 3.5 m/s below which the entrainment of liquid by air does not occur. At design operating conditions for the LDDX-WF CMS, the 1.3 m/s air velocity at the face of the corrugated fins is far below this limit.

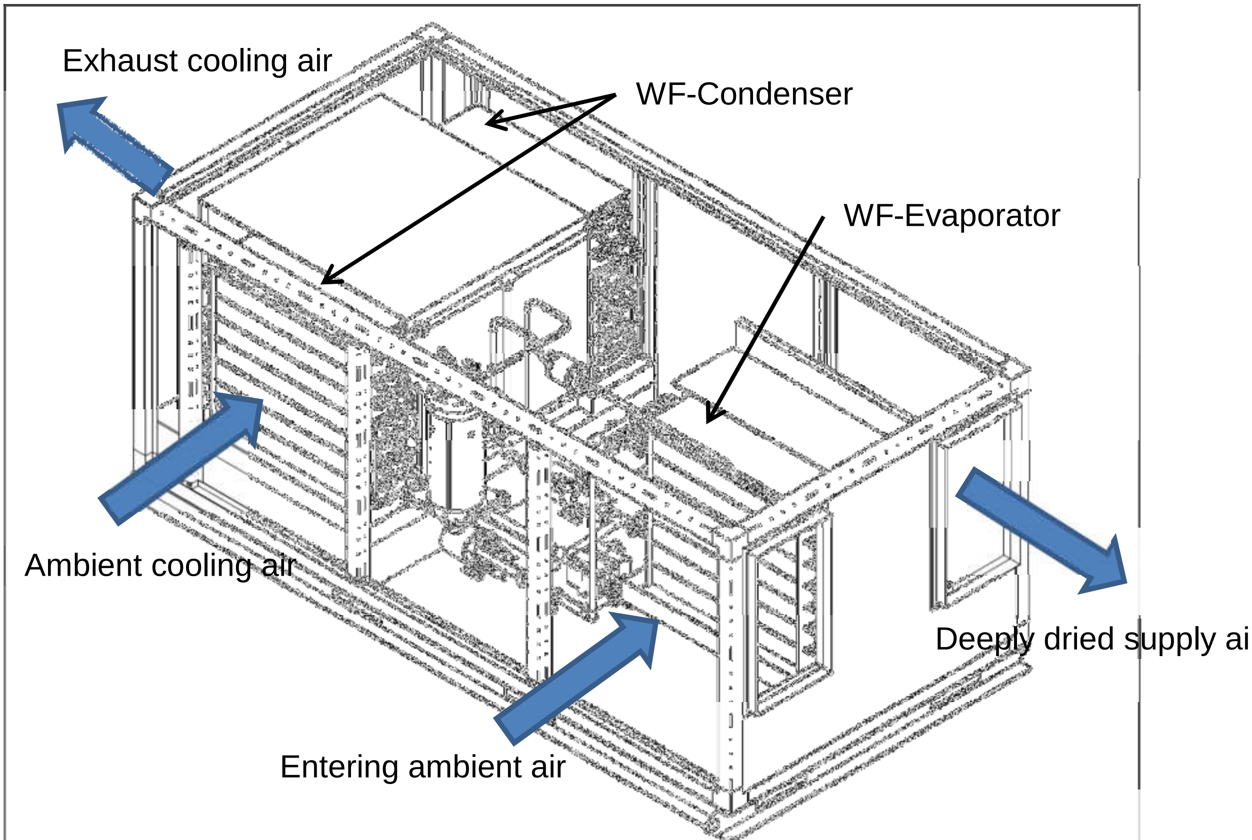


Figure 3.4 – 75 lb/min (1,000 scfm) LDDX CMS for Mobile Applications

Figure 4.1 – Tensioned Fabric and Pre-Engineered Steel Shelters provided by Logis-Tech

4.0 Liquid Desiccant Technology Applied to Shelters

4.1 Shelter Requirements

The requirements for an LDDX CMS that maintains a dry, chloride-free environment within a shelter for aircraft and AGE will be very different than those for the mobile system. In general, the shelter application requires that a larger volume of air be treated, but the supply dewpoint will not be as low.

Shelters will have varying needs for dehumidification that depend primarily on (1) size of the shelter, (2) geographical location, and (3) operations performed within the shelter. Since it was not possible to study more than one shelter application in the Phase I work, we chose a 20,000 square-foot structure that is similar to the shelters provided by Logis-Tech shown in Figure 4.1. The primary function of the target structure is the passive storage of aircraft or aerospace ground equipment with no significant maintenance activities performed in the shelter. Since maintenance activities do not occur within the shelter, this target structure has minimal internal sources of either heat or humidity. A low humidity environment can be maintained within the shelter by an LDDX-AD CMS that supplies the shelter with ambient air that is dried to a humidity that is slightly lower than the target humidity required to suppress corrosion.

For the design exercise presented here, we assume that the shelter is maintained at 78^{o}F and 38% rh. The indoor dewpoint and absolute humidity at these conditions are 50.4^{o}F and 0.007733 lb/lb. We also assume that positive pressure sufficient to prevent significant infiltration can be maintained by introducing 0.1 cfm/ft^2 of treated outdoor air into the shelter. For design day conditions representative of a southeastern U.S. location, the LDDX-AD CMS must then treat 2,000 cfm of ambient air initially at 86^{o}F and 0.0188 lb/lb (78^{o}F wetbulb temperature) and dried to a humidity somewhat below 0.007733 lb/lb. Sensible loads are relatively small for this target application, and, if necessary, they are served by a parallel cooling system that can be optimized for sensible cooling since the CMS handles all latent loads. With these assumptions, the key metric for evaluating alternative CMSs is the technology's water removal efficiency (expressed as either pounds water per kWh or watt-hours per pint of removed water—which are standard metrics for evaluating dehumidifiers).

4.2 State of Practice

The commercial off-the-shelf alternative to the LDDX CMS for aircraft shelters is a compressor-based DX air conditioner. In applications where sensible cooling loads are low, this cooling system can be modified so that some of the condenser heat is returned to the conditioned space so that indoor temperature does not drop to unacceptably low values (which would drive up relative humidity).

Whether or not the commercial off-the-shelf DX air conditioner uses condenser reheat, the absolute humidity of the air it supplies is determined by its evaporator temperature. A high efficiency DX air conditioner might supply saturated air at a temperature a few degrees above the evaporator. For the shelter application where air must be supplied with a dewpoint below 50.4^oF, a conventional DX air conditioner might operate with an evaporator at approximately 43^oF.

A DX air conditioner that processes warm, humid outdoor air (which is commonly called a Dedicated Outdoor Air System, or DOAS) provides much more cooling per volume of processed air than one that processes the return air from a building, e.g., return-air DX units typically provide cooling at 400 cfm per ton, while a DOAS might provide cooling at only 133 cfm per ton. The DOAS would use a very deep evaporator to reach this level of cooling. The equally high level of heat rejection by the condenser would be met by a combination of increased volume of cooling air and increased depth of coil. For the study presented here, we assume that the temperature of the cooling air increases 29^oF as it gains heat from the condenser and the condenser temperature is 7^oF above the temperature of the exiting cooling air. With these assumptions, the DX air conditioner is pumping heat from 44^oF to 119^oF. An efficient scroll compressor at these conditions would have a COP of 3.89. Allowing an additional 0.365 watts per cfm for fan power, the water-removal power requirement for the commercial off-the-shelf DX air conditioner is 6.22 lb/kWh (167.1 watt-hour/pint).

4.3 An Integrated Liquid-Desiccant DX (LDDX-AD) CMS for Shelters

The proposed LDDX CMS for shelters is a packaged cooling system that exploits the fact that the amount of water absorbed by a desiccant depends almost exclusively on the relative humidity of its environment—the higher the relatively humidity the more water absorbed by the desiccant. For a conventional DX air conditioner, the process air leaving the evaporator is close to 100% relative humidity. The relative humidity of the cooling air leaving the condenser will depend on its initial humidity and its temperature rise as it gains heat from the condenser. Since the relative humidity of air decreases by about a factor of two for every 20^oF increase in temperature and the temperature rise for the cooling air through the condenser is on the order of 20^oF, the relative humidity of the air leaving the condenser is almost always less than 50%, and often closer to 35%. Under these conditions, a desiccant—either solid or liquid—that circulates between the process air and the cooling air will passively "pump" moisture from the process air to the cooling air. The rate at which moisture is pumped can be high, more than doubling the amount of latent cooling provided by the air conditioner under many operating conditions.

As shown in the functional schematic that appears in Figure 4.2, the proposed LDDX CMS for shelters implements this humidity pump by recirculating a liquid desiccant between two desiccant-wetted, adiabatic porous pads—the high relative humidity air leaving the evaporator of the DX air conditioner flowing through one bed and the low relative humidity air leaving its condenser flowing through the other. Additional features of this LDDX with adiabatic pads (LDDX-AD) are:

- The compressor-based refrigeration circuit for the LDDX-AD is essentially identical to that used in a conventional DX air conditioner. Unlike the condenser and evaporator of the low-dewpoint LDDX-WF for the mobile CMS, the coils of the shelter LDDX use the same aluminum-fin/copper-tube technology that now is common in the HVAC industry.
- The desiccant desorber and absorber are simple pads of corrugated, fiberglass contact media, i.e., the same GLASdek ™ that functioned as wicking fins in the mobile LDDX-WF. The absorber/desorber pair will reduce the relative humidity of the supply air from 100% to less than 50% with minimal increase in electrical power for either the fans (to account for the pressure drop through the absorber and desorber) or the pumps.
- When ambient conditions are naturally dry, the desiccant flow can be turned off and the LDDX-AD reverts to a conventional DX air conditioner that supplies mostly sensible cooling.

With the liquid desiccant absorber/desorber pair shown in Figure 4.2, the LDDX-AD can match the supply dewpoint of a conventional DX system with an evaporator temperature that is at least

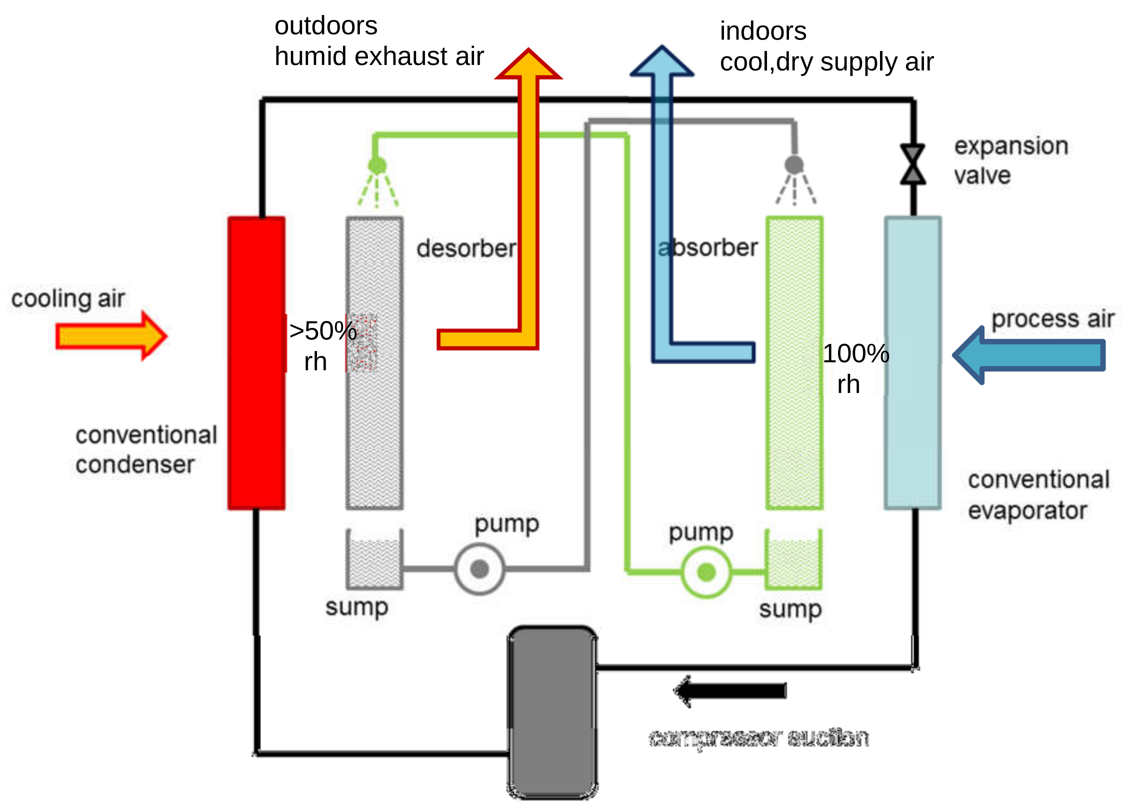


Figure 4.2 – Integrated Liquid-Desiccant DX Corrosion Mitigation System (CMS LDDX-AD) For Aircraft Shelter Applications

10°F higher. This reduction in temperature lift produces a significant increase in the efficiency of the compressor-based refrigeration circuit.

To illustrate the potential energy savings for the shelter LDDX-AD CMS, a system has been simulated that supplies air at the same dewpoint as the conventional DX system previously de-

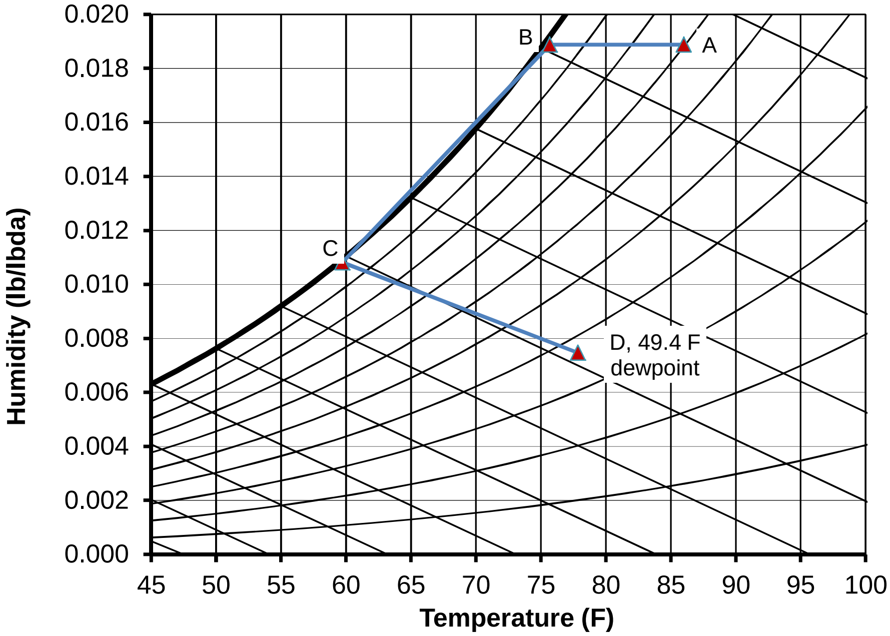


Figure 4.3 – Design-Day Operation of CMS LDDX

scribed that had a water-removal power requirement of 6.22 lb/kWh (167.1 watt-hour/pint). This simulation assumes that the DX evaporators for the two systems have identical approach temperatures (i.e., the evaporator suction temperature is 6.4°F below the air temperature leaving the evaporator), and both systems operate with the same condenser temperature (i.e., 122°F).

As shown in the psychrometric chart in Figure 4.3, the LDDX-AD CMS achieves the required 49.4°F supply dewpoint by first cooling the air to saturated conditions at 59.7°F and then passively pumping moisture from this saturated air to reduce its dewpoint to the required level. The DX evaporator for the LDDX-AD operates at 53.3°F as opposed to 43.0°F for the conventional system. Keeping the same assumption for fan power and condenser temperature as in the previous analysis, this increase in evaporator temperature reduces the water-removal power requirement from 6.22 lb/kWh (167.1 watt-hour/pint) to 9.93 lb/kWh (104.7 watt-hour/pint)—a savings of 39%.

As with the mobile LDDX-WF CMS, the system for aircraft shelters will use a HEPA filter that will remove at least 99.97% of 0.1 micron particles. (Although the corrugated fiberglass media used in the system's liquid-desiccant absorber and desorber provide some particle filtration, the degree of capture is not sufficient to insure a shelter environment that is essential free of chloride particles.)

Also similar to the mobile LDDX-WF CMS, the face velocities at the desiccant-wetted corrugated media in the shelter system will be well below levels that can entrain liquid desiccant. (Nominal face velocities will be less than half the value at which entrainment could be a problem.)

The O&M requirements of the shelter LDDX-WF CMS will be similar to those of a conventional DX air conditioner: air filters must be regularly replaced, fan belts must be inspected and replaced when worn, and motors must be serviced as necessary. As with the mobile system, the LDDX-WF CMS will have a roughing filter upstream of the desiccant-wetted components. This filter will reduce (or possibly eliminate) the need to replace liquid desiccant filters. If regular replacement of liquid filters is required, these filters will be cartridges that are easily replaced.

5.0 Monitoring of Chloride Deposition Rates

A comprehensive Corrosion Mitigation System (CMS) must both control indoor relative humidity and suppress airborne chloride particles. Whereas relatively inexpensive, reliable instrumentation is available to measure relative humidity, the same is not true for instrumentation that would measure chloride particles. Furthermore, since the corrosion induced by chloride particles only occurs after the particles have settled onto a sensitive surface, the required instrumentation should measure chloride deposition rates and not airborne concentrations.

The feasibility of a simple means to monitor chloride deposition rates was studied in the Phase I work. This simple means involved monitoring the chloride concentration of a known volume of water that is exposed to ambient.

Published data on chloride deposition rates at coastal and inland sites on Hawaii showed rates of 0.3 g to 1.4 g per square meter per day. At the maximum deposition rate in this range, a 1.0 cm deep pool of distilled water would gain chloride at the rate of approximately 140 ppm per day. This level of concentration is within the range of several instruments that are designed to continuously monitor the chloride concentration in supplies of potable water. As an example, the YSI 6050000 water-quality monitor has a range of zero to 1,000 ppm with a resolution of 0.01 ppm. A monitoring system that used an instrument similar to the YSI device and had the following additional characteristics could be a relatively low-cost, low-maintenance approach to continuously monitoring chloride deposition rates:

- a collection tray with a known face area open to the environment,
- a large reservoir of distilled water that fed water to the collection tray to make up for evaporative losses,
- a level sensor (or similar device) that metered the feed of distilled water from the reservoir to the collection tray so that the volume of water in the collection tray stayed at a preset value, and
- either a circulating pump or stirrer to insure a uniform concentration of chloride in the water sample.

The monitoring device would require routine maintenance to resupply the reservoir of distilled water and flush the collection tray when chloride levels exceeded the upper limit for the measuring device. However, the monitoring device could be designed so that the interval for this routine maintenance would be several months. In locations with very high deposition rates, the ratio of exposed open area of the tray to the volume of water could be adjusted to limit the daily increase in chloride concentration of the sample water.

The Phase I work included a first step towards defining the device for monitoring chloride deposition. In this work we demonstrated that chloride deposition rates could be determined by measuring the concentration of chloride in a distilled water sample after the sample has been mixed with salt that has deposited in a dish of known exposed surface area. Towards this end, a Petri dish with an exposed area of 62 cm^2 was placed in each of two areas: (a) a corner of an indoor office at AILR, and (b) an outdoor location that is approximately 0.25 mi from the ocean on the New Jersey shore (see photographs in Figure 5.1 and 5.2). After approximately two weeks exposure, chloride titrating strips were used to measure the chloride concentration of a 5 ml sample of water (initially distilled) from each Petri dish.

Both Petri dishes were weighed before and after the two-week exposure test. The “ocean” Petri dish gained approximately 40 mg. There was no measurable weight gain for the “office” Petri dish.

After the 5 ml sample of distilled water was added to each Petri dish, the water was stirred over the bottom surface of the dish. The titrating strips (shown in Figure 5.3) indicated a chloride concentration of 48 ppm in the water from the “ocean” Petri dish. No chloride was detected in the water sample from the “office” Petri dish.

Based on the chloride concentration and the exposure time, the chloride deposition rate at the ocean site was 34 mg/m^2-day. This value is consistent with chloride deposition rates measured at other ocean locations.

The preceding test supports the feasibility of the instrument to monitor chloride deposition that was described in the beginning of this section.

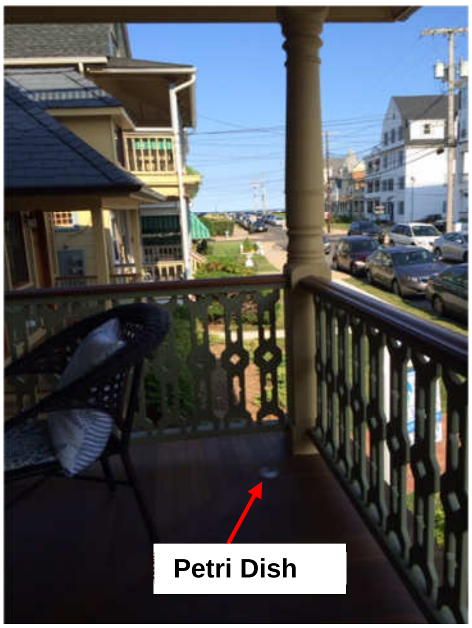


Figure 5.1 – Location for Sampling Chloride Deposition

Figure 5.2 – Aerial View of Sampling Site

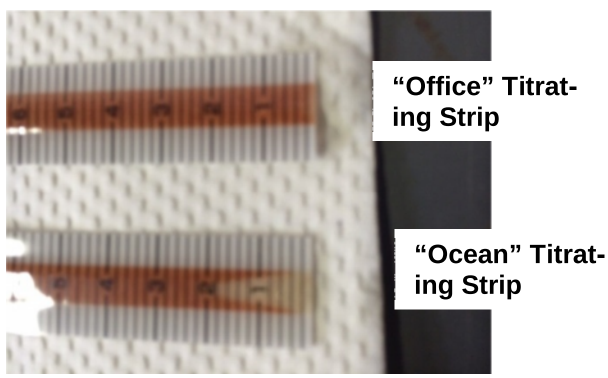


Figure 5.3 – Titrating Strip Measurement

6.0 Feasibility of a Membrane-Based Liquid Desiccant Conditioner

One of the original objectives of the Phase I work was to assess the feasibility of a liquid-desiccant CMS that used a membrane-based conditioner. This objective addressed the concern that a CMS that relied on a high chloride solution (i.e., lithium chloride) might inadvertently exacerbate corrosion.

A possible approach to insuring that a liquid-desiccant CMS does not create more problems than it solves would use a conditioner that prevented direct contact between the liquid desiccant and the process air. In work performed for the National Renewable Energy Laboratory (NREL), AILR developed a membrane-based conditioner that performs the required air/desiccant isolation. In this conditioner thin films of liquid desiccant flow behind a membrane that is highly permeable to gases (i.e., water vapor) but impermeable to aqueous liquids (i.e., solutions of lithium chloride).

The proposed Phase I task in which data was to be collected on the performance of the membrane-conditioner was not completed. This change in scope reflected the fact that AILR's direct-contact technology has proven its ability to operate with no entrainment of desiccant droplets. Furthermore, the addition of a HEPA filter to the LDDX provides additional security that desiccant droplets will not be present in the supply air.

7.0 The Detailed Design of a 2,000 cfm, 5-ton Mobile CMS for Shelters

Technical direction for the Phase II work was discussed at a May 26, 2016 planning meeting of the project participants. The meeting defined the major technical objective for the Phase II work: the design, fabrication and lab testing of a prototypical mobile LDDX CMS that could be applied to shelters.

An LDDX CMS will be most effective if it uses the technology in Figure 4.2 (i.e. adiabatic, desiccant-wetted pads—LDDX-AD). Following this design approach allowed us to build on our experience with the 5-ton LDDX-AD that was tested at Fort Belvoir under the ESTCP program. The Fort Belvoir field test did prove the performance of the LDDX-AD but it also uncovered several design weaknesses that created maintenance problems for the unit.

The design weaknesses in the Fort Belvoir prototype center on the desiccant-wetted pads that function as the absorber and desorber of water vapor. Approximately four weeks after start up, the desorber pad in the Fort Belvoir prototype collapsed. This failure was traced to a softening of the fiberglass media caused by contact with the desiccant that then allowed the pad to compress under its own weight. The compressed pad disengaged from its upper brace and then collapsed under the pressure from the flowing air.

Before finalizing the design of the CMS prototype, we proved the pad designs in a test rig that operated full size pads under conditions that duplicated operating conditions in the CMS prototype.

Engineering drawings of the CMS prototype appear in Figure 7.1 Key operating characteristics of the CMS prototype are as follows:

Supply Air Volume	2,000 cfm
Cooling Air Volume	3,400 cfm
Nominal Desiccant Flow Rate Absorber	0.35 gpm
Nominal Desiccant Flow Rate Desorber	0.52 gpm
Operating Voltage	208 V, 3 phase
Full Load Amps	40 A
Nominal Power	8.5 kW

The CMS prototype is designed to cool and dry a mixture of air that is mostly return air from the shelter with a minor fraction of outdoor air (on the order of 10%) so that the shelter is maintained at a positive pressure. At operating conditions at which the American Refrigeration Institute (ARI) rates roof-top air conditioners (i.e., the ARI A rating conditions with entering process air at 80/67 F DB/WB and ambient air for cooling at 95/75 F DB/WB), the CMS is projected to have the following performance:

Supply Air Temperature	2,000 cfm
Supply Air Humidity Ratio	3,400 cfm
Supply Air Relative Humidity	48.3%
Total Cooling	65,820 Btu/h
Latent Cooling	43,718 Btu/h
Sensible Heat Ratio (SHR) for Process	0.336
Moisture Removal Efficiency (compressor-based)	9.96 lb/kWh

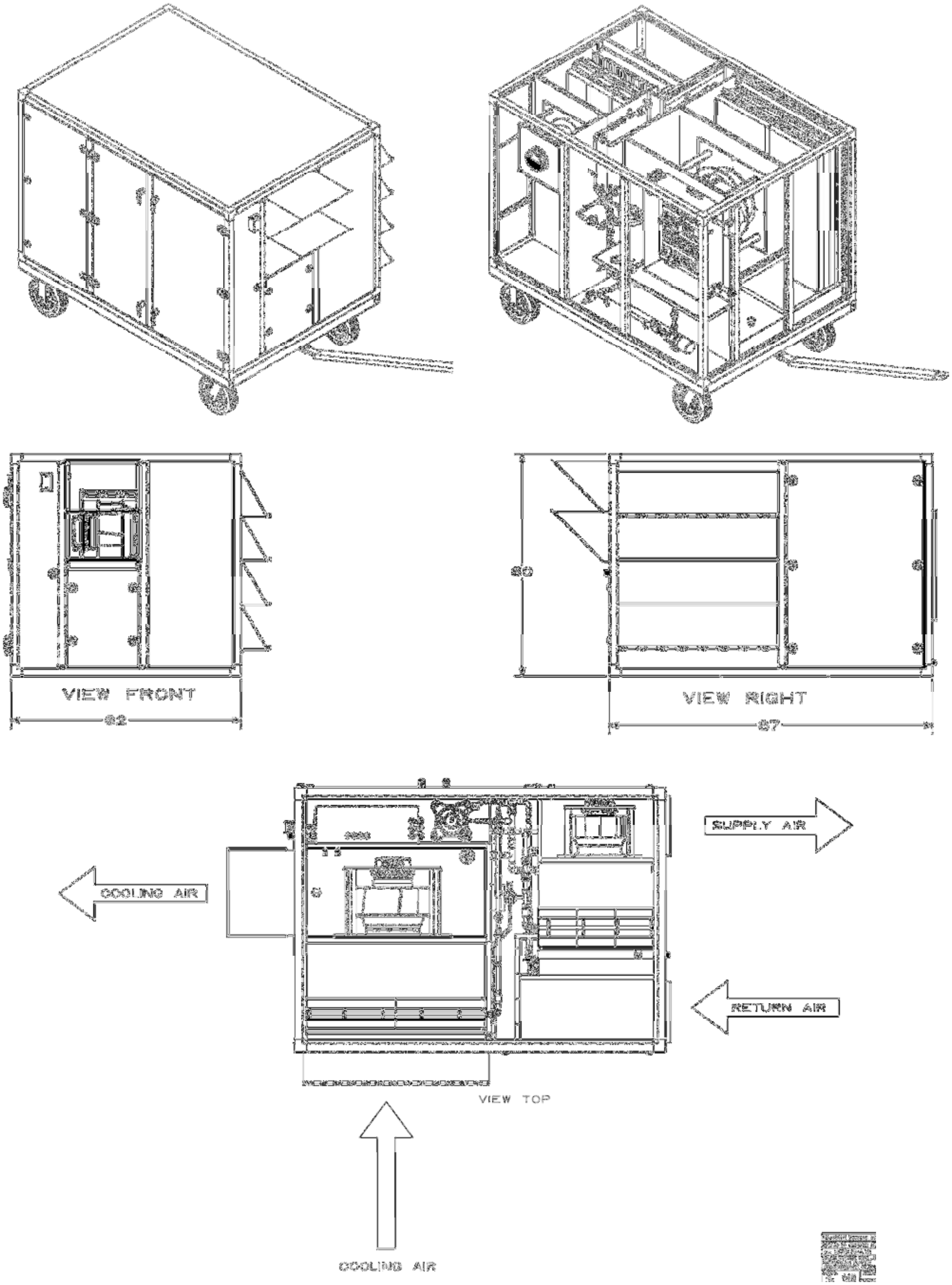


Figure 7.1 – Engineering Drawings of the LDDX-AD CMS Prototype

8.0 Fabrication of the Mobile CMS Prototype

Fabrication of the CMS prototype was a nine-month effort that began in January 2017 and ended in September 2017. Photographs of the CMS prototype, its mobile base and its sumps are shown in Figure 8.1.

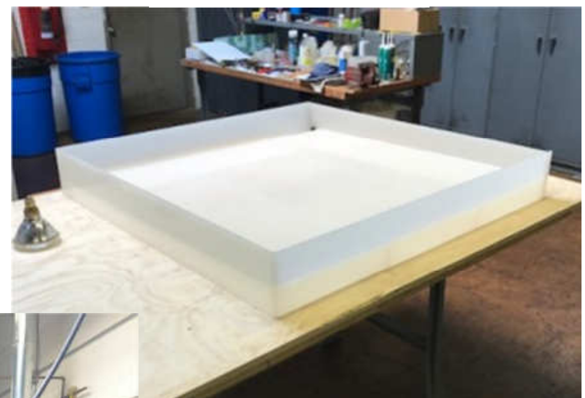
The most challenging aspect of the fabrication was the assembly of the polypropylene sumps for the liquid desiccant. Although the sumps in a commercial CMS will be relatively inexpensive, molded tanks, the sumps for the one-off prototype were welded assemblies that had requirements for (1) supporting the desiccant-wetted pads, (2) supporting droplet separators, (3) draining desiccant, (4) feeding desiccant to the supply pump. Photographs of the completed sumps are included Figure 8.1.

As built, the prototype has the following physical characteristic:

Height	60 in
Width	62 in
Length	87 in
Weight	1,300 lb

Absorber Sump

Mobile Base



Desorber Sump

Completed Unit

Figure 8.1 –Photographs of the LDDX-AD CMS Prototype

9.0 The Laboratory Verification of the CMS Prototype's Performance

The scheduling of work on the project required that the CMS prototype be tested in our shop during the winter when ambient sensible and latent loads are very low. Since it was not practical to create sensible and latent loads on the order of five tons, a test loop was implemented that simulated natural latent and sensible loads by directing a fraction of the warm, humid air discharged from the CMS prototype's condenser to its evaporator. Since the total heat rejected by the condenser includes the work of the compressor (in addition to the heat gained by the evaporator) the air directed from the condenser to the evaporator has too much sensible energy (relative to its latent energy). This excess sensible load in the air exchanged between the condenser and the evaporator was rejected to the shop through an air-to-air heat exchanger with a variable speed fan that controlled the amount of heat rejected to the room.

Figure 9.1 –LDDX-AD with Recirculation Plenums and Ducts

The CMS prototype with the plenums and ducts that comprise the test loop is shown in Figure 9.1.

Laboratory testing of the CMS prototype commenced in January 2018. Initial tests studied the performance of the CMS prototype without the liquid desiccant flowing. The objective of these tests was to confirm that the compressor-based direct-expansion (DX) portion of the system was operating correctly and that AILR's computer model of the DX subsystem accurately predicted its performance.

The laboratory test of the LDDX CMS without desiccant flow uncovered several operational problems in the unit and bugs in the analysis software. The most significant operational problem was a poorly secured air filter on the process side that allowed air to leak around the filter. The problem was corrected by installing a more robust mounting frame for the filter.

In reconciling the measured heat exchanges at the evaporator and condenser with the predictions of the analysis software an error was discovered in the conversion of the fan throat pressures into mass flows. Once the error was corrected, the predictions of the analysis software agreed with the measured heat exchange to approximately 6.0% for the evaporator and 8.9% for the condenser.

Laboratory testing of the CMS prototype fully charged with liquid desiccant commenced in February 2018. In the initial tests, it was not possible to reproduce ARI A test conditions. When the recirculation flow loop was adjusted to reproduce the test temperatures, the air was much too dry.

The test loop was modified so that 4.5 kW of steam could be injected into the air flow leaving the condenser. This modification is shown in Figure 9.2.

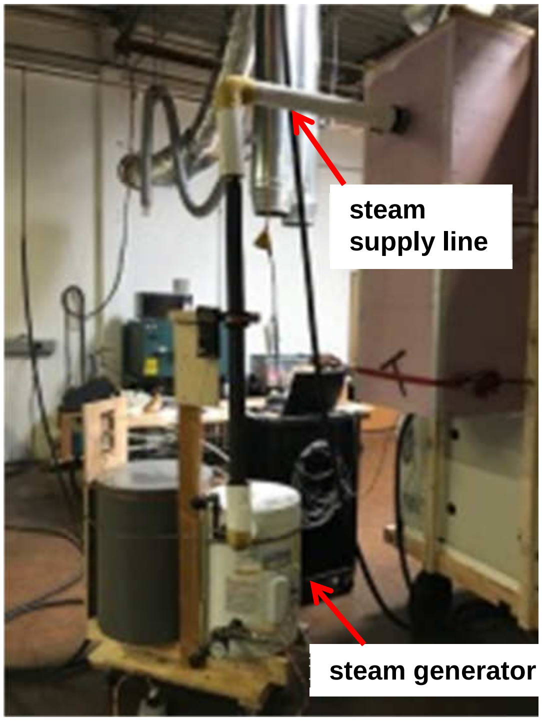


Figure 9.2 – Steam Augmentation for Recirculation Test Loop

One set of operating points averaged over 25 minutes of steady operation for the CMS prototype is plotted in the psychrometric chart shown in Figure 9.3 for the test loop running with full 4.5 kW steam generation. Under these operating conditions, the air humidity on both sides of the CMS prototype is higher than the values specified in the ARI A test conditions: process air and cooling air are entering the LDDX-AD at a 68.9 F and 79.4 F wetbulb temperatures versus ARI A conditions of 67.0 F and 75.0 F wetbulb temperatures.

For the measured performance in Figure 9.3 the enthalpy of the air increases as it flows through the desorber. This increase in enthalpy should not be possible since the desorber is flooded with relatively cool desiccant and the desorption of water from the desiccant is endothermic (i.e., the air must provide thermal energy to drive the desorption process which will decrease the air's enthalpy). Furthermore, although the air flowing through the absorber should increase in enthalpy (as shown), the measured increase is too great given the temperature and flooding rate of the desiccant.

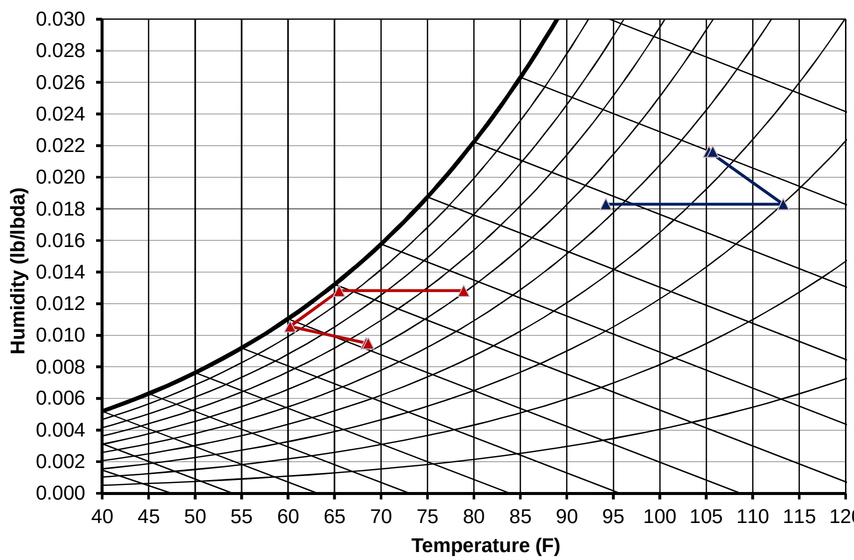


Figure 9.3 – Psychrometric Performance of the LDDX-AD during Initial Test with Steam Augmentation

A check on the calibration of the T/RH instruments did uncover an approximately four point error in two instruments. These instrumentation errors could account for the inconsistency in the performance data shown in Figure 9.3.

All T/RH instrumentation was recalibrated before proceeding with further tests.

The test procedure that was followed in the February tests unfairly penalized the CMS prototype's performance. The extremely low ambient humidity in our lab led us to operate the CMS prototype in a mode in which we returned all condensate that drained off the evaporator to the desiccant sump. This return of condensate was necessary to prevent the desiccant from becoming too concentrated and crystallizing.

However, in normal operation, the condensate draining off the evaporator would be discharged to a sewer line (or similar disposal line). By returning the condensate to the desiccant sump, we created an artificially large water-removal load on the desorption side of the prototype. The desiccant weakened under this mode of operation and the prototype supplied air at a higher relative humidity, i.e., the performance in Figure 9.3 shows the prototype supplying air at 64% rh while we expected a value closer to 50%.

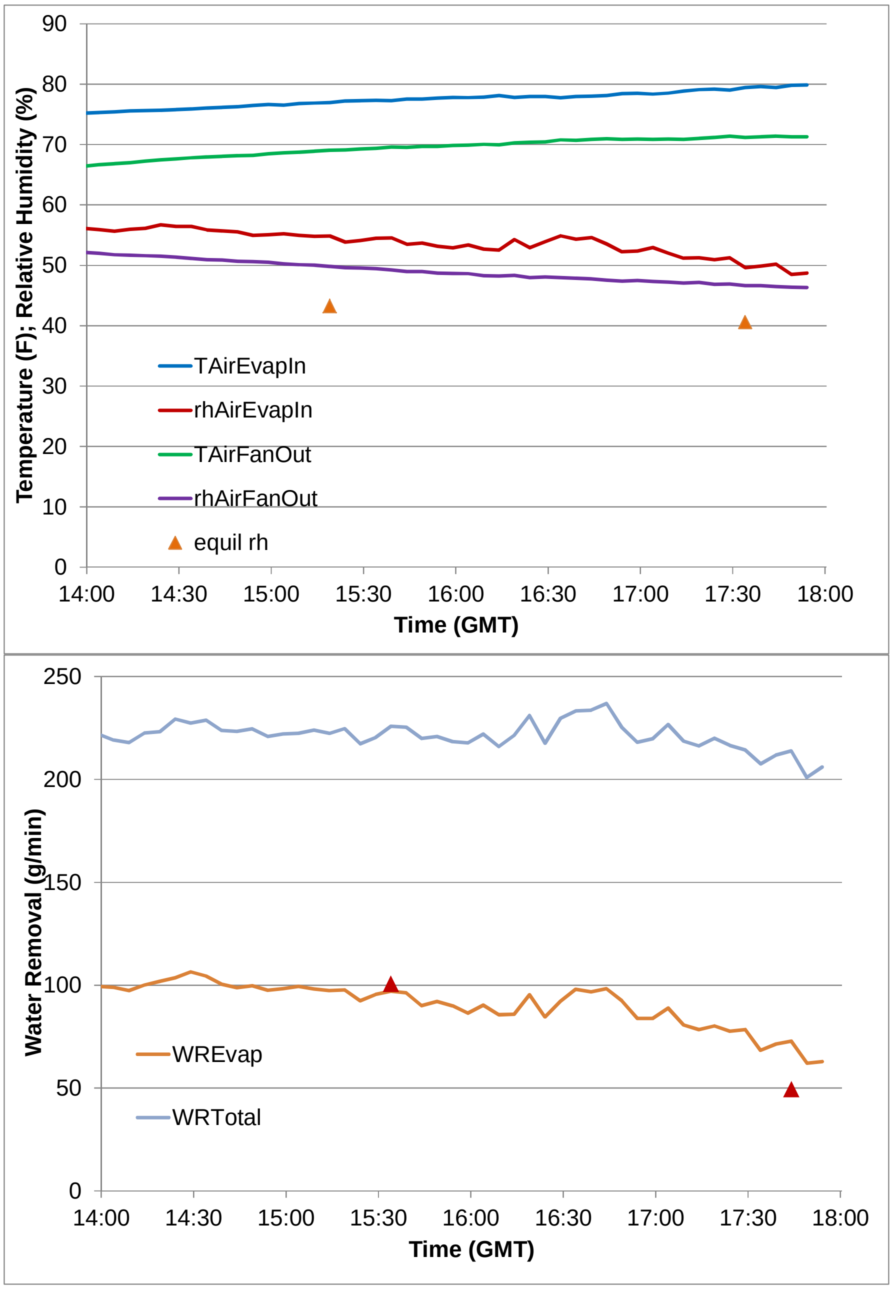


Figure 9.4 – Performance of the LDDX-AD on May 4, 2018

With March and April weather in central New Jersey unusually cool with low ambient dew-points, it was not possible to operate the CMS prototype in our shop in a mode in which evaporator condensate was discharged.

On May 4, 2018 the CMS prototype was operated in our shop for approximately four hours under near steady conditions. Humidity in the shop was sufficiently high to permit operation without exchanging air between the prototype's condenser and the evaporator (i.e., shop air was drawn directly into the evaporator.) In order to reproduce operation at a high ambient temperature and humidity, the condenser air was recirculated, and the air-to-air heat exchanger in this recirculated loop was modulated to adjust air temperature. All condensate draining off the evaporator was discharged to a sewer line.

As shown in the upper graph in Figure 9.4, the CMS prototype's desiccant-wetted absorber pad dried the essentially 100% rh air leaving the evaporator to between 46% to 52% (rhFanOut).

The desiccant concentration was measured at two times during the May 4 test. These concentrations, converted to an equilibrium relative humidity for the desiccant, are plotted in the upper graph in Figure 9.4. Consistent with the measured relative humidity of the supply air, the equilibrium relative humidity for the desiccant is about six points below the measured values.

The lower graph in Figure 9.4 presents a graph of the total water removal rate for the CMS prototype and the water removal rate for its evaporator. These water removal rates are calculated from (1) the temperature and relative humidity measurement of the air entering and leaving the prototype, (2) the air volumetric flow measured at the throat of the process fan, and (3) the assumption that the air leaves the evaporator at a 95% relative humidity. Also shown in Figure 9.4 are two data points for the condensate off the evaporator that was collected for 30 minutes and weighed to get a water removal rate.

As shown in Figure 9.4, the evaporator's water removal rate that is directly measured agrees well with the value that is calculated from the air-side measurements. Also, the data in this figure shows that the water removal provided by the desiccant-wetted absorber is greater than that provided by the evaporator.

The measured performance of the CMS prototype on May 4 at 15:35 is shown on a psychrometric chart in Figure 9.5. The state points on this chart are:

1 – entering process air (drawn from shop)
2 – air leaving evaporator
3 – exiting process air (delivered to shop)
4 – entering cooling air (recirculated air after cooled in AAHX)
5 – air leaving condenser
6 – exiting cooling air (recirculated air before cooled in AAHX)

Both the second and fifth state points are calculated to be consistent with the measured performance of the CMS prototype's refrigerant circuit with the additional assumption that the process air leaves the evaporator at 95% rh.

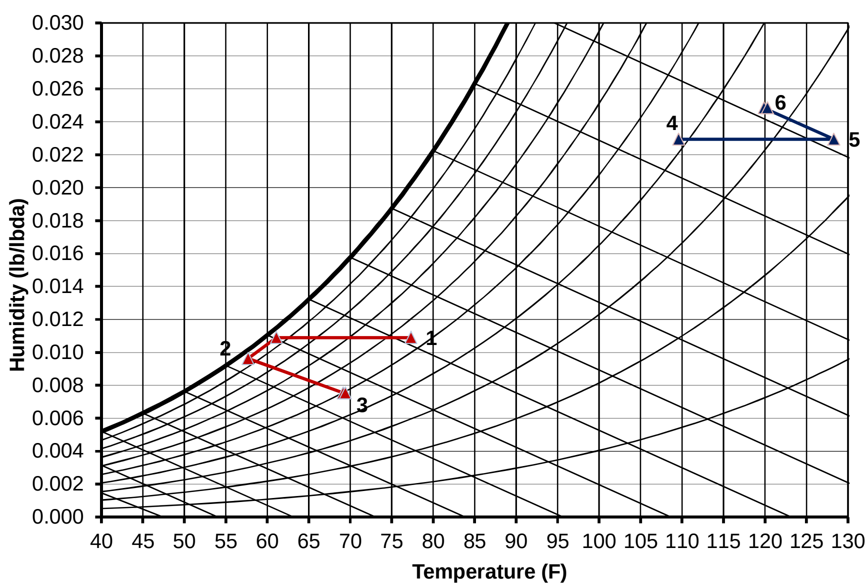


Figure 9.5 – Psychrometric Performance of the LDDX-AD on May 4

A detailed description of the CMS prototype's performance on May 4 at 15:35 appears in Table 9.1.

When reviewing the performance of the CMS prototype on May 4 at 15:35 it is important to realize that the unit is not operating at steady state, i.e., the data in Figure 9.4 shows a continuous decrease in

Table 9.1 – Detailed Performance of CMS Prototype on May 4

	T	w	rh
	F	lb/lb	%
process air entering CMS	77.3	0.0111	55.4
process air leaving evaportor	57.7	0.0096	95.0
process air exiting CMS	69.4	0.0078	51.0
cooling air entering CMS	109.6	0.0229	41.4
cooling air leaving condenser	128.3	0.0229	24.6
cooling air exiting CMS	120.3	0.0248	33.0

	measured unsteady	projected steady	
process air flow rate	2,097		cfm
cooling air flow rate	3,919		cfm
desiccant flow to absorber	0.35		gpm
desiccant flow to desorber	0.52		gpm
T desiccant supply	80.2		F
C desiccant supply (as LiCl)	0.297	0.308	
pump power	115		W
fan power	3,466		W
compressor power	4,639		W
total power	8,220		W
condenser Q rejection	72,380		Btu/h
evaporator Q absorption	57,719		Btu/h
net total cooling	52,856	55,877	Btu/h
evaporator moisture removal	11.86		lb/h
total moisture removal	31.35	34.21	lb/h
desorber moisture rejection	31.37		lb/h
EER (compressor-based)	11.4	12.0	
moisture removal efficiency (MRE) (compressor-based)	6.76	7.37	lb/kWh

the relative humidity of the supply air (rhAirFanOut), which then indicates a continuous increase in the concentration of the desiccant. This unsteady operation produces an imbalance in the water exchange between the desiccant-wetted absorber and the desiccant-wetted desorber: the desorber releases water at the rate of 31.37 kg/h, while the absorber gains water at the rate of 19.69 kg/h (i.e., the difference between the total moisture removal in Table 9.1 and the moisture removal of the evaporator).

Based on a computer projection of the CMS prototype's performance on May 4 at 15:35, the concentration of the desiccant delivered to both the absorber and desorber would increase from the measured value of 0.297 (LiCl equivalent) to 0.308. This increase in concentration would increase the prototype's total moisture removal by about 10% to 34.21 kg/h (11.86 kg/h for the evaporator and 22.35 kg/h for the desiccant-wetted absorber). The values in the column labeled "projected steady" are the simulated performance of the CMS prototype when operating under steady state conditions with 0.308 desiccant concentration (LiCl equivalent).

The computer projection of steady-state performance predicts that the net total cooling delivered by the CMS prototype is 3% less than the cooling effect provided by the evaporator (where the small amount of heat added to the supply air from the fans has been ignored). This loss in total cooling is the principal efficiency loss introduced by the liquid-desiccant circuit, which transfers a small amount of heat from the condenser-side to the evaporator-side of the air conditioner.

(It is noted that the performance data in Table 9.1 for the prototype's unsteady operation shows an 8% loss in total cooling caused by the exchange of desiccant. We expect that this measured loss of total cooling is too large and caused by a yet undetermined measurement error.)

The primary effect of the desiccant circuit is to almost triple the water removal of the DX air conditioner from 11.86 kg/h to 34.21 kg/h. The desiccant-wetted pads do increase fan power, but the pressure drops across these pads are projected to be small—0.10 in w.c. for the absorber and 0.05 w.c. for the desorber—and so the increase in fan power will not be significant. The 3% loss in total cooling is then the most significant cost to be paid for almost tripling the air conditioner's latent cooling.

During operation on May 10, 2018, samples of air from the inlet duct to and the supply duct from the CMS prototype were drawn through the Airnet II (model 501-4) particle measurement instrument that has been described in Section 2.0. The pleated filters for the supply air were removed for this measurement so that they would not capture desiccant droplets that might be stripped from the absorber.

Table 9.2 – Particle Concentrations into and out of the CMS Prototype

Particles Per CuFt Without Filter

Test #	Probe Position	0.5 micron	1.0 micron	5.0 micron	10 micron
5	Inlet	43,299	8,647	289	35.3
6	Outlet	36,655	5,392	30	0.0
7	Inlet	38,525	6,754	174	15.5
8	Outlet	34,543	5,334	19	0.0
	Pct Capture	13.0%	30.4%	89.4%	100.0%

Figure 9.6 – Polished Aluminum Sheet for Detecting Corrosion from Desiccant Droplets

The results of the particle measurement are shown Table 9.2 for sampling that alternated between the inlet and outlet of the CMS prototype. As shown in this table for all four size ranges, the concentration of particles was always lower at the outlet than at the inlet. Consistent with the particle measurements reported in Section 2.0, the desiccant-wetted absorber functions as a filter that is most effective for larger particles. Perhaps more importantly, the CMS prototype is not introducing desiccant droplets into the supply air.

A second, less quantitative diagnostic was used to detect the carryover of desiccant droplets from the CMS prototype. As shown in Figure 9.6, a highly polished, uncoated sheet of aluminum was installed on the floor of the outlet plenum for the CMS prototype. Although operating hours have been relatively short—on the order of 100 hour—no corrosion has been seen on the surface of the sheet.

10.0 Preliminary Safety Hazard Analysis for the CMS Prototype

The LDDX-AD CMS prototype is a direct-expansion air conditioner. Its refrigerant circuit is charged with R410a, a refrigerant commonly used in roof-top air conditioners. The liquid desiccant circuit is charged with a solution of potassium acetate. As shown in the MSDS included in the appendix at the end of this report, potassium acetate is not flammable and has a low toxicity, i.e. its LD50 rating on rats is 3250 mg/kg of body weight; for comparison LD50 for sodium chloride is 3000 mg/kg. As with all strong desiccants, potassium acetate is an irritant and as described in the MSDS "hazardous in case of eye contact, of ingestion…slightly hazardous in case of skin contact, of inhalation".

The CMS prototype operates on 208 V, 3-phase power. All electrical power components are UL listed. It should be recognized that the unit is a prototype and components such as the control panel were fabricated in-house. The CMS prototype should not be serviced by personnel who are not familiar with the unit and have not been trained to perform servicing.

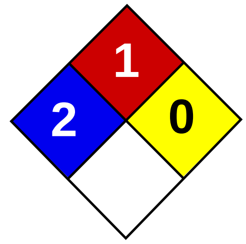
11.0 Conclusion

The Phase I work identified two configurations of liquid-desiccant Corrosion Mitigation Systems (CMS) with significantly lower power requirements than their commercial off-the-shelf counterparts. The configuration that delivers a small volume (i.e., 1,000 scfm, 75 lb/min) of deeply dried air (i.e., dewpoints at 32^{o}F or lower; supply relative humidity below 20%) is proposed for mobile applications. This configuration would use a novel desiccant-wetted evaporator that could operate below 32^{o}F without ice accumulating on its heat transfer surfaces. On a design-day in humid climates, the mobile liquid-desiccant CMS is projected to have power requirements that are 42% lower than a commercial off-the-shelf system that uses a solid-desiccant rotor.

The second configuration for a liquid-desiccant CMS provides an efficient means of maintaining an aircraft shelter at an indoor relative humidity below 40%. This second configuration adds a liquid desiccant circuit to a conventional DX air conditioner. The liquid desiccant circuit has an absorber that dries the nearly saturated air leaving the DX evaporator to a relative humidity on the order of 50%. The water absorbed by the desiccant is then released to ambient in a desorber through which passes the warm, low rh air leaving the DX condenser. The desiccant elements that absorb and desorb water are desiccant-wetted, porous pads that operate adiabatically (i.e., no internal heat transfer).

In the Phase II work, a 5-ton, 2,000 cfm liquid-desiccant DX CMS with adiabatic desiccant-wetted pads (LDDX-AD) was designed, fabricated and lab tested. In a test that simulated very hot, humid ambient conditions (110/87 F DB/WB) the LDDX-AD CMS prototype provided 31.1 lb/h of moisture removal at a moisture removal efficiency (MRE) of 6.76 lb/kWh when processing air at 77/66 F DB/WB. Accounting for the unsteady operating conditions of the test (i.e., the concentration of the desiccant slowly increased during the test), the prototype is projected to provide 34.2 lb/h of moisture removal at an efficiency of 7.37 lb/kWh when operating at steady state. This moisture removal rate for the prototype is almost three times the moisture removal rate for a conventional DX air conditioner operating under the same ambient conditions (i.e., the conventional DX air conditioner will remove 11.9 lb/h of moisture at a MRE of 2.6 lb/kWh.)

Measurements of particle concentrations in the air entering and leaving the LDDX-AD CMS prototype during laboratory operation showed the desiccant-wetted absorber pad to be a moderately efficient particle filter (i.e. capture efficiencies ranging from 13% for the smallest 0.5 micron particles to near 100% for the largest 10 micron particles.) Although operating hours were limited (i.e., on the order of 100 hours), the LDDX-AD CMS prototype operated with no detectable carryover of liquid desiccant droplets in the supply air.



Health	2
Fire	1
Reactivity	0
Personal Protection	E

Material Safety Data Sheet
Potassium acetate MSDS

Section 1: Chemical Product and Company Identification

Product Name: Potassium acetate

Catalog Codes: SLP1285, SLP4909, SLP2083

CAS#: 127-08-2

RTECS: AJ3325000

TSCA: TSCA 8(b) inventory: Potassium acetate

CI#: Not available.

Synonym:

Chemical Name: Not available.

Chemical Formula: CH_3COOK

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Potassium acetate	127-08-2	100

Toxicological Data on Ingredients: Potassium acetate: ORAL (LD50): Acute: 3250 mg/kg [Rat].

Section 3: Hazards Identification

Potential Acute Health Effects:
Hazardous in case of eye contact (irritant), of ingestion. Slightly hazardous in case of skin contact (irritant), of inhalation.

Potential Chronic Health Effects:
CARCINOGENIC EFFECTS: Not available. MUTAGENIC EFFECTS: Not available. TERATOGENIC EFFECTS: Not available. DEVELOPMENTAL TOXICITY: Not available. Repeated or prolonged exposure is not known to aggravate medical condition.

Section 4: First Aid Measures

Eye Contact:
Check for and remove any contact lenses. Immediately flush eyes with running water for at least 15 minutes, keeping eyelids open. Cold water may be used. Do not use an eye ointment. Seek medical attention.

Skin Contact:

After contact with skin, wash immediately with plenty of water. Gently and thoroughly wash the contaminated skin with running water and non-abrasive soap. Be particularly careful to clean folds, crevices, creases and groin. Cold water may be used. Cover the irritated skin with an emollient. If irritation persists, seek medical attention. Wash contaminated clothing before reusing.

Serious Skin Contact: Not available.

Inhalation: Allow the victim to rest in a well ventilated area. Seek immediate medical attention.

Serious Inhalation: Not available.

Ingestion:
Do not induce vomiting. Loosen tight clothing such as a collar, tie, belt or waistband. If the victim is not breathing, perform mouth-to-mouth resuscitation. Seek immediate medical attention.

Serious Ingestion: Not available.

Section 5: Fire and Explosion Data

Flammability of the Product: May be combustible at high temperature.

Auto-Ignition Temperature: Not available.

Flash Points: Not available.

Flammable Limits: Not available.

Products of Combustion: These products are carbon oxides (CO, CO2).

Fire Hazards in Presence of Various Substances: Not available.

Explosion Hazards in Presence of Various Substances:
Risks of explosion of the product in presence of mechanical impact: Not available. Risks of explosion of the product in presence of static discharge: Not available.

Fire Fighting Media and Instructions:
SMALL FIRE: Use DRY chemical powder. LARGE FIRE: Use water spray, fog or foam. Do not use water jet.

Special Remarks on Fire Hazards: Not available.

Special Remarks on Explosion Hazards: Not available.

Section 6: Accidental Release Measures

Small Spill:
Use appropriate tools to put the spilled solid in a convenient waste disposal container. If necessary: Neutralize the residue with a dilute solution of acetic acid. Finish cleaning by spreading water on the contaminated surface and dispose of according to local and regional authority requirements.

Large Spill:
Use a shovel to put the material into a convenient waste disposal container. Neutralize the residue with a dilute solution of acetic acid. Finish cleaning by spreading water on the contaminated surface and allow to evacuate through the sanitary system.

Section 7: Handling and Storage

Precautions:
Keep away from heat. Keep away from sources of ignition. Empty containers pose a fire risk, evaporate the residue under a fume hood. Ground all equipment containing material. Do not ingest. Do not breathe dust. Avoid contact with eyes Wear suitable protective clothing If ingested, seek medical advice immediately and show the container or the label.

Storage:
Keep container dry. Keep in a cool place. Ground all equipment containing material. Keep container tightly closed. Keep in a cool, well-ventilated place. Combustible materials should be stored away from extreme heat and away from strong oxidizing agents.

Section 8: Exposure Controls/Personal Protection

Engineering Controls:
Use process enclosures, local exhaust ventilation, or other engineering controls to keep airborne levels below recommended exposure limits. If user operations generate dust, fume or mist, use ventilation to keep exposure to airborne contaminants below the exposure limit.

Personal Protection:
Splash goggles. Lab coat. Dust respirator. Be sure to use an approved/certified respirator or equivalent. Gloves.

Personal Protection in Case of a Large Spill:
Splash goggles. Full suit. Dust respirator. Boots. Gloves. A self contained breathing apparatus should be used to avoid inhalation of the product. Suggested protective clothing might not be sufficient; consult a specialist BEFORE handling this product.

Exposure Limits: Not available.

Section 9: Physical and Chemical Properties

Physical state and appearance: Solid.

Odor: Not available.

Taste: Not available.

Molecular Weight: 98.14 g/mole

Color: Not available.

pH (1% soln/water): 10 [Basic.]

Boiling Point: Decomposes.

Melting Point: 292°C (557.6°F)

Critical Temperature: Not available.

Specific Gravity: 1.57 (Water = 1)

Vapor Pressure: Not applicable.

Vapor Density: Not available.

Volatility: Not available.

Odor Threshold: Not available.

Water/Oil Dist. Coeff.: Not available.

Ionicity (in Water): Not available.

Dispersion Properties: See solubility in water.

Solubility: Easily soluble in cold water.

Section 10: Stability and Reactivity Data

Stability: The product is stable.

Instability Temperature: Not available.

Conditions of Instability: Not available.

Incompatibility with various substances: Not available.

Corrosivity: Non-corrosive in presence of glass.

Special Remarks on Reactivity: Not available.

Special Remarks on Corrosivity: Not available.

Polymerization: No.

Section 11: Toxicological Information

Routes of Entry: Eye contact. Ingestion.

Toxicity to Animals: Acute oral toxicity (LD50): 3250 mg/kg [Rat].

Chronic Effects on Humans: Not available.

Other Toxic Effects on Humans:
Hazardous in case of ingestion. Slightly hazardous in case of skin contact (irritant), of inhalation.

Special Remarks on Toxicity to Animals: Not available.

Special Remarks on Chronic Effects on Humans: Not available.

Special Remarks on other Toxic Effects on Humans: Not available.

Section 12: Ecological Information

Ecotoxicity: Not available.

BOD5 and COD: Not available.

Products of Biodegradation:
Possibly hazardous short term degradation products are not likely. However, long term degradation products may arise.

Toxicity of the Products of Biodegradation: The products of degradation are more toxic.

Special Remarks on the Products of Biodegradation: Not available.

Section 13: Disposal Considerations

Waste Disposal:

Section 14: Transport Information

DOT Classification: Not a DOT controlled material (United States).

Identification: Not applicable.

Special Provisions for Transport: Not applicable.

Section 15: Other Regulatory Information

Federal and State Regulations: TSCA 8(b) inventory: Potassium acetate

Other Regulations: Not available..

Other Classifications:

WHMIS (Canada): Not controlled under WHMIS (Canada).

DSCL (EEC): R36- Irritating to eyes.

HMIS (U.S.A.):

Health Hazard: 2

Fire Hazard: 1

Reactivity: 0

Personal Protection: E

National Fire Protection Association (U.S.A.):

Health: 2

Flammability: 1

Reactivity: 0

Specific hazard:

Protective Equipment:
Gloves. Lab coat. Dust respirator. Be sure to use an approved/certified respirator or equivalent. Splash goggles.

Section 16: Other Information

References: Not available.

Other Special Considerations: Not available.

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Last Updated: 05/21/2013 12:00 PM