Dehumidification Strategies **for Critical Environments**

by Scott McVey, PE, Millig Design Build

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Introduction

Critical environments, such as those in pharmaceutical manufacturing facilities and hospitals, require stringent environmental control. Among all environmental parameters, tight humidity control is one of the most important, as uncontrolled humidity levels can compromise an entire product batch or increase the likelihood of patient infection.

Dehumidification and Carbon Emissions

In critical facilities, such as laboratories, hospital operating rooms (ORs), clean rooms, pharmaceutical manufacturing Good Manufacturing Practice (GMP) spaces, and industrial drying processes, dehumidification is often the largest driver of energy use and carbon emissions. This is due to a combination of the high air change rates needed for these spaces and the need to deliver low dew point air to maintain desired humidity levels.

Most commonly, dehumidification has been achieved through traditional refrigerant-cooling-based dehumidification systems (direct expansion or chilled water); however, this approach of overcooling and reheat is highly energy intensive, especially for buildings located in humid climates with high outside air needs and dry environmental requirements.

Consequently, controlling humidity has a large environmental impact and is responsible for 599 million tons of carbon dioxide released annually.[1]

This white paper aims to provide a framework for the different approaches to dehumidification for critical environments looking to reduce energy use and achieve a Net Zero carbon future.

Millig's work in 23 critical facilities, comprising more than 5M SF, demonstrated that environmental conditioning, driven by dehumidification, makes up on average 69% of carbon emissions.

Types of Dehumidification Systems

There are two primary ways to mechanically remove moisture from the air: 1. Refrigerant-cooling-based dehumidification, which condenses water vapor from the air by chilling the air below its dew point, and 2. Desiccant dehumidification, which adsorbs or chemically absorbs moisture by passing the air across a drying agent.

The optimal technology for each application depends on input air conditions and the ideal output air conditions. To determine the appropriate dehumidification approach, one must conduct a psychrometric analysis to determine air conditions at every step of the process for each hour of annual operation. Next, different dehumidification technologies and strategies must be evaluated in terms of energy efficiency and effectiveness of maintaining the desired air conditions based on the application within the facility. This white paper will guide application engineers through the process of selecting the optimal dehumidification strategy for different applications.

The table below compares the attributes of the most common types of dehumidification systems.

TYPE	COMMON AIRFLOWS	DEW POINT TEMPERATURE	MIN. DISCHARGE AIR MOISTURE* @ 29.921 in. Hg ATM. PRESSURE
DX Cooling	50 to 50,000 cfm	42°F normal 35°F special design min. (or lower)	39.45 29.92
Chilled Water	500 to 50,000 cfm	40°F	36.48 32.41
Chilled Brine/ Glycol	500 to 50,000 cfm	32°F (below 32°F with frosted coil or defrost control)	26.51
Liquid Desiccant	750 to 84,000 cfm	-80°F with LiCl Typical LiCl: 15°F (with 45 F CW**) 25°F (with 55 F CW) 32°F (with 65F CW) 40°F (with 75 F CW) 48°F (with 85 F CW)	0.063 12.89 19.78 26.51 36.48 49.68
Dry Desiccant	500 to 25,000 cfm	-8°F	0.063

* Humidity ratio - Grains of moisture per pound of dry air

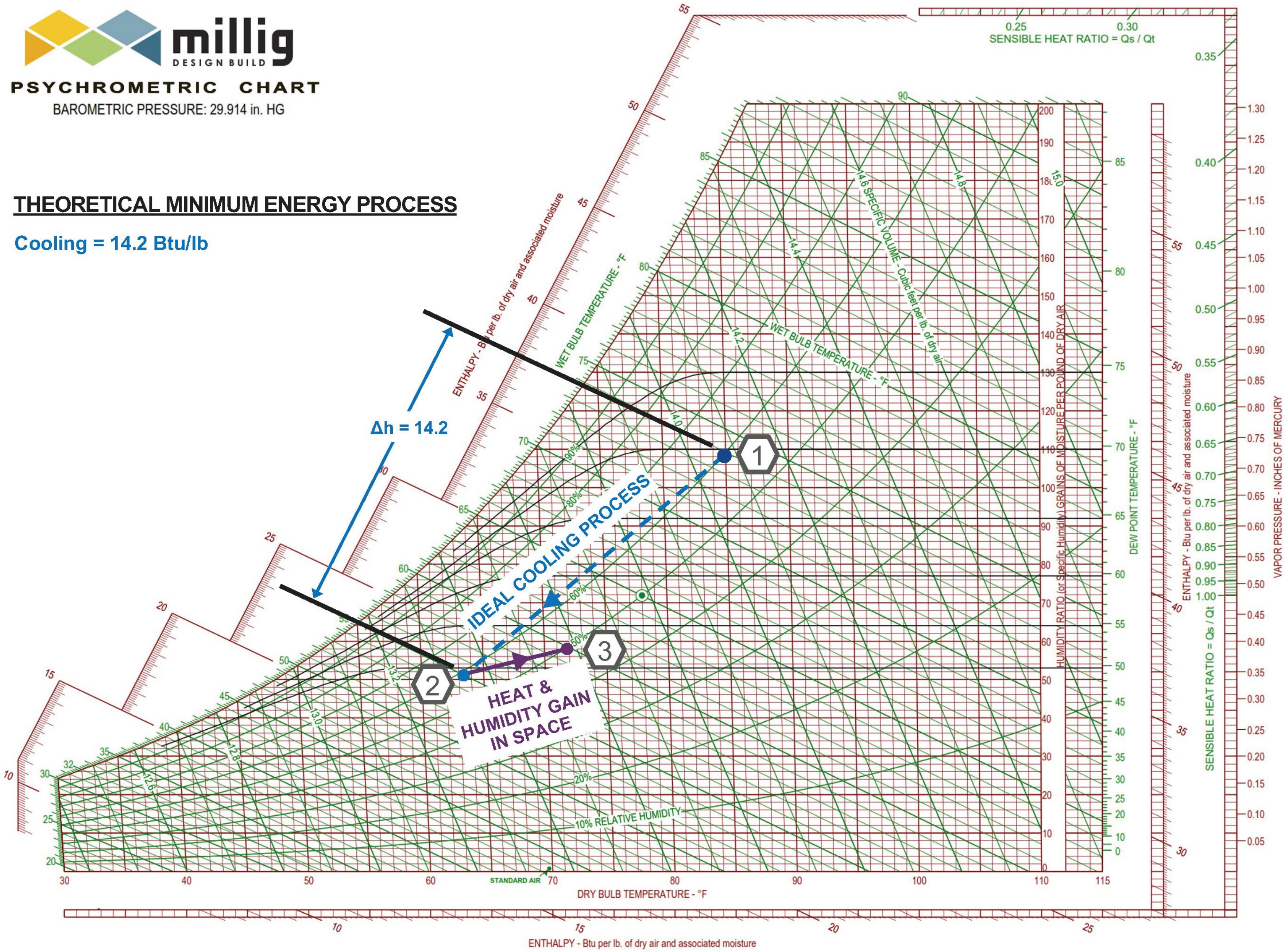
** Chilled water

For the purposes of illustrating different dehumidification strategies and their relative performance, see Psychrometric Chart 1, an example of conditioning 100% outdoor air from 85°F dry bulb and 74°F wet bulb (state 1, 1) to 63°F and 49°F dew point (state 2, 2) needed to maintain space conditions of 72°F and 50% RH (state 3, 3). (State 4, 4) represents a similar thermal energy comparison, but for an industrial drying application presented later in the paper.

The focus of this paper will be the most direct and efficient way to get between state 1 (outdoor ambient) and state 2 (supply air conditions to the space). The theoretically least thermal energy required to get from state 1 to state 2 is 14.2 Btu/lb of air, as shown in Psychrometric Chart 1. All subsequent dehumidification processes will be compared to this theoretical best case.

State #	CHART KEYNOTES
1	Outside Air Conditions: 85°F temperature 74°F wet bulb
2	Desired Supply Air Conditions: 63°F temperature 49°F dew point
3	Required Space Air Conditions: 72°F temperature 50% RH (also = Return Air Conditions)
4	Drying Application Required: Air Conditions: 85°F temperature 49°F dew point

Psychrometric Chart 1: SPACE CONDITIONING THEORETICAL MINIMUM ENERGY PROCESS



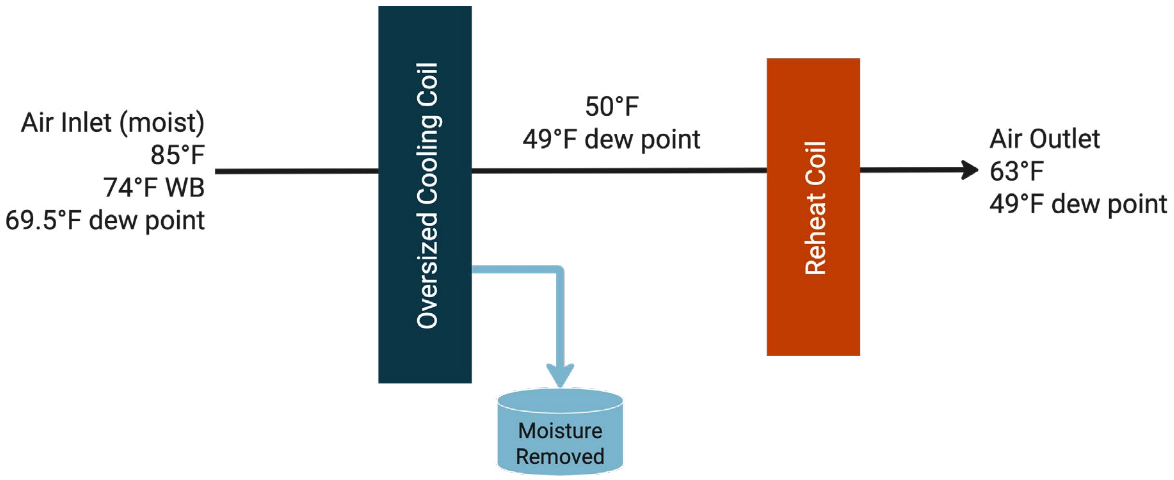
Refrigerant-Cooling-Based Dehumidification

Refrigerant-cooling-based dehumidification works by passing air over a cooling coil, which has a surface temperature below the dew point of the desired air conditions. This causes water vapor in the air to condense on the coil surface, thus drying the air. The cooling coils in this category can be either direct expansion (DX) or chilled water coils.

The temperature of the air leaving the cooling coils is dictated by dew point requirements of the discharge air and the temperature of the refrigerant or chilled water in the coil; however, this air is typically too cold to be delivered directly to spaces without reheating it. This is especially true in high air changes per hour (ACH) applications in critical environments.

> Overcooling and reheat is the most commonly deployed strategy for controlling humidity, but it is not an efficient approach to dehumidification as it results in excessive energy use.

Dehumidification Control via Overcooling and Reheat



In Psychrometric Chart 2, you see the process of overcooling and reheat for dehumidification of a 100% outdoor air system, at a given set of conditions. The blue process line labeled "Mechanical Cooling" depicts the thermal energy needed to cool and wring moisture out of the air. The process line labeled "Reheat" is the thermal energy required to return the dehumidified air to comfort conditions.

Psychrometric Chart 2: SPACE CONDITIONING OVERCOOLING & REHEAT

OVERCOOLING & REHEAT

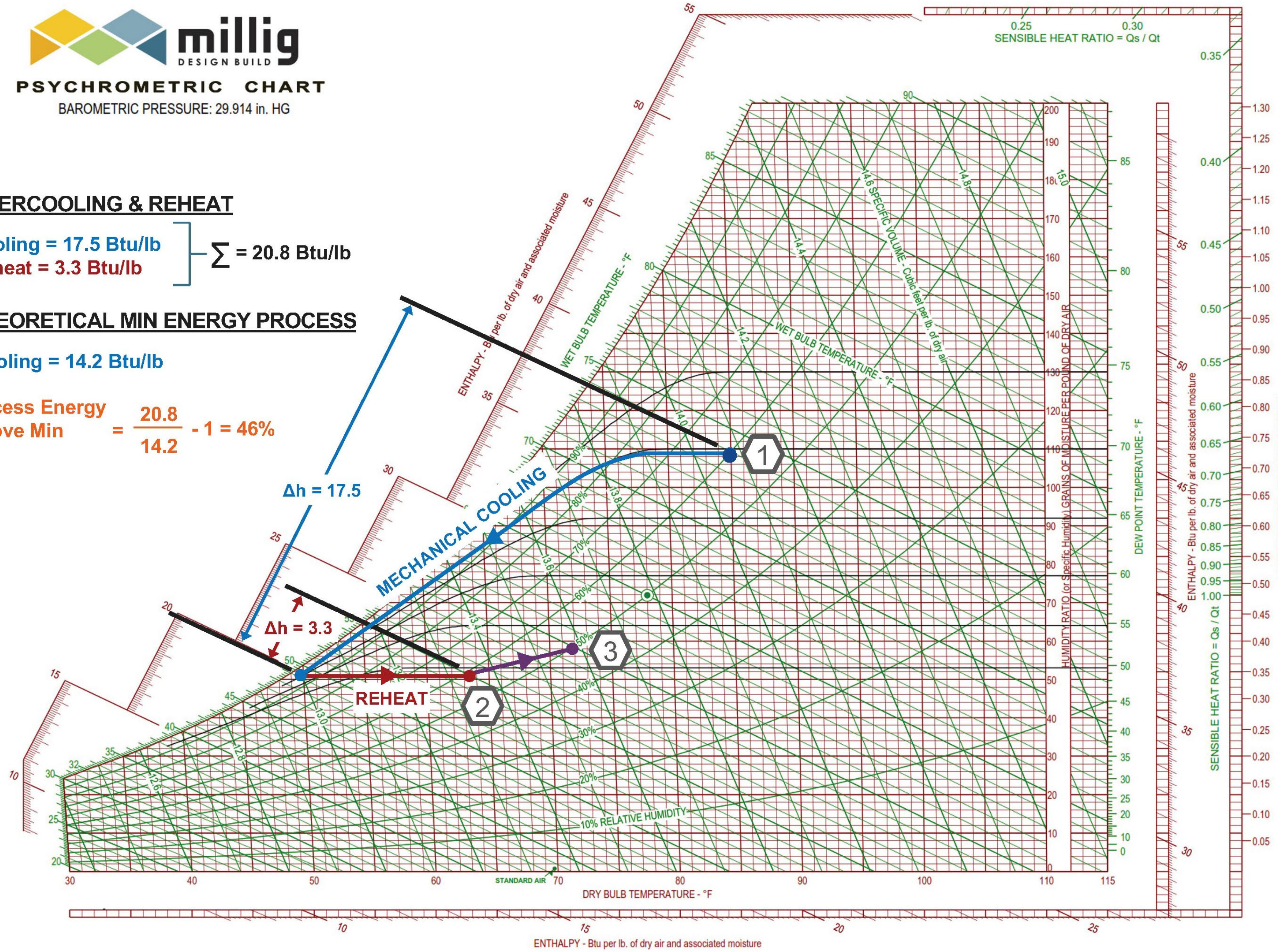
Cooling = 17.5 Btu/lb
Reheat = 3.3 Btu/lb

$\sum$ = 20.8 Btu/lb

THEORETICAL MIN ENERGY PROCESS

Cooling = 14.2 Btu/lb

Excess Energy above Min $= \frac{20.8}{14.2} - 1 = 46\%$



In Psychrometric Chart 2, 49°F dew point air is needed to absorb the moisture needed to maintain 50% RH in the space. However, this 50°F air, if delivered to the space without reheat, would result in an overcooled space and too high of relative humidity. Consequently, reheat is needed to add 13°F of sensible heat to result in the needed space conditions of 72°F and 50% RH.

This process is energy intensive. It not only consumes excess energy to overcool the air, it also requires heat to reverse the overcooling. With the given conditions in this example, the theoretical minimum specific energy transfer required is 14.2 Btu/lb of air; however, the brute-force cooling and reheat approach requires 17.5 Btu/lb of air in cooling and 3.3 Btu/lb of air in reheat energy transfer for the same result. This is 46% more energy transfer than the ideal process at 14.2 Btu/lb of air.

Additional Issues Related to Refrigerant-Cooling-Based Dehumidification

Beyond excessive energy consumption, refrigerant-cooling-based dehumidification can also lead to other issues in some applications.

Maintaining Relative Humidity in Hospital Operating Rooms

In hospitals, many existing refrigerant-cooling-based dehumidification systems for ORs are typically designed to maintain spaces between 68-75°F at 50% relative humidity (RH), in alignment with ASHRAE Standard 170. However, surgeons frequently prefer space temperature setpoints in the range of 60-65°F for comfort. This is because surgeons wear multiple layers of protective clothing and work under bright lights, while completing physically demanding work.

While the cooling systems can maintain the lower space temperature set points, they are not designed to maintain RH at these lower space temperature conditions. This leads to elevated RH levels, which are out of compliance with regulatory requirements and increases the risk of wound infections, surface condensation, mold and mildew growth, and surgeon discomfort.

ASHRAE STANDARD 170, DESIGN PARAMETERS - HOSPITAL SPACES							
FUNCTION OF SPACE	PRESSURE RELATIONSHIPS TO ADJACENT AREA	MINIMUM OUTDOOR ACH	MINIMUM TOTAL ACH	ALL ROOM AIR EXHAUSTED	AIR RECIRCULATED BY ROOM UNITS	DESIGN RELATIVE HUMIDITY %	DESIGN TEMP °F
OPERATING ROOM	POSITIVE	4	20	NR	NO	20-60	68-75

https://www.ashrae.org/technical-resources/ashrae-journal/featured-articles/conditioning-for-the-enviro›nment-of-critical-care-hospital-operating-rooms

Minimum Dew Point Limitations

There is a practical limit to how cold air can be chilled, which is the main parameter determining its moisture content. The minimum discharge air dew point temperature of traditional refrigerant-cooling-based dehumidification systems is typically in the range of 40-42°F using energy-intensive low-temperature glycol/chilled water. Maintaining spaces in the range of 30-35% RH represents the low end of practical application for this technology and comes at a severe energy penalty.

Refrigerant Leakage

Approximately 30% of the greenhouse gas emissions associated with the use of refrigerant-cooling-based systems comes from the leakage of refrigerants.[2] These fugitive emissions can sometimes occur at the time of start-up due to installation errors, but most often develop over time due to normal wear and tear on equipment. All of the alternate dehumidification technologies discussed below have the added benefit of minimizing or replacing refrigerant-cooling-based systems. Whenever refrigerant-cooling-based systems are designed, they should be selected with low global warming potential refrigerants.

Dehumidification using overcooling and reheat is an old-school, brute force approach that should be reconsidered and ultimately phased out as we work towards decarbonization and energy efficiency across all building types.

Alternatives to Traditional Overcooling and Reheat

Wrap-Around Heat Recovery Coils

Ideal Application: Light-duty comfort cooling and humidity control; most cost effective in high humidity, high outside air applications.

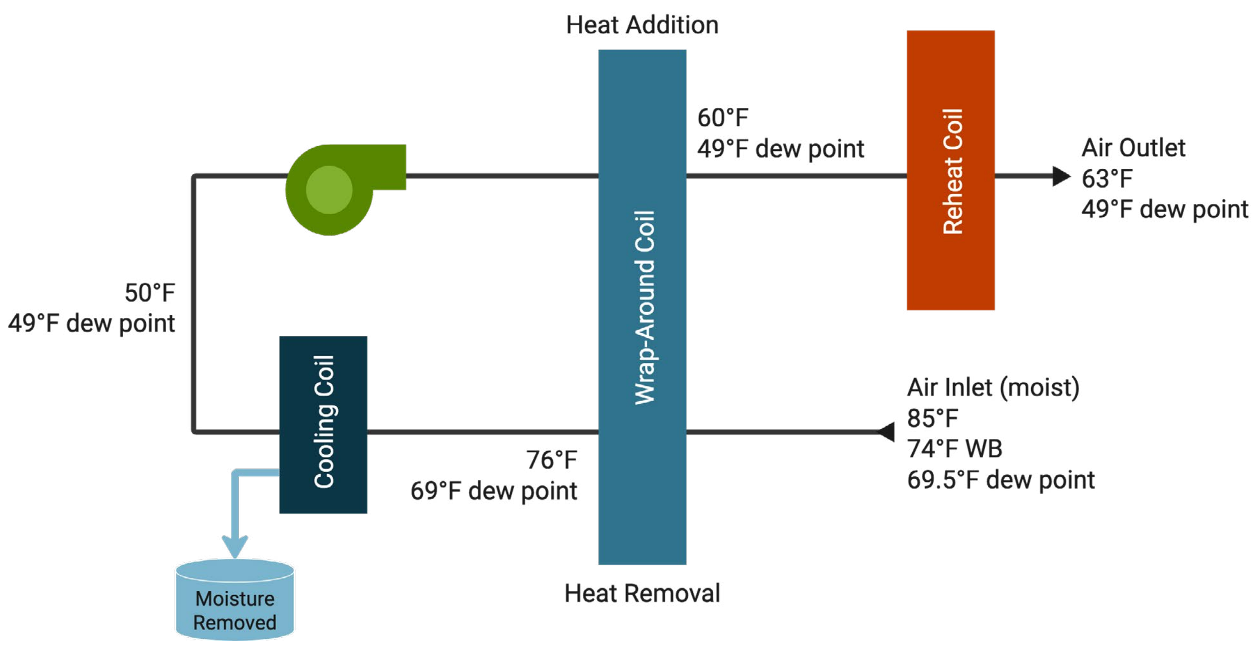
Wrap-around heat recovery coils should be considered for light-duty applications where the discharge air temperature requirement is within 10°F of the dew point temperature being supplied. This solution can be included as part of an original design and is an ideal retrofit solution for existing systems.

Wrap-around coils can save 20 to 35% more energy than overcooling and reheat for high-humidity comfort applications.

Wrap-around heat recovery coils (either a heat pipe or pumped runaround loop) are installed on both sides of the primary cooling coil to precool the airstream and remove heat from the air stream and transfer it to the reheat position. The wrap-around coil simultaneously reduces the cooling requirements of the primary cooling coil and the heating requirements of the zone reheat coils, saving significant energy.

Compared to a traditional overcooling and reheat system, this system reduces the load on the primary chilled water and reheat coils by 20-40%. In the diagram below, the wrap-around coil saves the chilled water coil 9°F of cooling (85°F to 76°F) and the reheat coil(s) 10°F (50°F to 60°F) for no additional energy other than fan energy required to overcome the extra static pressure of these coils.

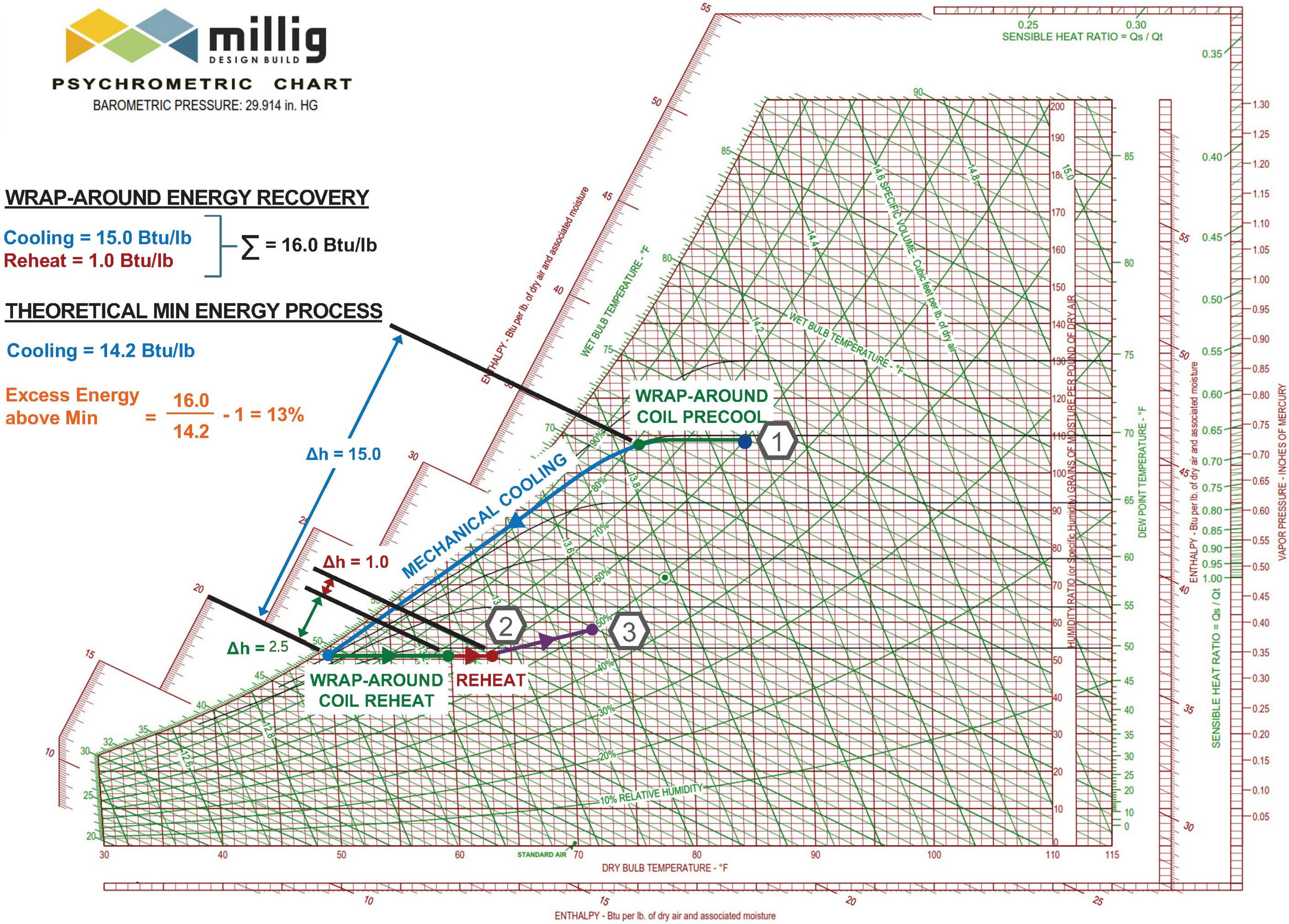
Dehumidification via Wrap-Around Heat Recovery Coil



In Psychrometric Chart 3, you see the enthalpy implications of retrofitting a 100% outdoor air system with wrap-around coils, at a given set of conditions. The green lines depict the free cooling and free heating provided by the wrap-around coil. The cooling coil is still used to do the bulk of the dehumidification, but significant load is removed from the chilled water plant and the heating plant. This simple retrofit can be implemented with little downtime and is typically a very cost effective upgrade for light-duty dehumidification.

Overall, in this example, the wrap-around coil results in only 13% more energy transfer needed than the ideal process (16.0 Btu/lb of air vs. 14.2 Btu/lb of air), and it requires 23% less than the overcooling and reheat case (16.0 Btu/lb of air vs. 20.8 Btu/lb of air).

Psychrometric Chart 3: SPACE CONDITIONING WRAP-AROUND ENERGY RECOVERY



Desiccant Dehumidification

A desiccant dehumidifier works differently than a traditional refrigerant-cooling-based dehumidification system in that instead of cooling the air to condense its moisture, a desiccant system attracts and removes moisture from the air by way of contact with a desiccant—either a solid adsorbent or liquid absorbent. These systems are appropriate for heavy dehumidification applications, as they are much more effective at achieving low humidity levels than refrigerant-cooling-based dehumidification strategies. Because desiccant dehumidification requires specialty equipment, the application needs to be well matched to the desiccant technology.

A recent NREL study shows that the theoretical efficiency of desiccant systems is 10 times higher than that of refrigerant-cooling-based dehumidification systems.[3]

Dry Rotary Desiccant

Ideal Application: Need for low dew point, high-temperature discharge air; product drying.

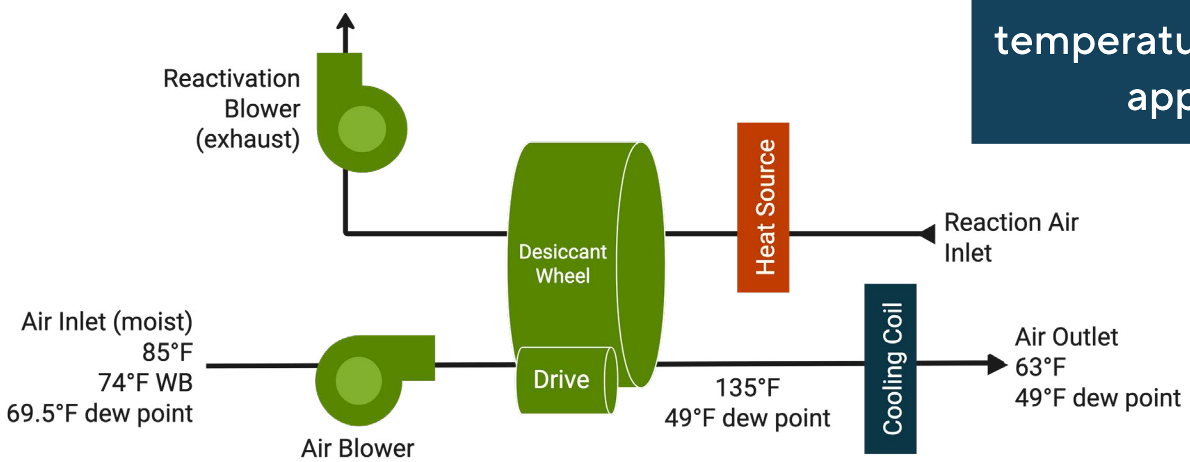
Dry rotary desiccant systems operate on the principle of adsorption. In a dry rotary desiccant system, ambient air is passed through a solid desiccant wheel, where it interacts with the solid desiccant material and adsorption of water vapor takes place. This process releases the latent heat of vaporization (or condensation), which is transferred as sensible heat to the process air stream. This, combined with reactivation system heat leakage passed to the process air (referred to as heat dumpback), results in a high discharge air temperature.

Moisture absorption (or desorption) is driven by the difference between the vapor pressure at the desiccant surface and the partial pressure of water vapor in the air. Adsorption removes water vapor from the airstream to the desiccant when vapor pressure of the desiccant surface is lower than the partial pressure of water vapor in the air. When sufficient moisture is adsorbed by the desiccant, the desiccant is moved into the reactivation air stream, where added heat and increased moisture content raises the vapor pressure at the desiccant surface. Moisture leaves the desiccant as the desiccant surface vapor pressure exceeds the partial pressure of water vapor in the reactivation air.

Following the reactivation process, the hot and dry desiccant rotates back into the process air, where it is cooled (thus lowering the desiccant vapor pressure). At this point, the desiccant can collect moisture from the process air stream. This process is shown in the following schematic diagram.

Dry rotary-desiccant dehumidifiers save 45 to 75% more energy than overcooling and reheat for high-temperature drying applications.

Rotating Dry Desiccant Dehumidifier



The key with this approach is that the discharge air comes out of the desiccant system at a high temperature, making this perfect for process applications like those found in confectionery, pharmaceutical, and chemical manufacturing plants. For environmental conditioning, this discharge air is too high and requires significant post cooling.

It should be noted that there is some free cooling potential given the difference in the ambient air temperature and the temperature leaving the rotary wheel. This can be achieved by utilizing an indirect evaporative cooler within the desiccant unit. Still, rotary desiccant units are not ideal for space conditioning, as they are only slightly more efficient than traditional overcooling and reheat for providing supply air suitable for occupied spaces. Psychrometric Chart 4 shows that Rotary Desiccant requires a total of 19.4 Btu/lb of air of energy transfer, which is only 6.7% more efficient the 20.8 Btu/lb of air of energy required by previous overcooling and reheat scenario when providing supply air at 63°F temperature and 49°F dew point (2).

Psychrometric Chart 4: SPACE CONDITIONING ROTARY DESICCANT (NOT IDEAL APPLICATION)

ROTARY DESICCANT

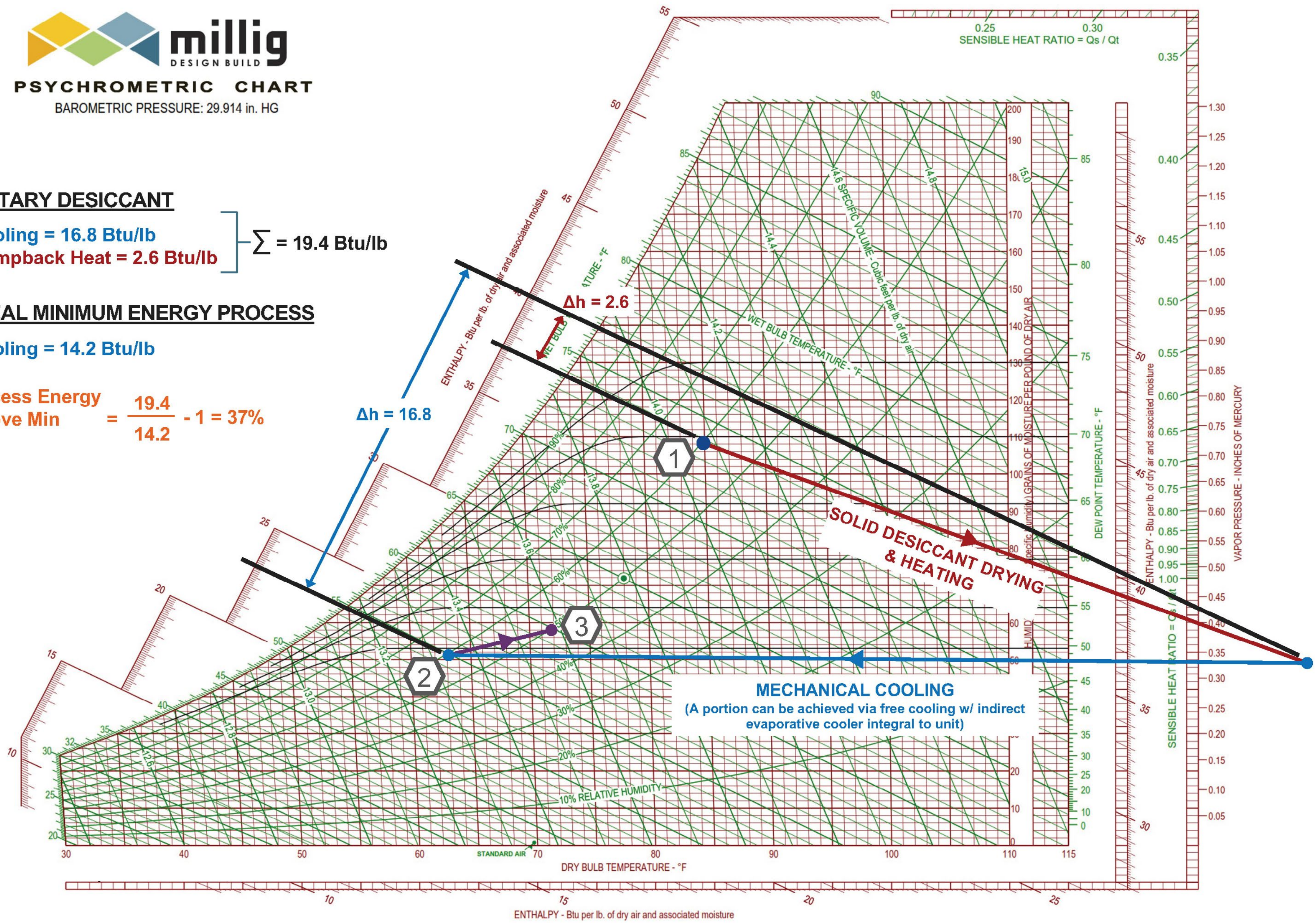
Cooling = 16.8 Btu/lb
Dumpback Heat = 2.6 Btu/lb

$\sum$ = 19.4 Btu/lb

IDEAL MINIMUM ENERGY PROCESS

Cooling = 14.2 Btu/lb

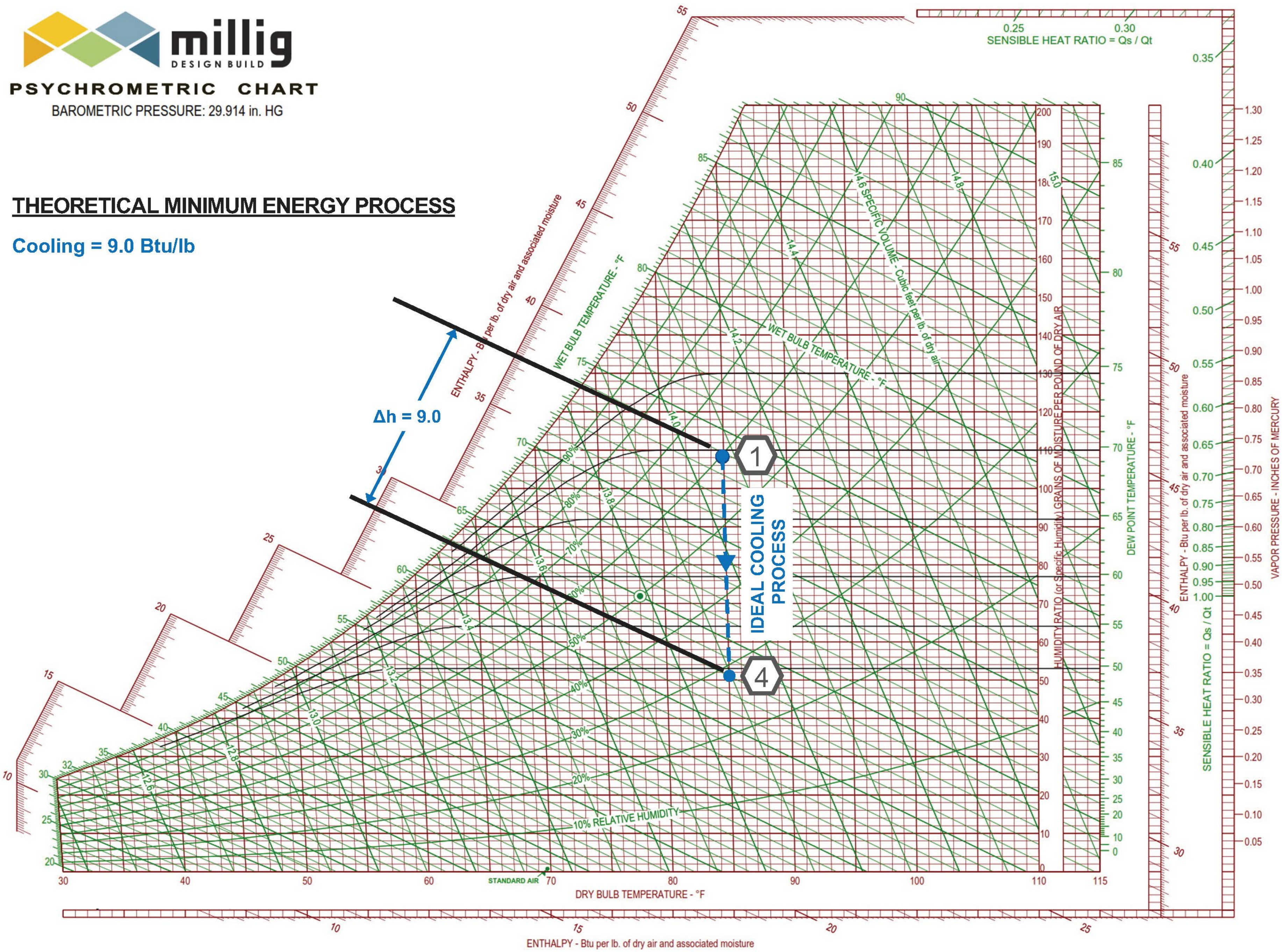
Excess Energy above Min $= \frac{19.4}{14.2} - 1 = 37\%$



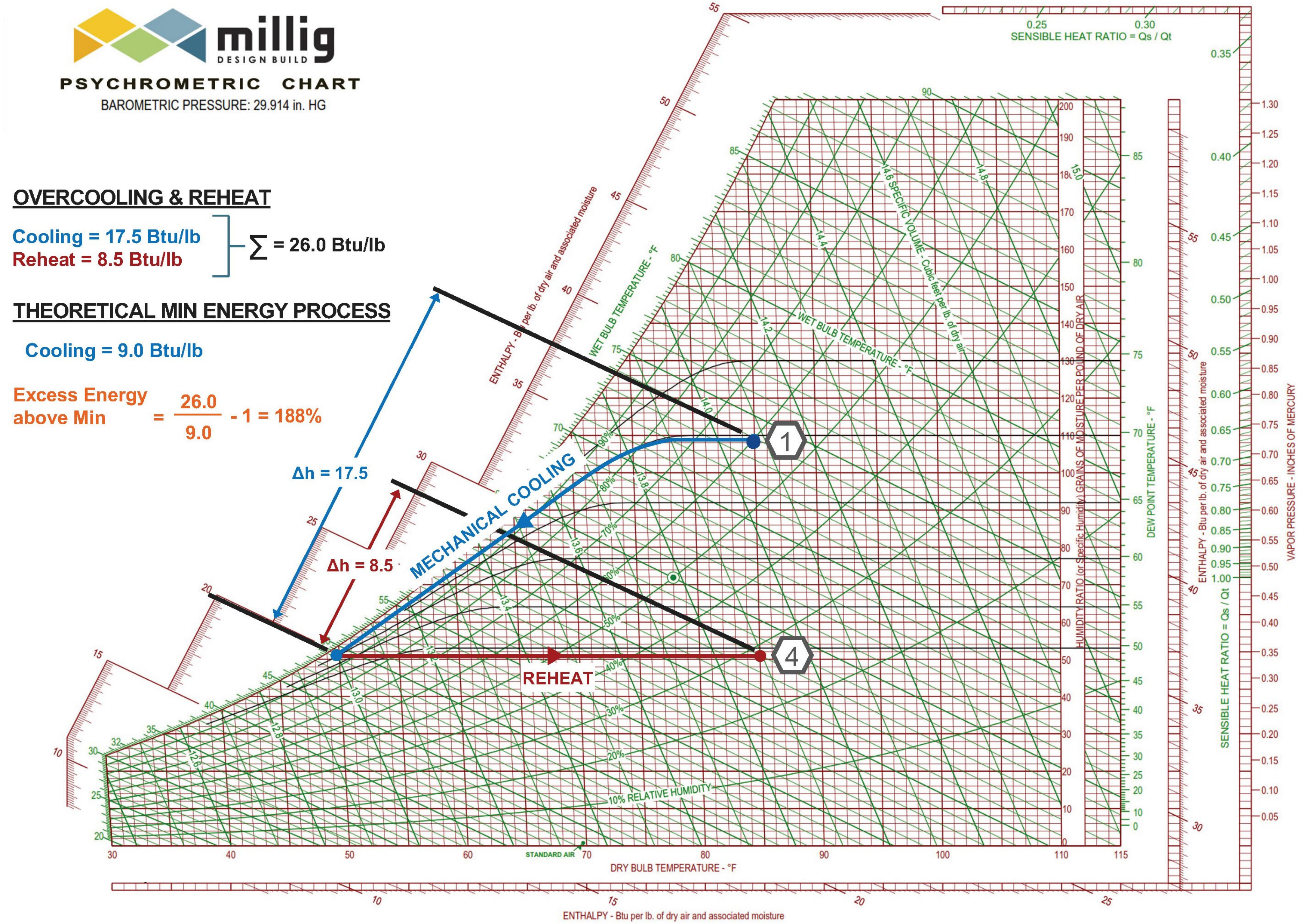
Compare this to an application where higher temperature, low humidity supply air is desired. In Psychrometric Chart 5, the desired supply air conditions are (4), 85°F temperature, 49°F dew point. Again, it is important to establish the theoretical minimum cooling energy required to achieve the given conditions.

Psychrometric Chart 5 shows that the minimum theoretical Δh is 9.0 Btu/lb of air. Psychrometric Chart 6 demonstrates that achieving this with overcooling and reheat will require an energy expenditure of 26.0 Btu/lb of air, which is 188% more than the ideal theoretical minimum energy transfer. Psychrometric Chart 7 shows that the Rotary Desiccant system requires only 14.2 Btu/lb of air, or 59.7% more than the theoretical minimum. This energy expenditure can be further reduced if a unit can be selected with an integral indirect evaporative cooler to provide free cooling.

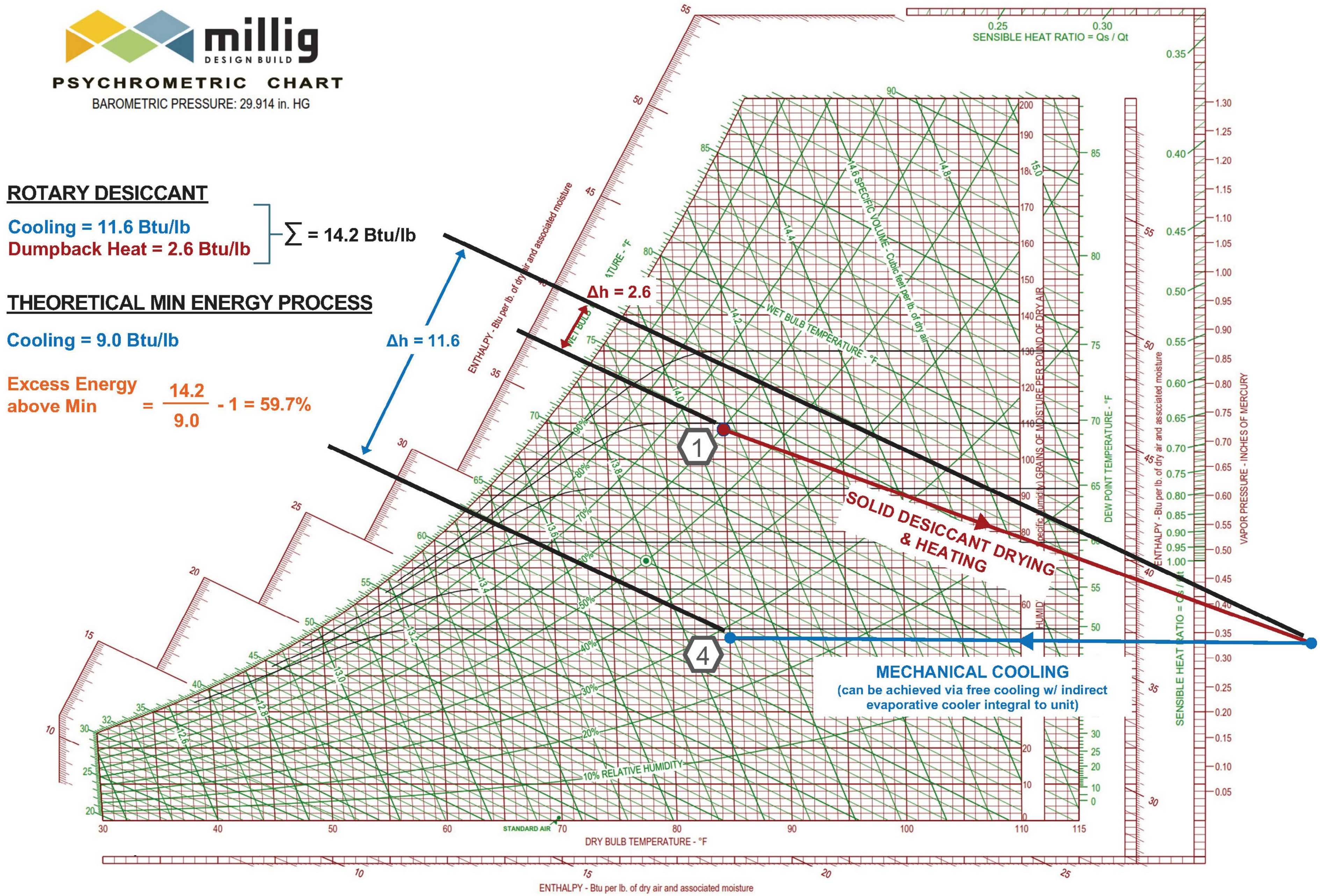
Psychrometric Chart 5: PROCESS CONDITIONING THEORETICAL MINIMUM ENERGY PROCESS



Psychrometric Chart 6: PROCESS CONDITIONING OVERCOOLING & REHEAT



Psychrometric Chart 7: PROCESS CONDITIONING ROTARY DESICCANT



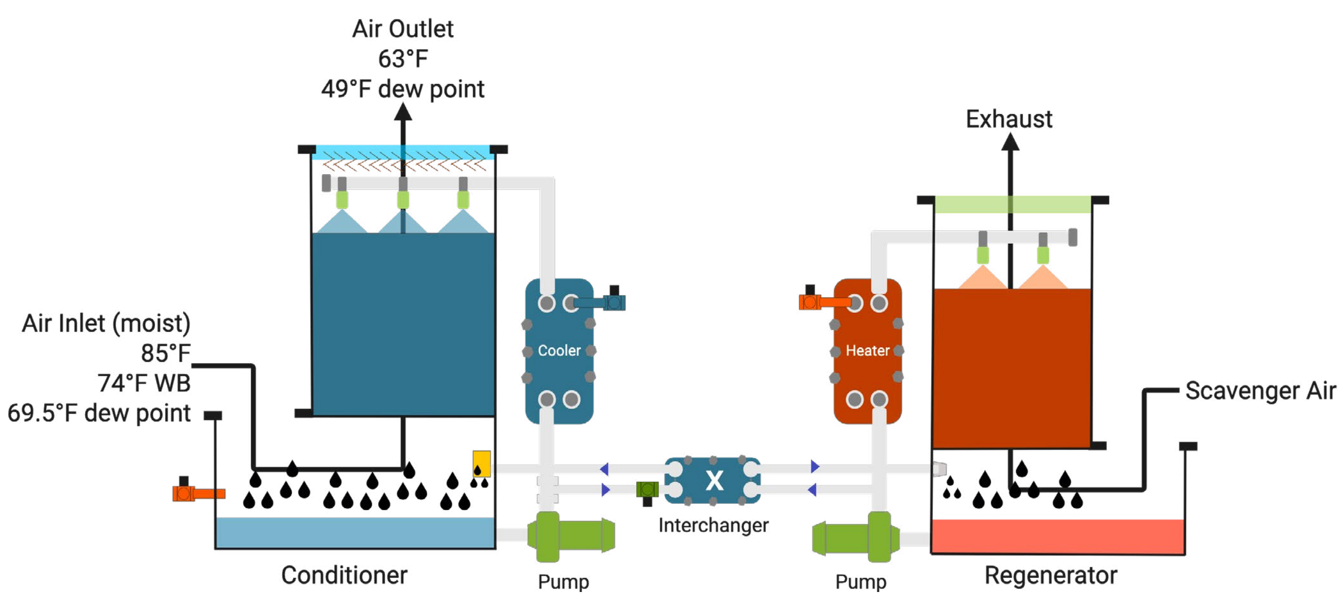
Liquid Desiccant Systems

Liquid desiccant systems operate on the principle of chemical absorption of water vapor from air. In a liquid desiccant dehumidification system, moist air passes through a packed medium saturated with a liquid desiccant solution (commonly lithium chloride) that has been cooled. This cool solution absorbs the moisture, and associated heat of vaporization, from the air stream, decreasing the concentration of the liquid desiccant. The weak liquid desiccant solution is then heated as it travels to the regenerator, raising the vapor pressure of the solution above the partial pressure of water vapor in the airstream. This vapor pressure imbalance drives moisture out of the liquid desiccant, increasing its concentration so it can be sent back to the conditioner. This process is shown in the following schematic diagram.

The humidity and temperature of the air exiting the unit is controlled by adjusting the concentration and temperature of the liquid desiccant solution through the heater and cooler, respectively. Generally, these systems produce cooler discharge air temperatures than rotary desiccant systems due to less dumpback heat carried over from the regenerator to the conditioner. This makes liquid desiccant systems ideal for applications that require air at moderate dry bulb and low dew point temperatures like hospital ORs and low-humidity manufacturing areas.

Further, these systems can be designed for lower regeneration temperatures, therefore, enabling the use of low-grade heat recovered from processes, refrigeration condensers, or solar to minimize overall system energy. Some sources of low-grade heat may be of heated air from a nearby process exhaust system, boiler stack economizer, or a thermal oxidizer; this is shown in the following illustration as the "scavenger air stream."

Liquid Desiccant Dehumidifier



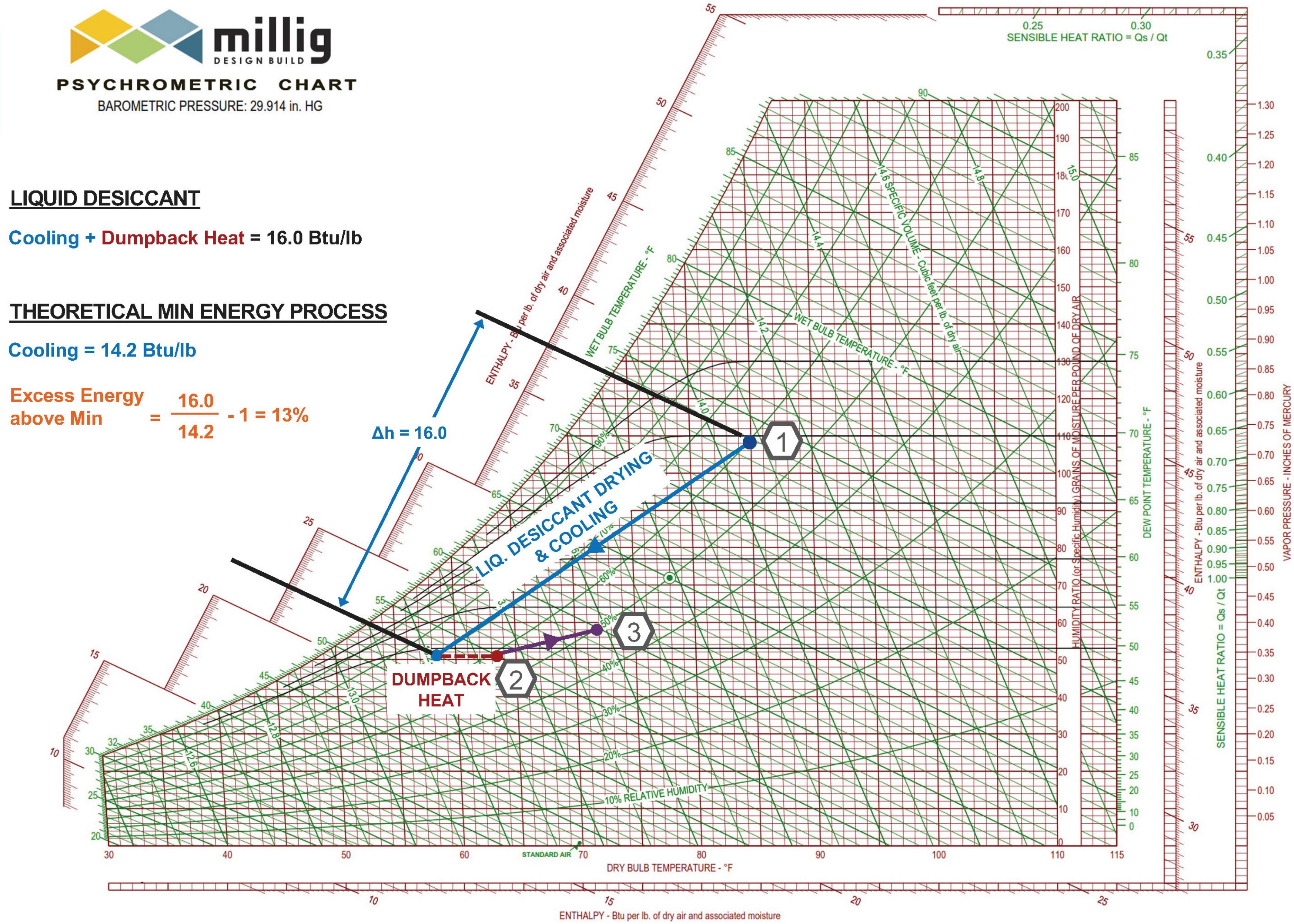
This process is significantly less energy-intensive than traditional low-temperature cooling and reheat or dry desiccant dehumidification in applications that require deep drying at moderate temperatures, such as food processing plants and hospital ORs. These systems are also ideal for large-batch product drying and in environments with high latent loads, like ice arenas. See the Psychrometric Chart 8 for more details.

It's important to note that liquid desiccant systems require more maintenance attention than their dry desiccant counterparts because most liquid desiccants are corrosive, demanding vigilance in leak detection.

The energy savings potential makes liquid desiccant a viable and practical solution for some applications. In the following example, the liquid desiccant system requires only 16.0 Btu/lb of air, which is only 13% above the theoretical minimum cooling energy required to meet the needs at the given conditions.

Liquid desiccant dehumidifiers save ~20 to 30% more energy that overcooling and reheat for low-humidity applications.

Psychrometric Chart 8: SPACE CONDITIONING LIQUID DESICCANT



Hybrid Desiccant Dehumidification

Refrigerant-cooling-based dehumidification and desiccant dehumidification can complement one another—especially in pharmaceutical manufacturing, laboratories, and hospital ORs, where the strength of one covers the weakness of the other.

For example, as shown in Psychrometric Chart 9, plants can use a refrigerant-cooling-based dehumidification system as first-stage dehumidification to remove moisture at higher dew points, then a liquid desiccant-based system as second-stage dehumidification to remove moisture and achieve lower dew points.

This approach is the most efficient under the scenarios presented in this paper, and it has the added economical benefit of preventing the oversizing of the desiccant system.

Psychrometric Chart 9: SPACE CONDITIONING MECHANICAL COOLING + LIQUID DESICCANT

MECHANICAL COOLING + LIQUID DESICCANT

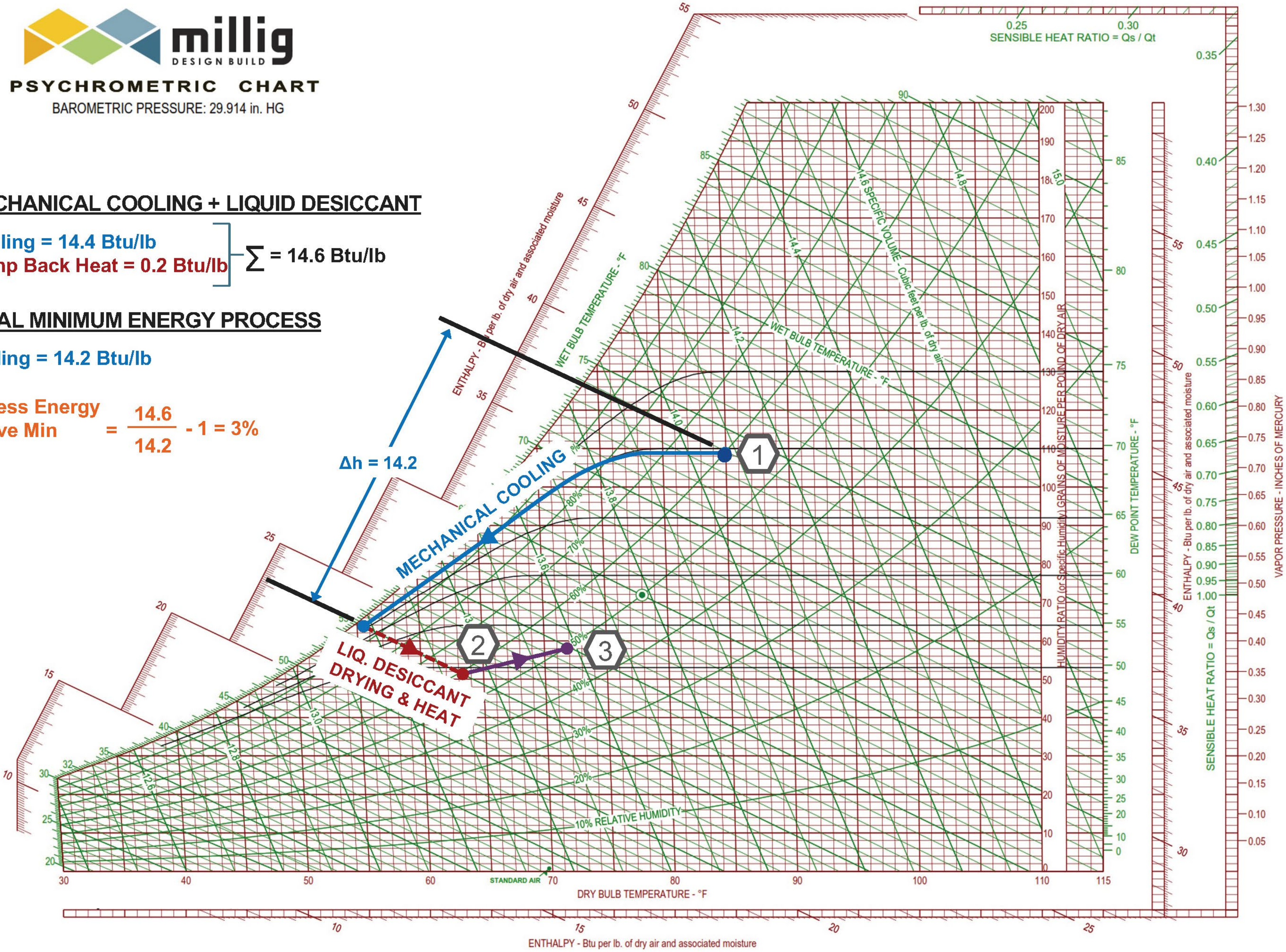
Cooling = 14.4 Btu/lb
Dump Back Heat = 0.2 Btu/lb

$\sum$ = 14.6 Btu/lb

IDEAL MINIMUM ENERGY PROCESS

Cooling = 14.2 Btu/lb

Excess Energy above Min $= \frac{14.6}{14.2} - 1 = 3\%$

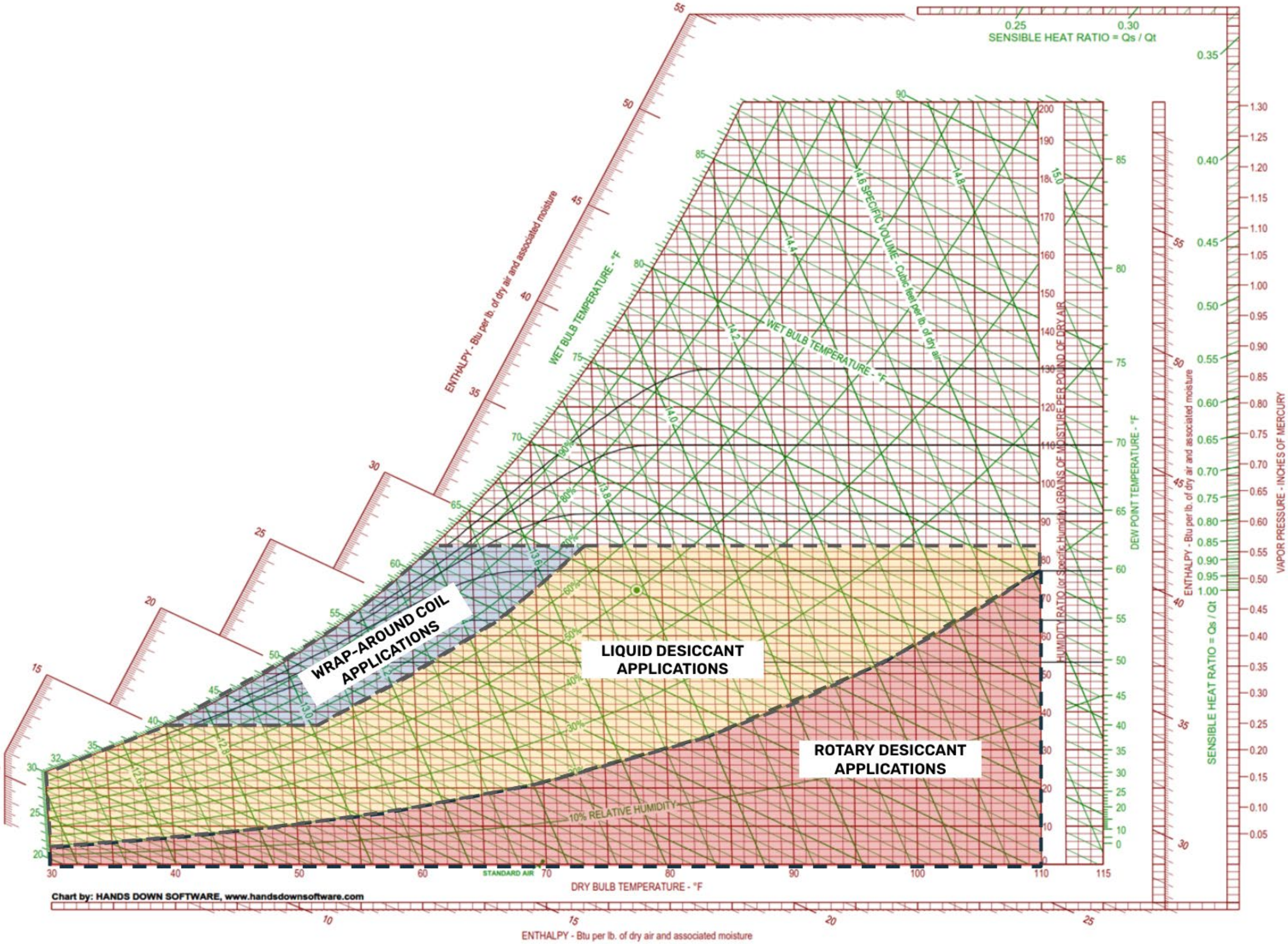


Application Summary

Psychrometric Chart 10 is intended to provide general guidance on the optimal application range for each alternate dehumidification strategy discussed in this paper based on needed conditions of the delivered air.

One must consider that, in most climates, these systems operate under highly dynamic conditions throughout the year; the conditions of the entering and exiting air vary based on space and outdoor conditions. Therefore, a comprehensive 8,760 hour analysis of each alternative should be performed to best understand their full performance and energy implications.

Psychrometric Chart 10: Ideal Dehumidification Technology Based on Characteristics of Desired Air



The horizontal lines are absolute humidity, and the curved lines are relative humidity.

Conclusion

Refrigerant-cooling-based dehumidification with reheat is an old-school, brute force approach that should be reconsidered and ultimately phased out as we work toward decarbonization and energy efficiency across all building types.

Depending on the application, strategies such as wrap-around coils, desiccant dehumidification, and decoupling of sensible and latent loads, can present benefits in terms of annual energy use and reduced system size.[2]

Key Takeaways

- Selecting the right dehumidification technologies and strategies depend heavily on the environmental conditions outside the building and the desired conditions inside. These choices have a tremendous impact on not only the ability for HVAC equipment to maintain critical space conditions, but the energy expended doing so.
- There are two primary ways to mechanically remove moisture from the air: 1. Refrigerant-cooling-based dehumidification, which condenses water vapor from the air by chilling the air below its dew point, and 2. Desiccant dehumidification, which adsorbs or chemically absorbs moisture by passing the air across a drying agent.
- Refrigerant-cooling-based dehumidification is well understood and reliable for light-duty dehumidification requirements, but it is not an efficient approach to deep dehumidification as it results in excessive energy use. Wrap-around coils should be considered for light- to moderate-duty HVAC applications.
- While refrigerant-cooling-based dehumidification can maintain lower space temperature set points, it is not designed to maintain low temperature and humidity requirements in critical environments such as operating rooms.
- Desiccant dehumidifiers can efficiently achieve much lower humidity levels than refrigerant-cooling-based dehumidification strategies.
- Wrap-around coils can save 20 to 35% more energy than overcooling and reheat for high-humidity comfort applications.
- Dry rotary-desiccant dehumidifiers save 40 to 75% more energy than overcooling and reheat for high-temperature drying applications.
- Liquid desiccant dehumidifiers save 20 to 30% more energy than overcooling and reheat for low-humidity applications.

[1] March 14, 2022 | C. media relations. (n.d.). News release: Scientists show large impact of controlling humidity on greenhouse gas emissions. NREL.gov. Retrieved June 7, 2022, from https://www.nrel.gov/news/press/2022/nrel-shows-impact-of-controlling-humidity-on-greenhouse-gas-emissions.html

[2] Dong, Y., Coleman, M., & Miller, S. (2021, June 3). Greenhouse Gas Emissions from Air Conditioning and Refrigeration Service Expansion in Developing Countries. Annual Review of Environment and Resources. https://doi.org/10.1146/annurev-environ-012220034103

[3] News Release: Scientists Show Large Impact of Controlling Humidity on Greenhouse Gas Emissions. (n.d.). Retrieved October 10, 2022, from https://www.nrel.gov/news/press/2022/nrel-shows-impact-of-controlling-humidity-on-greenhouse-gas-emissions.html

About Millig Design Build

Millig Design Build is an integrated engineering, design, and construction firm specializing in facility improvements that address energy efficiency, building health and safety, and core infrastructure needs.

For more information on the dehumidification strategy right for your critical environment, contact the Millig Design Build team.

Contact

913.214.2680

info@milligdb.com