APPLICATIONS AND IMPLICATIONS OF PDRC IN DAIRY FARMING

ADVANCING EFFICIENCY, SUSTAINABILITY, AND ANIMAL WELFARE IN ARIZONA'S DAIRY INDUSTRY

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Key Takeaways

- Livestock heat stress costs American dairy farmers $1.5 billion annually in lost milk production and decreased animal welfare.
- Global warming is accelerating heat stress risk and productivity loss.
- Passive daytime radiative cooling (PDRC) is a sustainable and cost-effective technology to de-risk modern dairy farming, especially in hot and arid regions like Arizona.
- Applying PDRC to dairy barns can improve milk production as much as 2.55%, with 3.6% and 4.5% improvements in milk protein and fat content, respectively.
- Large scale PDRC projects have shown success and economic viability in adjacent industries and applications, with average internal temperature reduction of 6.6°C (11.9°F).

Abstract

Dairy farming operations face significant challenges related to heat stress in livestock, which can lead to reduced milk production, compromised animal welfare, and increased operational costs. These challenges are only expected to increase in severity in the coming decades due to climate change. This paper explores a novel and sustainable solution to mitigate heat stress in dairy farming operations through the application of Radi-Cool passive daytime radiative cooling (PDRC) films and membranes.

Passive daytime radiative cooling is an emerging technology that utilizes specialized materials tuned to reflect incoming solar radiation and emit thermal radiation in the mid-infrared range. This enables objects to cool below the ambient temperature even under direct sunlight.

In this paper, we 1) review the principles of PDRC and its potential applications in dairy farming, 2) present an overview of the installation of Radi-Cool PDRC films and membranes on dairy farm structures in Southern Arizona, including barns, milking parlors, and calf housing, 3) propose a model for the cascade effects of roofing material and active heat mitigation (fans and misters) to provide a quantitative analysis of PDRC's expected impact on heat stress indicators, and 4) examine the economic impact of implementing PDRC technologies in dairy farms, especially the potential for significant increases in milk production.

In so doing, we analyze key performance indicators, such as temperature reduction, energy savings, and livestock health improvements, based on experimental data and case studies from real-world PDRC projects.

These findings demonstrate that the integration of daytime radiative cooling films and membranes into dairy farming operations presents a promising avenue to address the challenges posed by heat stress. PDRC technology can enhance livestock comfort, increase productivity, and help reach sustainability goals by providing supplemental cooling. These benefits represent an improvement in the resiliency and efficiency of the dairy industry, while minimizing its environmental footprint.

Introduction

Dairy farming is a critical component of global agriculture, providing milk and essential dairy products for consumers. However, dairy cows are particularly susceptible to heat stress, which causes detrimental effects to their health and milk production. This susceptibility has been increasing due to breeding practices that prioritize increased milk output and feed-to-milk ratio in exchange for reduced heat tolerance. In regions characterized by hot climates, managing heat stress in dairy cows becomes an even more pressing concern.

Dairy cows are homeothermic animals, meaning they have a relatively narrow range of optimal body temperature. When exposed to high ambient temperatures cows can struggle to regulate their body temperature effectively. The consequences of heat stress in dairy cows include:

- **Reduced Milk Production:** Elevated temperatures lead to decreased feed intake and metabolic changes, which lowers milk production. Heat stressed dairy cows experience a drop in milk production of up to 30%, impacting the economic viability of dairy farming operations.

- **Animal Health and Welfare:** Heat-stressed cows are prone to various health issues, including heat exhaustion, reduced fertility, and increased susceptibility to diseases. This not only results in animal suffering but also necessitates additional veterinary care and management.

- **Economic Losses:** Heat stress-induced decreases in milk production and increased veterinary costs represent substantial economic losses for dairy farmers, especially in hot climates. Table 1 shows the estimated economic losses due to heat stress for various animal agriculture activities, as surmised by Key, N. et. al. Losses due to heat in dairy farming represent the majority of the total economic losses due to heat stress in the United States, with heat stress losses roughly 9x higher than poultry and 5x higher than swine farming.

Table 1 - United States' loss of economic output due to heat stress in livestock species[1]

	% of total heat stress losses	Estimated loss in USD/yr
Dairy	63.9%	$1.5B
Beef	15.7%	$370M
Swine	13.4%	$316M
Poultry	7%	$165M
Total	100%	$2.35B

Table 2 - Estimated losses due to heat stress, with and without high-pressure misters and fans[2]

	Loss due to heat stress with minimal abatement ($/head/year)	Costs with high-pressure misters and fans ($/head/year)	Percent savings
Arizona	$265	$105	60%
New Mexico	$168	$87	48%
Texas	$698	$376	46%

Historically, dairy farmers in hot regions have employed various cooling methods to alleviate heat stress in their cattle. These methods include:

- **Shade Structures:** Providing shade for the animals is a common practice, but it may not be sufficient to mitigate heat stress, particularly during the daytime when high solar radiation levels persist. In hot desert regions, like Southern Arizona, ambient air temperatures in the shade often exceed the 38°C (101°F) normal homeothermic body temperature of cattle. To reduce the risk of heat related illness in cattle, dairy farms in hot regions often must rely on other forms of cooling.

- **Water Sprinkling and Misting:** Dairy farms often employ sprinkler systems to wet cows, aiding in evaporative cooling. While effective, this approach consumes large quantities of

[1] Key N., Sneeringer S., Marquardt D. (2014). *Climate change, heat stress, and U.S. dairy production*. United States Department of Agriculture.
[2] Atkins, I, Choi, C. (2017). *Dairy Cooling in Arid and Semi-Arid Climates.*

water, a precious resource in arid regions. Sprinklers and misters can use more than 100 gallons of water per head per day, depending on shade, ambient temperature, and water delivery technology. With dwindling water resources and water use restrictions already in place, or soon expected in many parts of Arizona, water-based cooling systems are not a sustainable solution in the long-term. These systems also require regular maintenance and cleaning to fix and repair leaks and unclog misting heads. This is a particularly common issue at farms fed by wells with hard water, as is common in Arizona.

- **Mechanical Ventilation:** Some farms use fans and ventilation systems to increase air circulation within livestock shelters. Combined with misting, this can bring down internal air temperatures within structures and increase livestock comfort. While effective, these systems consume electricity and are expensive to install, run, and maintain.

- **Air Conditioning (Refrigeration):** While air conditioners are rarely, if ever, used in direct cooling of cattle in large-scale Arizona dairy farming, farmers in similarly hot and arid regions like Northern Italy have turned to air conditioning to cool their cattle. Large-scale air conditioning is by far the most expensive cooling method, both in installation and running expenses, and requires unique barn designs that use insulated building envelopes to minimize heat exchange with the outdoors. Because of this, air conditioning cannot be efficiently combined with more traditional and common dairy farming cooling methods of misting and mechanical ventilation. With a single cooling strategy, if the electrical grid goes down, farmers are at risk of severely heat stressed, or even dead, cows. In addition, air conditioners act as heat pumps, removing heat from inside barns, parlors, and/or calf housing and dumping it directly outside into the yard. This creates a warmer microclimate outdoors and further compounds farm heat issues. For this reason, air conditioning is often referred to as a negative feedback loop.

- **Selecting and Breeding for Heat Tolerance:** Some farms breed cows with a genetic mutation, called “slick gene”, which yields cows with improved heat tolerance due to their shorter coats and increased sweat production.[3] These cows have increased feed consumption and milk production at higher temperatures, potentially up to 13°F beyond the next most heat tolerant cattle breed. However, there are limits to the improvements

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[3] Osborne, M. (2023). *Farmers are Breeding Cows to Withstand Heat Waves*. Smithsonian Magazine.

yielded by this approach – a cow either has the gene or does not – unlike active cooling, which can be increased in intensity, and it is costly to implement on a large-scale.

Passive daytime radiative cooling (PDRC) films and membranes have recently emerged as a versatile and effective cooling technique in a range of applications. PDRC operates solely on the principles of thermal radiation, requiring no electricity or water consumption. The adoption of PDRC technology can contribute to a reduced carbon footprint for dairy farming operations, aligning with global efforts to combat climate change.

Radi-Cool PDRC films and membranes have the capacity to reduce environmental temperatures both within dairy farm structures and in the areas directly surrounding structures. This provides cows with a comfortable and conducive environment for optimal milk production in their barns, parlors, and yards.

Addressing heat stress in dairy cows is not only a matter of economic viability for dairy farming but also a crucial element in ensuring animal welfare and sustainability against the backdrop of global climate change. The introduction of Radi-Cool PDRC films and membranes represents a promising step forward in improving the living conditions and productivity of dairy cattle.

Measuring Heat Stress Risk for Dairy Cattle

In dairy farming, the temperature humidity index (THI) is a commonly used metric to evaluate the risk of heat stress on cattle. THI can be calculated as follows[4]:

$$\mathrm{THI} = (1.8 \text{ x } \mathrm{T} + 32) - [(0.55 - 0.0055 \text{ x } \mathrm{RH}) \text{ x } (1.8 \text{ x } \mathrm{T} - 26)]$$

where T is dry bulb temperature (°C) and RH is the relative humidity (%)

THI takes into account both temperature and humidity to provide a comprehensive measure of the environmental conditions affecting livestock. Early research provided an estimate to the level of expected heat stress on dairy cattle at different THI values, as summarized in Table 3.

[4] NRC (1971). *A guide to environmental research on animals*. (Washington, DC: National Academy of Sciences).

Table 3 - Original heat stress in dairy cattle model at various THI values[5]

THI	<73	73-79	80-89	90-98	99+
Heat Stress	None	Mild	Moderate	Severe	Death

While these values are still often cited today, there is little backing for these values and more recent research has suggested dairy cattle experience heat stress that negatively impacts their health and productivity at much lower THI values than originally surmised. M.O. Ignono, et. al. proposed a lower limit of 64, with mean and maximum THI of 72 and 76, respectively for critical THI values.[6] In a study of the effect of THI on milk production in northern-arid Mexico, THI cutoffs of 68, 72, and 77 were found to significantly affect total milk production and feed-to-milk efficiency.[7]

Table 4 - Updated THI heat stress values by Ignono, et. al.

THI	<64	64-72	73-76	77+
Heat Stress	None	Mild	Moderate	Severe

Table 5 - Updated THI heat stress values by Rodriguez-Venegas, et. al.

THI	<68	68-71	72-76	77+
Heat Stress	None	Limited	Moderate	Intense

We adapt a previous study[8] to relate the number of days with a maximum THI at each level to corresponding milk quantity and quality. We simplify the model and production levels at baseline until a max THI of 72, after which milk quantity declines by 0.76% per THI increment, milk fat declines by 1.3% per THI increment, and milk protein declines by 1.06% per THI increment. We apply the max THI per day to the milk production of that day. This simplified model allows us to translate the heat distribution experienced by dairy cows into financial impact.

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[5] Armstrong D.V. (1994). *Heat stress interaction with shade and cooling.* J Dairy Sci. 1994;77:2044–50.
[6] Ignono M.O., et. al. (1992). *Environmental profile and critical temperature effects on milk production of Holstein cows in desert climate*. Int. Journal of Biometeorology. 1992;36:77-87.
[7] Rodriguez-Venegas R., et. al. (2023) *Effect of THI on Milk Production, Percentage of Milking Cows, and Time Lying in Holstein Cows in Northern-Arid Mexico*. Animals (Basel). 2023 May 22;13(10):1715.
[8] Ravagnolo, O., I. Misztal, and G. Hoogenboom. *Genetic component of heat stress in dairy cattle, development of heat index function.* Journal of dairy science 83.9 (2000): 2120-2125.

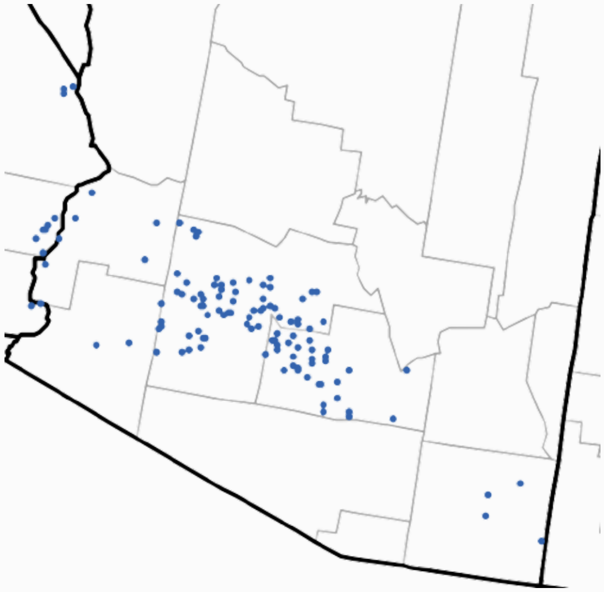
THI and Heat Stress Score for Arizona Dairy Farms

In Southern Arizona, high temperatures are common for a majority of the year. While average humidity in the Arizona desert is significantly lower than most places on Earth, summer monsoons in July and August bring relatively high humidity alongside heat, leading to a significant number of expected days each year with THI values that pose a severe threat to dairy cow health and productivity.

In addition, June and July in Arizona regularly see night time ambient temperatures in excess of 35°C (95°F), meaning cattle cannot sufficiently cool their core body temperature from the day before, potentially leading to multi-day compounding heat stress.[9] As Earth's climate warms, days with THI associated with heat stress are expected to increase significantly, with projected milk yields declining by 1.3% to 2.2% per cow by 2050, depending on greenhouse gas emission scenarios.[10]

Commercial dairy farms in Arizona are concentrated in the south-central part of the state, with the majority clustered in Maricopa, Pinal, La Paz and Yuma counties, as shown in Figure 1.

Figure 1 - Locations of Dairy Cattle in Arizona



Source: USDA 2017 Census of Agriculture

[9] Ignono M.O., et. al. (1992). *Environmental profile and critical temperature effects on milk production of Holstein cows in desert climate*. Int. Journal of Biometeorology. 1992;36:77-87.
[10] North, M., et. al. (2023). *Global risk of heat stress to cattle from climate change.* Environ. Res. Lett. 18;094027.

In order to analyze and predict this risk based on the geographic location of Arizona dairy farms, we developed a Javascript program to parse and analyze .clm files from the free and open source climate data repository hosted at climate.onebuilding.org, which is itself derived from NOAA's Integrated Surface Database. These climate files contain hourly temperature and humidity data, normalized between 2007 and 2021 and are generally used for building climate modeling and other climate research.

Table 6 shows the number of hours in a normalized year at various THI values at four different locations with dairy farming activity in Southern Arizona. In addition, THI values for Hermiston, Oregon are provided, as this is the location of the largest dairy farm in the United States with over 70,000 heads of cattle. It is evident that the heat in Arizona presents a significant challenge for Arizona dairy farmers, with common farm locations experiencing heat stress conditions for roughly half of the year and severe heat stress conditions for between 7.8% and 9.9% of an average year.

Table 6 - Ambient THI Hours per year at AZ dairy farming locations and Hermiston, OR

	<66	66-73	72-76	77-80	80+
Casa Grande, AZ	4,416 50.4%	1,429 16.3%	1,095 12.5%	1,031 11.8%	789 9.0%
Coolidge, AZ	4,315 49.3%	1,457 16.6%	1,092 12.5%	1,154 13.2%	742 8.5%
Buckeye, AZ	4,343 49.6%	1,573 18.0%	883 10.8%	1,113 12.7%	848 9.7%
Yuma, AZ	3,670 41.9%	1,590 18.2%	1,059 12.1%	1,097 12.5%	1,344 15.3%
Hermiston, OR	7,182 82.0%	998 11.4%	529 6.04%	51 5.8%	0 0.0%

Modern Dairy Farm Design in Arizona

Most Arizona dairy farms use so-called "Saudi barns" as their main structures. Interestingly, this style of barn is commonly called an "Arizona barn" in Saudi Arabia, due to its development by collaborative research efforts between the University of Arizona and experts from Saudi Arabia. Saudi-style barns utilize open corrals and walls under long ventilated roofs. Feed is spread in the center of the barns so that cows don't have to leave shade to feed. In summer months, it's common for cows to never leave the shade of their barn.

Figure 2 - Example of the Saudi-style barn, common in Arizona

In Arizona, these barns are fitted with active cooling systems, most commonly fans and misters. During the spring and fall, fans and misters may turn on for a few hours a day. During the summer, it's common for fans and misters to run 24/7. In addition, white galvanized panels or cool roof white coatings are usually applied to the galvanized metal roofs in order to minimize solar heat gain.

An Overview of Passive Daytime Radiative Cooling

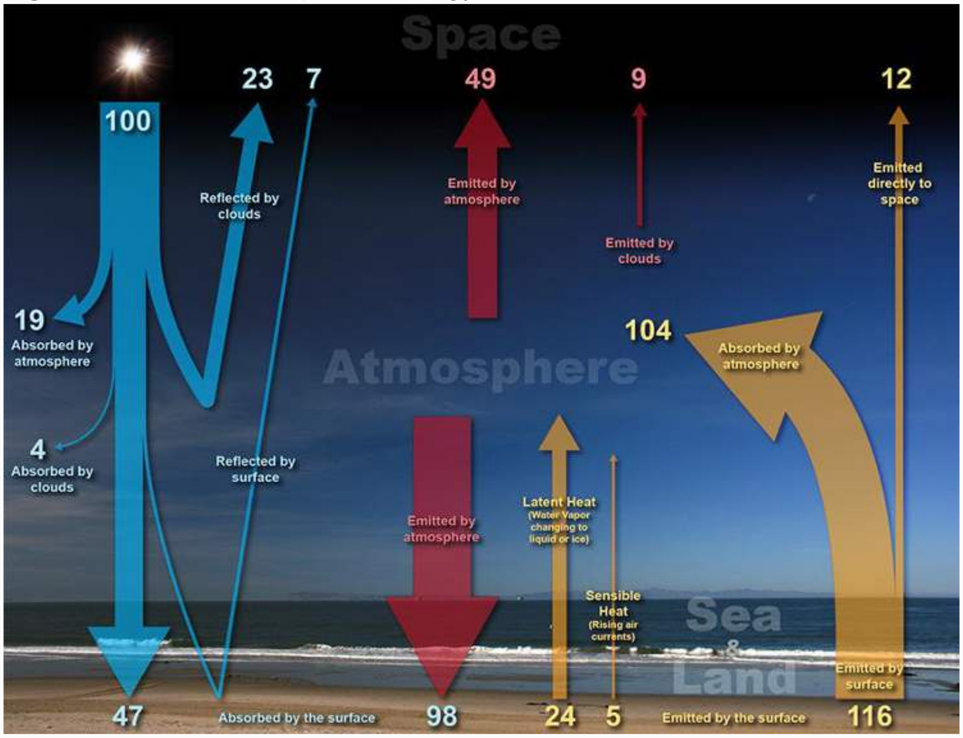
The concept of radiative cooling has ancient roots, with early human civilizations using materials like clay pots and water-filled vessels to take advantage of nighttime radiative cooling effects. Ancient Persians utilized nighttime radiative cooling to make and store ice in the hot and arid climate of Iran by employing dome-shaped, insulated buildings known as Yakhchāls. During the daytime, the outer walls of the Yakhchāl absorbed heat from the sun, causing the interior temperature to rise. However, at night, when the surroundings cooled down, the outer walls began to radiate their accumulated heat into the cold night sky. This radiative cooling process caused a significant drop in interior temperature, preserving the ice and chilled water stored within the Yakhchāl.

However, while nighttime radiative cooling has been utilized for millenia, passive daytime radiative cooling, which operates in the presence of sunlight, is a recent innovation. In the early 2010s, scientists began exploring the idea of achieving radiative cooling even under direct sunlight, challenging the conventional wisdom that sub-ambient cooling via radiating heat to the cold of space can only occur at night. In 2017, a paper was published showing that large-scale manufacture of PDRC is feasible, heralding a major breakthrough for the technology.

PDRC relies on advanced photonic principles that allow materials to emit thermal radiation while reflecting incoming solar radiation. Several key concepts and developments enable PDRC technology:

- **Earth's Energy Balance:** Energy from the sun enters Earth's atmosphere as ultraviolet, visible, and near-infrared (NIR) light. Without a way for the atmosphere to shed this energy back into space, the planet would continually heat until it eventually reached thermal equilibrium with the sun. Fortunately for all living things on Earth, the planet and its atmosphere maintain a complex energy balance through the interaction of reflection, absorption, and emission (Figure 3).

Figure 3 - Earth/Atmosphere Energy Balance



Source: *NOAA*

- **The Infrared Atmospheric Window:** Earth's infrared atmospheric window represents a range of mid-infrared (MIR) wavelengths, between ~8μm to 14μm, where the atmosphere is relatively transparent to outgoing thermal radiation. This allows heat to escape freely into the cold of outer space. All objects facing the unobstructed sky constantly radiate heat through the atmospheric window, but during the day, this cooling effect is almost always overshadowed by the heating effect of incoming solar radiation, even with white or light-colored objects.

- **Selective Radiative Properties:** The emissivity-reflectivity duality is a fundamental principle in PDRC. PDRC materials emit thermal radiation in the mid-infrared (MIR) range while being highly reflective in the solar spectrum (i.e., the visible and near-infrared range). This selectivity allows objects to radiate heat effectively into space, while minimizing absorption of solar energy. Put another way, these materials minimize heating from incoming solar radiation while maximizing cooling through atmospheric window emissivity. When the cooling effect surpasses the heating effect, PDRC materials can reach sub-ambient temperatures.

- **Photonic Structures:** Advanced photonic structures play a critical role in achieving selective radiative emission. Precisely engineered metamaterials and material voids interact with and manipulate electromagnetic waves, allowing for narrow control over a material's radiative properties. By combining 90%+ emittance in the atmospheric window, using these photonic structures, with 90%+ reflectance to the suns' energy, using highly reflective materials like silver or titanium dioxide, composite PDRC materials can stay sub-ambient, even under direct noon sunlight.

Given the recent invention of PDRC, applications are just beginning to be explored. Initial pilot studies have successfully shown zero-energy cooling in a wide range of applications including structures, vehicles, refrigerant pre-coolers, and even clothing. Deployed at scale, PDRC could be used to curb urban heat islands or even limit global warming. PDRC coverage of 1%-2% of Earth's land area (roughly half the size of the Sahara Desert) has been proposed as a way to tackle anthropomorphic climate change.[11] Despite promising pilot studies amid successful early commercialization, application of PDRC materials to dairy farming is yet to be explored.

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[11] Munday, J. (2019). *Tackling climate change through radiative cooling*. Joule. 2019;3(9):2057-2060.

Model for PDRC Deployment in Arizona Dairy Farms

Impact on Roof Temperature

As discussed in the section titled “Modern Dairy Farm Design in Arizona”, many Arizona dairy farmers already utilize cool roof products on their barns and parlors. While working under a similar principle as passive daytime radiative cooling (keep sky-facing sunlit areas cooler during the day), even the best traditional cool roof materials stay at or above ambient temperatures. Because cool roof coatings are reflective across visible, near-IR, and mid-IR wavelengths, they do little to radiate heat away from buildings and work solely by reflecting incoming solar radiation away.

While they may look similar in color, switching from traditional cool roof coatings to a PDRC material keeps roofs significantly cooler. In fact, switching from an average cool roof coating to a Radi-Cool PDRC film coating would have almost the same impact on roof temperature as switching from a galvanized steel roof to a cool roof, as shown below in Table 7. In other words, Radi-Cool PDRC represents a major step forward in our ability to cool roofs, as compared to even our best traditional cool roof coatings.

Table 7 - Summer noontime absorbed (insolation of 1100w) versus emitted (mid-IR) wattage of various roofing materials and associated temperature rise based on values from Berkeley Lab Heat Island Group.[12]

Material (At Noon)	W/m² Absorbed	W/m² Emitted	Net Heating (W/m²)	Temp Rise
Asphalt Shingles (Black)	1045W	145W	900W	82°F (45.6°C)
Galvanized Steel	429W	6W	423W	55°F (30.5°C)
Aluminum	429W	40W	399W	48°F (26.7°C)
Elastomeric Cool Roof Coating (Avg.)	352W	146W	206W	25°F (13.9°C)
Elastomeric Cool Roof Coating (Best)	165W	146W	19W	9°F (5°C)
Radi-Cool PDRC Film	88W	155W	-67W	-10°F (-5.6°C)

[12] Berkeley Lab Heat Island Group. https://heatisland.lbl.gov/resources/cool-roofing-materials-database

As a case study, we use insolation data from June 6, 2022 to compare the average net heating of Radi-Cool PDRC Film vs that of state-of-the-art cool roof coatings. We find Rad-Cool PDRC Film has a net average cooling of **350W** compared to galvanized steel and **103W** compared to state-of-the-art cool roof coatings. Note that this cooling is over 24 hours, not just during daytime hours.

To compute net heating per head, we consider a 7,500 m^2 barn housing 1,000 heads and a 3/12 roof slope, yielding 9.4m^2 of roof material per head. This results in a net heating of 1kW to 4kW, depending on the roofing material, compared to Radi-Cool PDRC Film.

Next we compare this to the cooling power of evaporative cooling. We consider resource consumption as 98 gallons/head/day and 4.0kWh/head/day.[13,14] Assuming a 75% evaporation efficiency, 98 gallons/day corresponds to 9.7kW of cooling per cow. Accordingly, **PDRC provides between 10% and 40% of the cooling power of evaporative cooling**, without consuming any water or power. Moreover our calculations assume very low June humidity; in the presence of higher humidity in the later summer months, the cooling power of Radi-Cool PDRC relative to evaporative cooling increases.

In highly simplified terms, a galvanized steel or aluminum roof will act as a heater, driving roof temperatures significantly higher than ambient temperatures. A high-quality cool roof will be neutral and keep roof temperatures roughly equivalent to ambient temperatures. A Radi-Cool PDRC roof will act as a cooler and allow for better-than-ambient roof temperature and associated interior THI values.

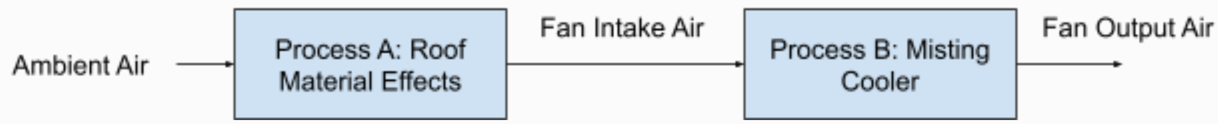
Impact of Roof Material + Misting Cooler on THI

We model the effects of PDRC on heat stress on dairy cows. We compare against traditional cool roof elastomeric coatings and uncoated galvanized metal roofing.

[13] Atkins, I., Choi, C. (2017). *Dairy Cooling in Arid and Semi-Arid Climates*
[14] Ortiz, X. A., Smith, J. F., Villar, F., Hall, L., Allen, J., Oddy, A., al-Haddad, A., Lyle, P., Collier, R. J. (2015). *A comparison of 2 evaporative cooling systems on a commercial dairy farm in Saudi Arabia*, J. Dairy Sci. 98:8710–8722

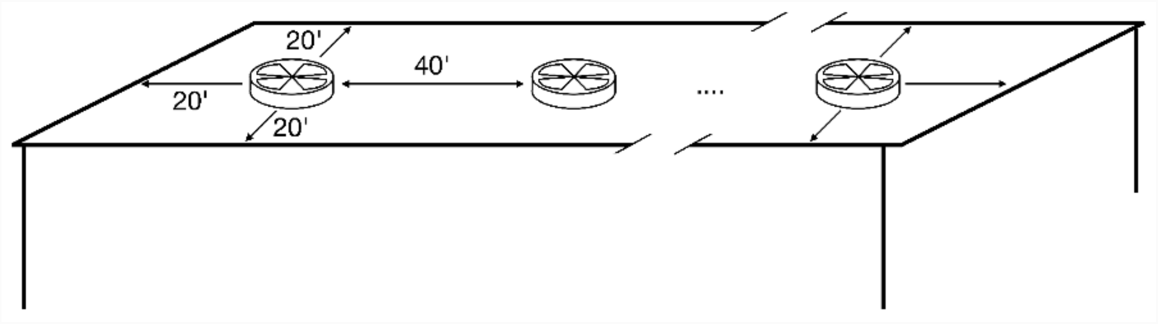
For each, we use weather data from climate.onebuilding. We focus on Casa Grande, AZ, using weather from the 2009 calendar year. Weather data is hour-by-hour, and we leverage values for 1. dry bulb temperature, 2. direct solar intensity, and 3. relative humidity.

Figure 4 - Cascade of roof effects and misting cooler



We study a cascade of PDRC cooling on the roof and evaporative cooling, as shown in Figure 4. We assume a through-the-roof fan cooler, which is a fan that pulls air from above the structure and adds water at a high pressure to evaporatively cool the inside of the structure. Though through-the-roof coolers gather the greatest benefit from rooftop PDRC, a similar analysis can be performed with roof-adjacent coolers. We consider coolers spaced from edges by 20 feet and from other coolers by 40 feet (making each cooler responsible for 400 ft^2 of area). This is illustrated in Figure 5.

Figure 5 - Roof spacing of misting coolers



Most fan coolers use measured environmental conditions to control the frequency of fan cycling and water spraying. Cycling is important in order to allow water to evaporate so as to prevent overdamping, which can lead to infection and disease. We assume the following parameters for cooler cycle frequencies.[15]

Table 8 - Misting cooler fan scheduling based on ambient temperature

Temperature range	Cooler on duration	Cycle period
< 68 °F	-	-
68 - 78 °F	1 minute	15 minutes
79 - 88 °F	1 minute	10 minutes
> 88 °F	1 minute	5 minutes

At low temperatures, the cooler will run one minute every 15 minutes (or ~6.6% of the time), at moderate temperatures the cooler will run one minute every 10 minutes (10% of the time), and at high temperatures the cooler will run one minute every 5 minutes (20% of the time). We denote the duty cycle at time t as D^t, which is between 0 and 1.

We use psychrometric charts to model the air qualities through PDRC and through the misting coolers. We assume ambient air pressure is 1 atm. Since cooling from PDRC will change the relative humidity, it is important to model this change before calculating the change in temperature and relative humidity from the misting cooler, since relative humidity of air at the intake of a misting cooler has a large effect on the effectiveness of the cooler.

Thus, for a given dry bulb temperature decrease due to PDRC, we calculate (a) the resulting relative humidity of the air, (b) the dry bulb temperature after the resulting air is run through the misting cooler, and (c) the relative humidity of the resulting air. We then use our previously referenced model to calculate THI.

Calculating a-c above is nontrivial. We make a few assumptions to make this modeling tractable.

1. PDRC cooling does not affect the *total* moisture content (i.e. the humidity ratio) of the air.
2. Density of the air remains constant during PDRC cooling. This is a simplifying assumption, but in the regimes we explore (~15 °F cooling) this does not have a significant effect on the results.

3. Misting coolers run at 75% efficiency.[15] Misting coolers will have lower efficiency than evaporative coolers for residential or commercial buildings, which have efficiency of approximately 85-95%.
4. Misting coolers do not change the wet bulb temperature of the air. In other words, we assume a perfect adiabatic process (heat does not enter or leave the system).

Accordingly, we use assumption 1 to calculate (a), the relative humidity of the air after PDRC, giving us the qualities of the air upon intake to the misting cooler. We use assumptions 2 and 3 to calculate the qualities of the air after going through the misting cooler. In the above analysis we took for granted the temperature decrease from PDRC. We use assumption 2 as part of calculating this value. We describe this calculation in the following subsection.

Note that an ideal evaporative cooling system can only lower the air temperature to the wet bulb temperature of the intake air; this would occur at 100% relative humidity. In contrast, PDRC cooling *lowers the wet bulb temperature of the air*, since PDRC is not a closed system, and in fact emits heat from the adjacent air into the upper atmosphere.

In describing the details of how we calculate the temperature/humidity changes, we split our discussion into what happens before the intake into the fan for the misting cooler, and what happens after.

Cooling Before Fan Intake

Instead of calculating just the cooling from PDRC, we instead calculate the effect of the roof surface on the fan cooler intake. Roof surfaces may heat or cool the air, depending on the physical properties of the roof and the weather conditions; modeling this way allows us to compare the resulting THI from any number of roof types.

We calculate the intensity of the surface (W/m^2) as follows:

$$I^t_{roof} = \epsilon_{vis} * I^t_{sun} - \epsilon_{IR} * I_{max\_IR} * (1 - \gamma^t),$$

where I^t_{roof} is the energy absorbed (if positive) or emitted (if negative) from the roof surface at time t, in W/m^2, ϵ_{vis} is the emissivity of the roof surface for visible wavelengths (for

[15] Atkins, I, Choi, C. (2017). *Dairy Cooling in Arid and Semi-Arid Climates.*

non-transparent roof materials, this is equal to 1 - reflectivity for these wavelengths), ϵ_{IR} is the emissivity for infrared (IR) wavelengths, I^t_{sun} is the solar irradiance (in W/m^2) at time t, I_{max_IR} is the max IR intensity (ie W/m^2 of energy that can be emitted in the form of IR into the upper atmosphere), which we take to be 235 W/m^2, and γ^t is the cloudiness (between 0 and 1) at time t.

To go from roof intensity to the power of the heating/cooling, we multiply by the area associated with each fan. Accordingly, roof power transfer per fan (P^t_{roof} , W) is

$$P^t_{roof} = I^t_{roof} * A_{fan} * mpf^2 ,$$

where A_{fan} is the roof area per fan, which we take to be 400 ft^2, as mentioned above, and mpf^2 is a unit conversion from square feet to square meters.

The temperature change of the air will be a function of P^t_{roof} and the roof airflow. As described above, roof airflow will depend on ambient temperature. We use CFM^t to denote the average cubic feet per minute for time t, which depends on temperature at time t. We consider a nominal airflow of 1500 ft^3/min.[16] Accordingly, at time t, average airflow is

$$CFM^t = 1500 * D^t,$$

where D^t is the duty cycle at time t, as described above.

We then compute heating/cooling per volume air, H^t, which is the Joules of heating or cooling per cubic meter of air (heating if positive, cooling if negative).:

$$H^t = \frac{P^t_{roof}}{CFM^t} * fpm^2 * jpwh / mph$$

Where the last three terms are unit conversions (feet per meter, Joules per Watt Hour, minutes per hour).

We arrive at H^t, from which we can calculate the updated air temperature. We then do a series of psychrometric calculations, which we provide in pseudocode.

[16] Using specifications from the FlipFan 36 Inch High Velocity Fan. https://schaeferventilation.com/wp-content/uploads/2020/01/flipfanflyer2014.pdf

We then perform the following steps (where the psychrometric calculations assume an atmospheric pressure of 1 atm).

Process A:

1. Get the starting humidity ratio from the dry bulb temperature and relative humidity.
2. Get the starting moist air density from dry bulb temperature and relative humidity.
3. Get the starting moist air enthalpy from the dry bulb temperature and relative humidity.
4. Calculate the heating per mass as H^t / moist air density.
5. Find the updated moist air enthalpy by adding H^t / moist air density to the previous moist air enthalpy.
6. Get the updated dry bulb temperature and relative humidity from the updated moist air enthalpy and starting humidity ratio (note that we use the *starting* humidity ratio due to Assumption 1 above).
7. If the updated dry bulb temperature is below the dew point, clip it to the dew point.

Steps 1, 2, 3 and 6 are direct psychrometric calculations. Step 4 is a conversion from H^t, a measure of heating per mass, to a measure of heating per volume, so that we can use the moist air enthalpy. Step 5 is a simplifying approximation, since the air volume changes, which we discuss in Assumption 2 above. Step 7 follows from Assumption 1.

Cooling After Fan Intake

The above calculations give us the dry bulb temperature and relative humidity of the air upon the intake to the misting fan. To calculate the same quantities after the misting cooler, we do the following steps:

Process B:

1. Get the input air wet bulb temperature from the dry bulb temperature and the relative humidity, denoted $T^t_{wb,\, fan\_in}$.

2. Calculate the new dry bulb temperature ($T^t_{db,\,fan\_out}$) from the input dry bulb temperature $T^t_{db,\,fan\_in}$, input wet bulb temperature $T^t_{wb,\,fan\_in}$, and efficiency ϵ_{evap} as

$$T^t_{db,\,fan\_out} = (1 - \epsilon_{evap}) * T^t_{db,\,fan\_in} + \epsilon_{evap} * T^t_{wb,\,fan\_in} .$$

3. Get the new relative humidity from the dry bulb temperature of the air coming out of the misting fan ($T^t_{db,\,fan\_out}$) and the wet bulb temperature of the incoming air ($T^t_{wb,\,fan\_in}$).

Steps 1 and 3 are psychrometric calculations, where 3 assumes that the wet bulb temperature of the air does not change during the process, in accordance with Assumption 4. Step 2 is a simple manipulation of the definition of efficiency for evaporative cooling.

Calculating THI Statistics

With all the above, we are ready to aggregate THI statistics for structures with each rooftop surface type. We use the instantaneous THI calculation for day d and hour t as described above, repeated here with a slight redefinition of notation

$$\mathrm{THI}^t_d = (1.8 \times \mathrm{T}^t_{db,\,fan\_out} + 32) - [(0.55 - 0.0055 \times \mathrm{RH}^t) \times (1.8 \times \mathrm{T}^t_{db,\,fan\_out} - 26)]$$

where T is dry bulb temperature (°C) and RH is the relative humidity (%).

We calculate THI for each hour as above. We then take THI of the hour with maximum THI for each day, then count the number of days with each THI index. In the following section we translate this to milk productivity. Formally, we construct a histogram which is a vector with elements as follows:

$$c_i = \sum_{d \in D} 1_i(THI_d),$$

where we define the indicator function

$$1_i(x) := \begin{cases} 1 \; if \; x = i \\ 0 \; if \; x \neq i \end{cases},$$

and we aggregate THI by maximum THI each day:

$$THI_d = \max_{t \in \{1,2,\ldots 24\}} THI^t_d .$$

We choose maximum THI hour per day to capture the fact that nighttime overcooling will not increase milk production. In summary, for each roof type, we produce a histogram of the number of days with the maximum THI hour at each THI value. In the following section, we leverage existing milk production models to predict the effect of rooftop material type on milk production.

Figure 6 - Histogram of the number of days with max THI hour in each bin for the sample year in Casa Grande, AZ.

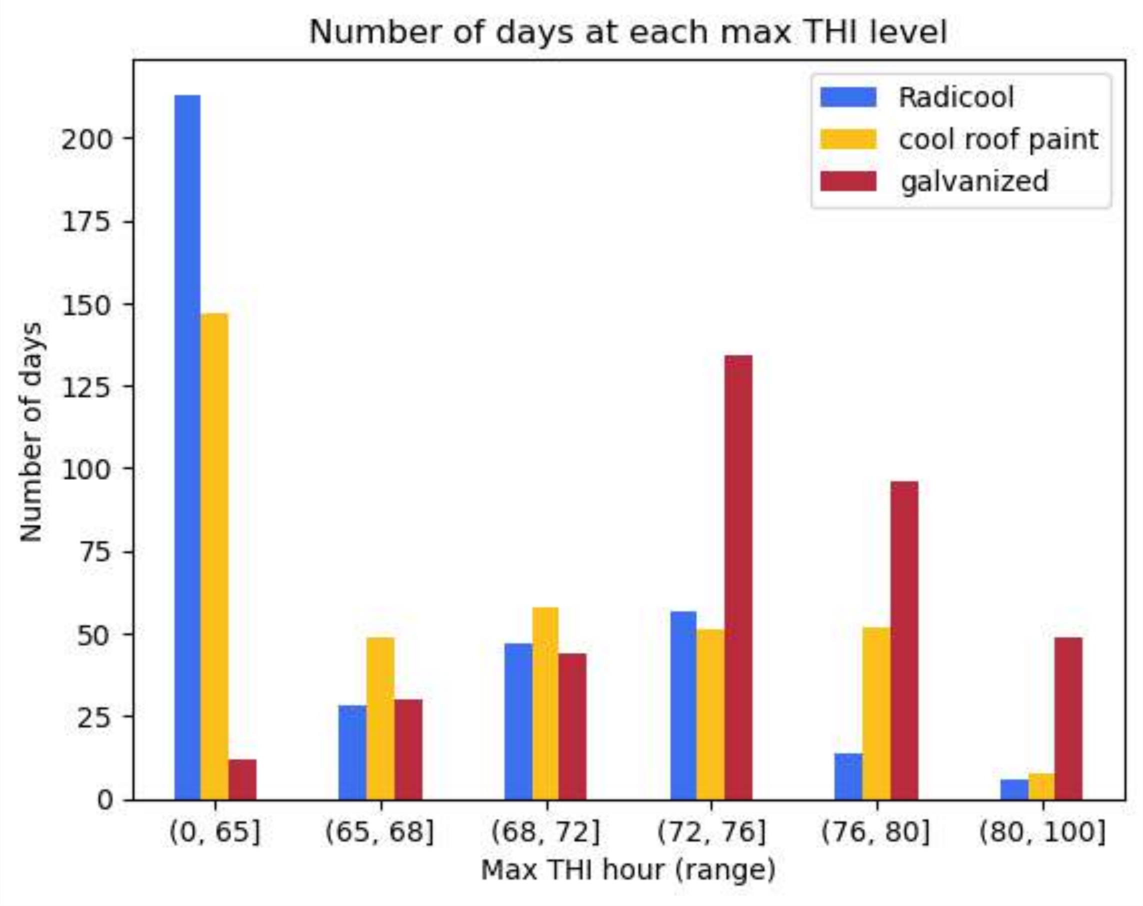


Figure 6 shows a summary of the results, incorporating modeling of rooftop material heating/cooling effects in concert with misting coolers, using the weather data from Casa Grande in 2009. We show the number of days with maximum THI level in each bin. While cool roof paint cools more than galvanized steel, Radi-Cool is most effective at decreasing the number of high THI days.

Economic Feasibility Analysis

Economic feasibility is perhaps the biggest consideration for the adoption of any new technology. A technology must create economic value, in the form of increased revenue, decreased operational expenditure, or both to find successful adoption.

To measure expected excess economic value, modeled improvements to THI can be converted to various improvements in production and efficiency. These include excess milk production, improved feed to milk ratios, improved milk fat and protein content, increased summer fertility, and decreased disease and mortality.

Table 9 shows expected production under uncoated galvanized steel roofs, elastomeric coated cool roofs, and Radi-Cool PDRC roofs for Casa Grande, Arizona using THI values obtained in the analysis above. Production is estimated using the heat index function proposed by Ravagnolo, et al.[17]

Table 10 shows the percent expected increase in total milk, fat, and protein production when switching from a galvanized roof to an elastomeric cool roof or a galvanized room to a Radi-Cool PDRC roof.

Table 9 - Annual expected total milk, fat, and protein measured in kilograms per head of cattle (total weight in kg)

Roof Type	Total Milk (kg)	Fat (kg)	Protein (kg)
Galvanized Steel	9,303	318	297
Elastomeric Cool Roof	9,497	330	306
Radi-Cool PDRC	9,540	332	308

Table 10 - Expected improvement in total milk, fat, and protein production for PDRC roof compared to galvanized steel and a high quality elastomeric cool roof (% by weight)

[17] Ravagnolo O., Misztal I., Hoogenboom G., (2000). *Genetic Component of Heat Stress in Dairy Cattle, Development of Heat Index Function*. J Dairy Sci. 2000 Sep;83(9):2120-5

Roof Type	Total Milk	Fat	Protein
Galvanized Steel	2.55%	4.47%	3.59%
Elastomeric Cool Roof	0.46%	0.8%	0.64%

Compared to existing roof technologies in use in Arizona dairy farms, we expect PDRC to provide economically significant improvements to both total milk production and milk quality.

While improvements in milk quantity and quality account for the majority of economic benefit for PDRC adoption, we expect improvements of a similar magnitude in feed-to-milk ratio. Feed represents the largest input to dairy farming, by cost. In addition, it is accepted practice to increase forage quality in response to heat stress THI values. With higher protein and fat ratios and improved vitamin and additive profiles, these high-THI feeds are more expensive and lead to lower IOFC (income over feed costs). Improvements in feed-to-milk ratio, especially with expensive summer forage, leads to economically significant improvements in gross margins.

Additional benefits not captured in our model are expected improvements to fertility. In a 2020 study, Djelailia et. al. found that in arid Tunisia, average Holstein calving intervals increase from 420 days to 487 days in the presence of heat stress and for each point increase in THI above 67 there is a decrease in first conception rate by 1.39%.[18] Conception rate and calving intervals are important economic metrics for farmers and improvements to expected THI values and PDRC adoption should reasonably translate into improved fertility at the herd level.

Finally, while not modeled here, it is reasonable to assume that PDRC implementation would decrease both annual water and electricity usage, with the majority of improvements occurring in early spring and late fall as fan/misting systems could remain off for longer stretches of the year. Given the relatively low cost of water and electricity in relation to total inputs, the savings would be modest. That said, a number of government and non-profit grants and credits are available to help subsidize technologies that improve energy and water efficiency on US farms.

[18] Djelailia, H., Bouraui, R., Jemmali, B. (2020). *Effects of heat stress on reproductive efficiency in Holstein dairy cattle in the North African arid region*. Reproduction in Domestic Animals. 2020 Jul;55(9):1250-1257

While the cost of Radi-Cool PDRC implementation depends heavily on farm layout and barn style, we estimate a simple payback period of between three and five years when applied to galvanized roofing in the most common Arizona dairy farm layouts. With the ability to qualify for efficiency grants and/or credits, simple payback periods could be even further accelerated. Given an expected lifespan of 15+ years, the adoption of Radi-Cool PDRC rooftop membrane represents a compelling business case for Arizona dairy farmers.

Conclusion

This paper analyzed the applicability of Passive Daytime Radiative Cooling materials to dairy farming in Arizona. Specifically, we proposed the application of using Radi-Cool PDRC membranes on dairy farm barns, milking parlors, and calf housing, and proposed a model for analyzing the impact of this roof material on the Temperature Heat Index experienced by the cows in barns with misting coolers. We conducted an economic analysis in which we translated the THI impact into impact on quantity and quality (fat and protein content) of produced milk. The comprehensive analysis shows that when barns incorporate PDRC roof material, milk productivity is significantly improved, both from barns with galvanized steel roofs, as well as from barns using existing cool roof technology.

All-in-all, this paper shows a promising new direction for improving productivity on dairy farms, as well as decreasing resource consumption and improving cow wellbeing. The primary next step is to conduct a medium to large-scale pilot study to validate these results. Should the empirical results validate the analysis in this paper, this represents significant economic and public interest opportunities for dairy farms in the Southwestern United States.

Appendix

Table of Notation

Table 11 - notation definitions. Notation with superscript t is at time t.

Notation	Definition	Unit
D^t	Fan duty cycle	Unitless
ϵ_{vis}	Rooftop emissivity for visible light	Unitless
ϵ_{IR}	Rooftop emissivity for infrared light	Unitless
I^t_{sun}	Solar irradiance	W/m^2
I_{max_IR}	Max IR emission intensity	W/m^2
I^t_{roof}	Rooftop intensity (energy absorbed/emitted)	W/m^2
γ^t	Cloudiness	Unitless
A_{fan}	Rooftop area associated with each fan	ft^2
P^t_{roof}	Roof power transfer per fan	W
CFM^t	Average fan flow (depending on duty cycle)	ft^3/min
H^t	Heating/cooling per volume air	J/m^3
ϵ_{evap}	Efficiency of evaporative cooler	Unitless
$T^t_{wb,\_}$	Wet bulb temperature	°C
$T^t_{db,\_}$	Dry bulb temperature	°C
$T^t_{\_,fan\_in}$	Air temperature at input to misting cooler	°C
$T^t_{\_,fan\_out}$	Air temperature at output of misting cooler	°C

mpf	Unit conversion, meters per foot	m/ft
$jpwh$	Unit conversion, Joules per Watt Hour	J/Wh
mph	Unit conversion, minutes per hour	min/hr

Review of Analogous PDRC Applications

While the mechanism of action for passive daytime radiative cooling was first theorized in the mid-1900s, it took until 2014 for the field of photonics to advance to the point where researchers were able to create a material that cools below ambient temperatures under full noon sunlight.[19] As of late-2023, commercialization of PDRC materials is still in its infancy, with only a handful of companies producing and selling PDRC films, membranes, fabrics, paints, and/or coatings at scale. With that said, a number of large-scale PDRC pilot projects have proven the effectiveness and economic feasibility of the technology.

To our knowledge, no known pilot-projects for dairy farming exist, but projects in related industries or on similar structures to those found on a dairy farm can provide significant insight into potential dairy farm applications.

Grain Storage in Zhejiang, China.

As with dairy farming, grain storage is a highly temperature reliant activity. The Arrhenius equation, as a rule of thumb, describes a doubling of oxidation reaction rates for every increase of 10°C in temperature. Due to this, grain stored at higher temperatures shows significantly worse nutrient profiles, including in vitro protein digestibility, and water soluble amylose content.[20] Like dairy farming, grain storage requires scientifically sound balancing of energy use for cooling with improvements in economic value and nutrition provided by cooler temperatures.

In a full-scale granary pilot-project in Zhejiang, China, researchers applied Radi-Cool PDRC membrane to a granary building with a roof area of 1256m² and measured temperatures of the PDRC granary and a control granary building located on the same site over the course of 15

[19] Raman A., et. al. (2014). *Passive radiative cooling below ambient air temperature under direct sunlight*. Nature. 2014;515(7528)
[20] Rehman Z.U., Shah W.H. (1999). *Biochemical changes in wheat during storage at three temperatures.* Plant Foods Hum Nutr. 1999;54(2):109-17

months.[21] Figure 7 shows internal air temperatures of the experimental and control granary between mid-2020 and late-2021.

Figure 7 - Experimental granary layout and PDRC membrane

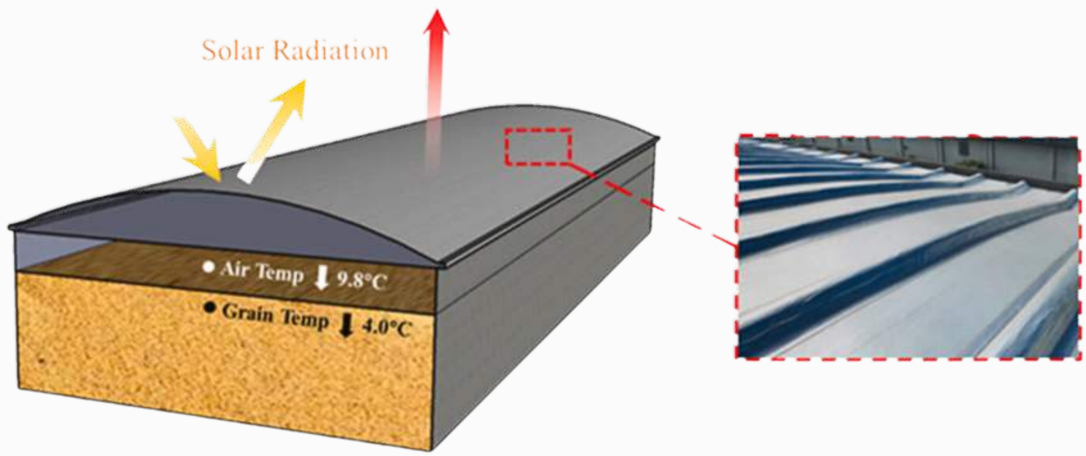
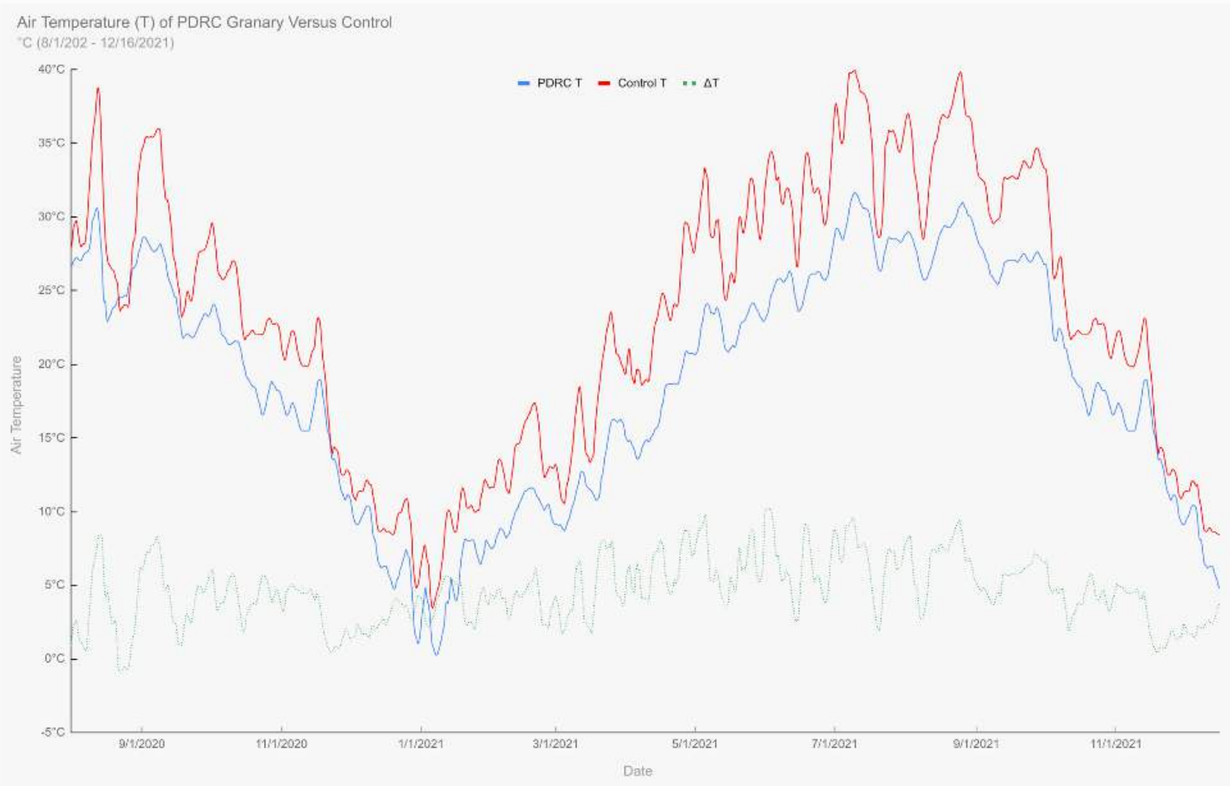


Figure 8 - Air temperature of Radi-Cool and control granary, measured mid-2020 to late-2021



[21] Xu, W, Et. Al. (2023). *Temperature reduction and energy-saving analysis in grain storage: Field application of radiative cooling technology to grain storage warehouse.* Renewable Energy. 2023;218.

Key findings of the study include:

- Temperatures of the outer surface of the experimental granary reached a maximum 27.1°C (48.8°F) below those of a control granary.
- Air temperatures in the inner ceiling were reduced by a maximum of 20.5°C (36.9°F).
- Temperatures of both the outer surface and inner ceiling of the experimental granary stayed sub-ambient for the entirety of the experiment.
- Between June, 2021 and August, 2021, average internal air temperatures in the PDRC granary averaged 6.6°C (11.9°F) below those of the control granary.
- Over the full year of 2021, internal air temperatures in the PDRC granary averaged 5.1°C (9.2°F) below those of the control granary.
- With air conditioners off, granary temperatures were reduced by a maximum of 8.8°C (15.8°F) compared to control.
- With air conditioners on, PRDC granary power savings were between 33.4-43.3% compared to control, with average power savings of 39.5%.
- Increase in core grain temperature in the experimental granary was delayed by 1.8°C (3.2°F) over 15 days.

Passenger Loading Bridge in Hangzhou, China

Anatomically, humans and cattle have more in common than we are likely comfortable to admit. Human bodies exhibit normothermia within a few degrees of those of bovines. At heat stress temperatures, bovines will pant and sweat, although they can only sweat at 10% of the rate of humans. When cows are hot, they will naturally seek out shade and water. In other words, if we are in an environment that is uncomfortably warm, cows likely feel that heat in a very similar way. Public areas frequented by hundreds of humans, like airports, can thus provide a useful analogue to large farm structures.

Researchers applied reflective and transparent Radi-Cool PDRC films to the metal roof and glass windows, respectively, of a passenger loading bridge (PLB) in Terminal 1 at Hangzhou Xiaoshan International Airport in Hangzhou, China. Total install area for both products was 1582m². The researchers compared the experimental PLB to a control that had an existing light-colored “cool roof” metal roof and no window film or tint. Temperature readings within and outside the experimental and control PLBs were gathered. In addition, PMV scores (Figure 9), an index for thermal sensation, were gathered to evaluate perceived passenger comfort.

Figure 9 - PMV Index

-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

Figure 10 - Infrared photo of Radi-Cool PDRC film on metal PLB roof (left) versus control PLB roof (right)

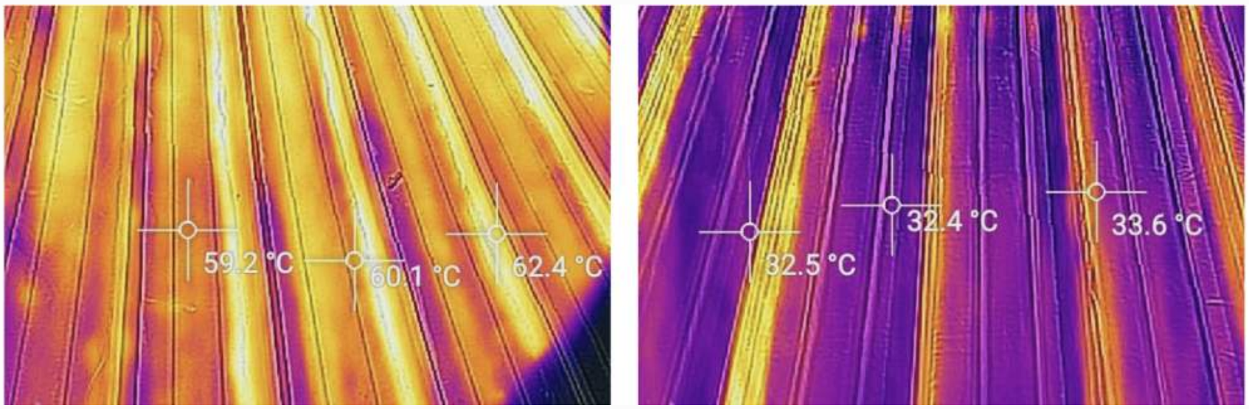
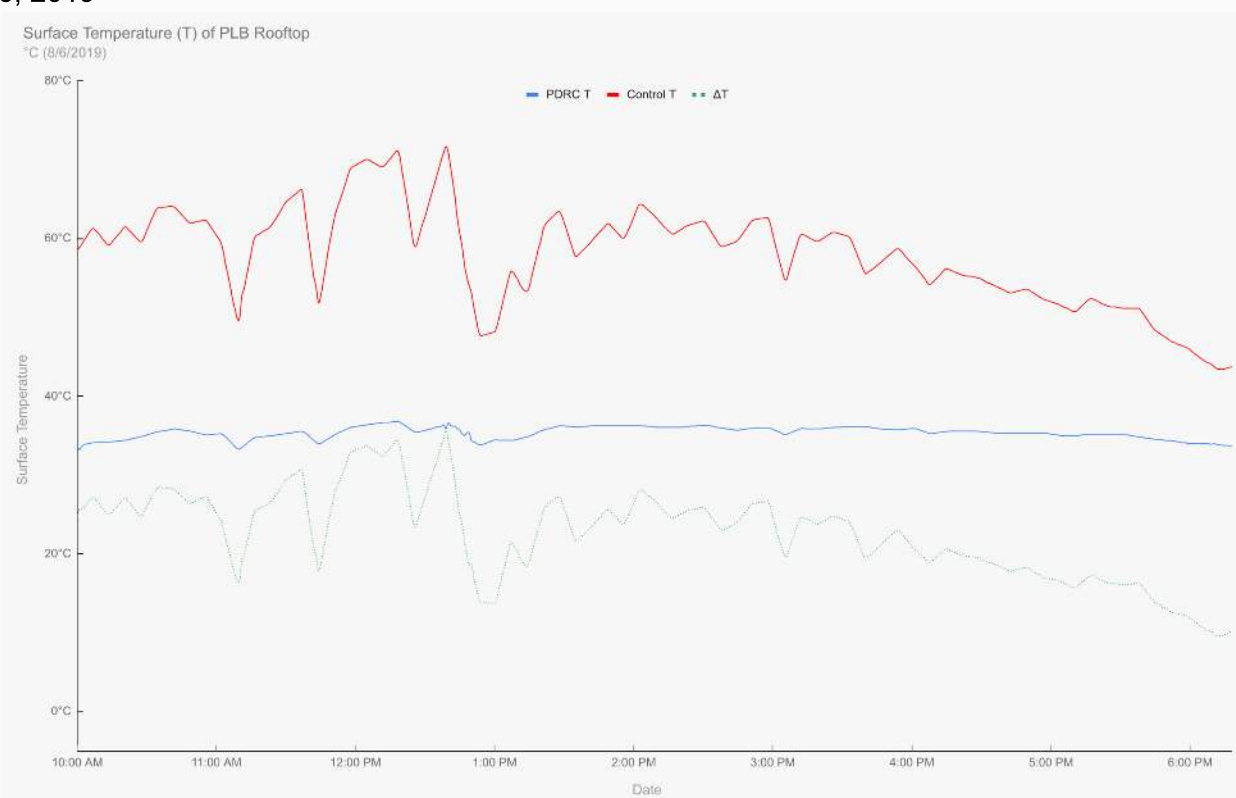


Figure 11 - Roof surface temperatures of Radi-Cool PDRC and control PLBs, measured August 6, 2019



Key findings of the study include:

- Roof surface temperatures of the experimental PLB always stayed below those of the control
- The maximum difference in roof surface temperature was recorded at 35.5°C (63.9°F)
- Interior air temperatures in the experimental PLB always stayed below those of the control
- With air conditioning off in both the experimental and control PLBs, the maximum difference in interior air temperature was recorded at 14.8°C (26.6°F)
- With air conditioning on in both the experimental and control PLBs, the maximum difference in interior air temperature was recorded at 5.7°C (10.3°F)
- Energy savings for air conditioning for the experimental PLB is estimated to be greater than 30% based on energy modeling
- PMV for the experimental PLB was measured at 0.21 (slightly above neutral) versus 1.29 (between slightly warm and warm) for the control

Table 12 - Estimated total milk, fat, and protein output for Casa Grande, AZ given modeled max THI days

		Days at Max THI			Total Milk	-0.2kg/unit >72		Milk Fat	-0.012kg/unit >72		Milk Protein	-0.009 kg/unit >72	
Units over 72	**Max THI**	**Galvanized**	**Cool Paint**	**Radi-Cool**	**Galvanized**	**Cool Paint**	**Radi-Cool**	**Galvanized**	**Cool Paint**	**Radi-Cool**	**Galvanized**	**Cool Paint**	**Radi-Cool**
0	**65**	12	147	213	316	3866	5602	11.0	135.2	196.0	10.2	125.0	181.1
0	**66**	11	13	12	289	342	316	10.1	12.0	11.0	9.4	11.1	10.2
0	**67**	5	21	7	132	552	184	4.6	19.3	6.4	4.3	17.9	6.0
0	**68**	14	15	9	368	395	237	12.9	13.8	8.3	11.9	12.8	7.7
0	**69**	12	18	11	316	473	289	11.0	16.6	10.1	10.2	15.3	9.4
0	**70**	15	13	13	395	342	342	13.8	12.0	12.0	12.8	11.1	11.1
0	**71**	7	15	10	184	395	263	6.4	13.8	9.2	6.0	12.8	8.5
0	**72**	10	12	13	263	316	342	9.2	11.0	12.0	8.5	10.2	11.1
1	**73**	13	13	8	339	339	209	11.8	11.8	7.3	10.9	10.9	6.7
2	**74**	31	17	14	803	440	363	27.8	15.2	12.5	25.8	14.1	11.6
3	**75**	50	11	13	1285	283	334	44.2	9.7	11.5	41.2	9.1	10.7
4	**76**	40	10	22	1020	255	561	34.9	8.7	19.2	32.6	8.1	17.9
5	**77**	40	17	10	1012	430	253	34.4	14.6	8.6	32.2	13.7	8.1
6	**78**	23	19	2	577	477	50	19.5	16.1	1.7	18.3	15.1	1.6
7	**79**	12	13	2	299	324	50	10.0	10.9	1.7	9.4	10.2	1.6
8	**80**	21	3	0	519	74	0	17.3	2.5	0.0	16.3	2.3	0.0
9	**81**	15	4	4	368	98	98	12.2	3.2	3.2	11.5	3.1	3.1
10	**82**	19	0	1	462	0	24	15.2	0.0	0.8	14.4	0.0	0.8
11	**83**	7	3	1	169	72	24	5.5	2.4	0.8	5.3	2.3	0.8
12	**84**	3	1	0	72	24	0	2.3	0.8	0.0	2.2	0.7	0.0
13	**85**	3	0	0	71	0	0	2.3	0.0	0.0	2.2	0.0	0.0
14	**86**	1	0	0	24	0	0	0.8	0.0	0.0	0.7	0.0	0.0
15	**87**	1	0	0	23	0	0	0.7	0.0	0.0	0.7	0.0	0.0
				Total	**9303.3**	**9496.5**	**9540.3**	**318.0**	**329.6**	**332.2**	**296.9**	**305.6**	**307.6**