# RAIN ON THE ROOF-EVAPORATIVE SPRAY ROOF COOLING

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## ABSTRACT

This paper describes evaporative spray roof cooling systems, their components, performance and applications in various climates and building types. The evolution of this indirect evaporative cooling technique is discussed. Psychrometric and sol-air principles are covered and a simplified method of evaluation presented. A life cycle energy savings example is discussed. Benefits of roof life and roof top equipment efficiency and maintenance are covered as well as water consumption and performance trade-offs with alternate methods of roof heat gain control. Testimonials and case studies are presented.

The gradual migration of business, industry, and populace to the southern United States was largely brought on by the advent of the practical air-conditioner, cheap electricity, and the harshness of northern winters. But while "wintering at Palm Beach" has been replaced by "Sun Belt industries"; the compression-refrigeration cooling cycle is about the only thing separating millions of southerners (native and adopted) from August heat stroke and the Detroit News employment ads. This migration has been spurred by economic recessions which hit harder at the competitively populated northern centers than at the still growing industries of the south.

These trends are important illustrations of the concern for efficient cooling strategies. Not only are homes in hot climates vulnerable to the now not-so-low cost of electricity but large, compact, and heavily occupied buildings (offices, schools, hospitals, theaters, etc.) often must air-condition year-around. In 1968, air-conditioning was 3% of U.S. end energy consumption compared to 18% for space heating and 25% for transportation. By 1980, according to Electric Power Research Institute's Oliver Yu, air-conditioning use was 12.5% of all electricity generated and by the year 2000 is projected to reach 16.7% "as migration slows and the GNP reaches a stable 3% growth rate" (EPRI 1982 to 1986 Overview and Strategy).

Of further significance is the effect of air-conditioning loads on the peak generating requirements of electrical utilities. Because utilities must build generating capacity to meet peak requirements, they normally charge a higher summer kWh rate (for residential) and levy a peak kW demand charge on a monthly or even annual "ratchet" rate (for larger service customers). The June '83 cover of Houston City Magazine, in reference to future electrical rates, promised: "Pay or Sweat".

Typical of many cooling or heat gain prevention strategies being employed on "innovative" buildings in warm climates, evaporative spray roof cooling (ESRC) systems (not to be confused with roof ponds) are not new. Like ventilated structures, ice house roofs, enhanced ventilation, masonry walls, night sky radiation and ground contact cooling, evaporative cooling in many forms has been around for centuries. (See Solar Age, July '82 and February '81 for related articles). Even the development of roof spray systems is not as newly founded as one might suspect.

## HOW IT STARTED

The earlier references to evaporative cooling invariably mention the Egyptians. On the banks of the Nile, large porous urns were filled with water and air fanned across their wet outside surfaces, cooling and moistening the desert air.

It is not clear when or where in history people began to douse roofs in order to cool their buildings evaporatively, but the distinction from direct evaporative cooling such as the Egyptian example is significant. By cooling the exterior skin of a structure, the space inside is cooled indirectly and excess humidity is kept outside. Further, by attacking at the roof surface, evaporative cooling is utilized where temperatures are highest (due to greater exposure to radiation) and relative humidity is lowest (air will hold more water vapor at higher temperatures). As a result, solar impacts on the roof surface can be negated before any of the other building's defense mechanisms come into play. And since no humidity is added to the space, this strategy is suitable even in humid climates.

The first known successful U.S. application of "roof sprinklers" occurred during the summer of 1934. Leonard Holder, an irrigation engineer, installed an irrigation system on the roof of the three story Belvedere Apartments in Washington D.C.. And so the ESRC industry was started, albeit with



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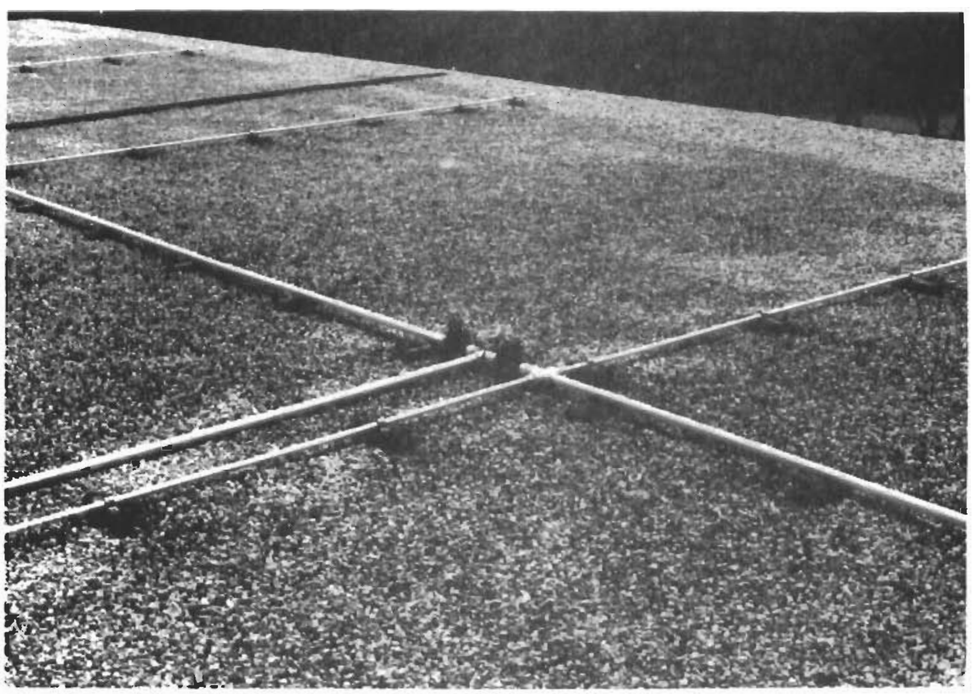
Roof spray grid at the Armco Steel plant Engineering Office, Houston, Texas.



Supply pipe and control valves for two zone Armco Steel system adopted and somewhat inefficient techniques. At any rate, the third floor occupants of the Belvedere were pleased.

And a good many systems, based on irrigation or fire safety hardware were sold. Muller Aeromist, an irrigation company and a pioneer of early systems, is still marketing a system ("FanJet", now refined and engineered for roof applications). Noxema was an early client with warehouse temperature control problems. Textile industries were and remain users of roof spray systems for space "tempering" applications.

By 1940, interest had grown sufficiently to merit an ASHVE (The American Society of Heating and Ventilating Engineers, which preceded ASHRAE, The American Society of Heating, Refrigerating and Air-Conditioning Engineers) study at the Pittsburgh Experiment Station. "Summer Cooling Load as Affected By Heat Gain Through Dry, Sprinkled and Water Covered Roofs" (Houghton, Olson and Gutberlet) compared time and heat flow relationships through nine different roof constructions for dry, sprinkled and ponded surfaces. Their conclusions indicated that the sprinkler system was, in all constructions, the most effective measure of reducing heat flow into the building. The ASHVE guide contained a table summarizing their findings for many years.

Since then several systems (and several papers) have appeared. The primary difference in today's systems is control, a necessary evolution if the problems of excess water consumption and potential roof ponding were to be overcome. Along the way, water distribution systems have evolved into two types: a grid of spray bars, either copper or plastic pipe with special perforations, and the sprinkler sprayhead type systems.

The concept prevails: to simulate the conditions which occur when it rains on the roof. This operation is controlled by temperature, time and duration, which means that periodically (every 4 to 10 minutes) the system checks to see if the roof is warm enough (over 90° or 95°F) to merit a misting (4 to 10 seconds). The parameters vary from manufacturer to manufacturer and are usually field adjustable to account for variance in climate and roof color.

Roof spray systems work with normal city water and water pressure, as long as the system is designed to allow about 20 psi at the end of every spraybar. Alternately, waste water can be used if a pump is provided. To keep pressure requirements low (and therefore pipe sizes), roofs are divided into zones of separate control and are sprayed sequentially. Check valves are provided to prevent the entire grid from draining onto the roof after each cycle and expansion chambers are installed at the zone control valve in larger systems where the shock of water-hammer may occur. Drain valves are provided for winterizing the system. But even with all the controls and safeguards, roof spray grids still resemble misplaced lawn sprinkler systems.

Actual design of individual systems is usually done at the factory to insure proper distribution and control. Generally, however, spraybars perforated on both sides spray 8-10 feet both ways and single sided pipe is used around the building perimeter, skylights and roof-top equipment, spraying away from protected boundaries. A temperature sensor is imbedded on the roof and is read by the controller located within the building.

To round out this sketch description, spray systems use about 1 gal. of water per 10 sq. ft. of roof surface during a summer day. In larger installations, roof spray water is metered separately to avoid sewage charges. Finally, current installed system costs run upwards from 25¢ to more than 40¢ per square foot depending on roof size and system desired. The copper systems tend to be the more expensive variety.

## THE ROOF ENVIRONMENT

One of the significant benefits of indirect evaporative cooling is that it adds little moisture to the enclosed space and thus makes roof spray systems applicable even in humid climates. To comprehend how an evaporative system could work in an already humid climate, it is necessary to understand something of the psychrometric relationships of air temperature, relative humidity and absolute humidity ratios; including such terms as wet-bulb, dry-bulb, dew point, saturation, sensible and latent heat, and enthalpy. It is most important to this discussion to point out that as air temperature increases, so does a volume of air's ability to hold moisture - hence the air is now less saturated and the relative humidity decreases, while the amount of moisture actually contained (absolute or specific humidity) remains unchanged. Refer to Fig. 1.

That is precisely what occurs in the roof environment (Fig. 2). As a roof is usually totally exposed to the sky from horizon to horizon, it absorbs solar radiation steadily, converts it directly to heat and often reaches surface temperatures in excess of 170°F. At that temperature, even the subtropical air of Miami, Houston, or Atlanta is less than 10% saturated (10% RH). By evaporating just enough water on the roof to drive the air to saturation (100% RH), the roof surface and the air film against it approach the wet bulb temperature. The radiant energy which raised the roof temperature (sensible heat) has been relieved by causing a phase change (latent heat) from liquid to vapor. But true to what we know about physics, the total enthalpy (sensible heat + latent heat) of the air has not changed. The roof is evaporatively (and somewhat convectively) cooled and Newton's Laws are safe for yet another day.



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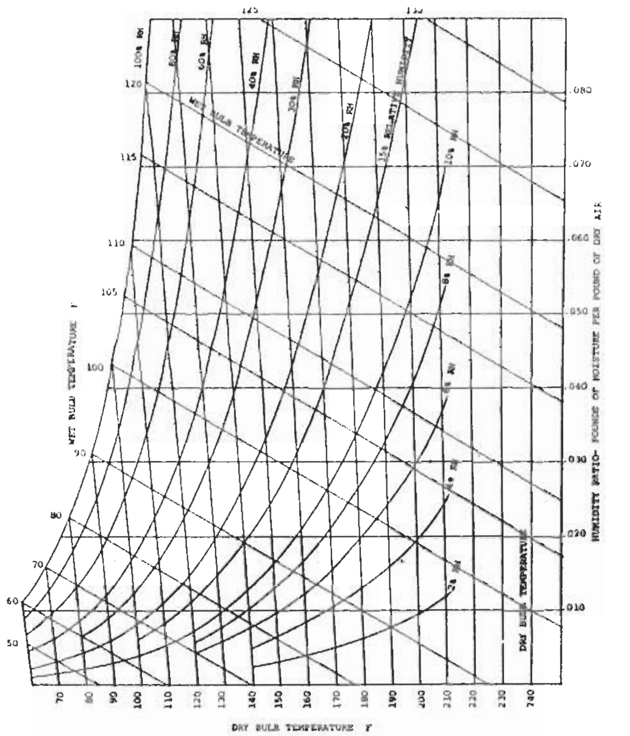


Figure 1. A simplified psychrometric chart adapted from the ASHRAE High Temperature Psychrometric Chart. This figure graphically represents the relationships of dry bulb and wet bulb temperatures, relative and absolute humidity, and related data. Air vapor conditions can be plotted from any two known criteria and the remaining factors determined graphically by reading the appropriate scale. In Houston, for example, the 90°F and 60% RH summer design factors represent a wet bulb temperature of 78.5°F and a humidity ratio (the "absolute humidity") of .018 lbs of moisture (130 grains) per lb of dry air.

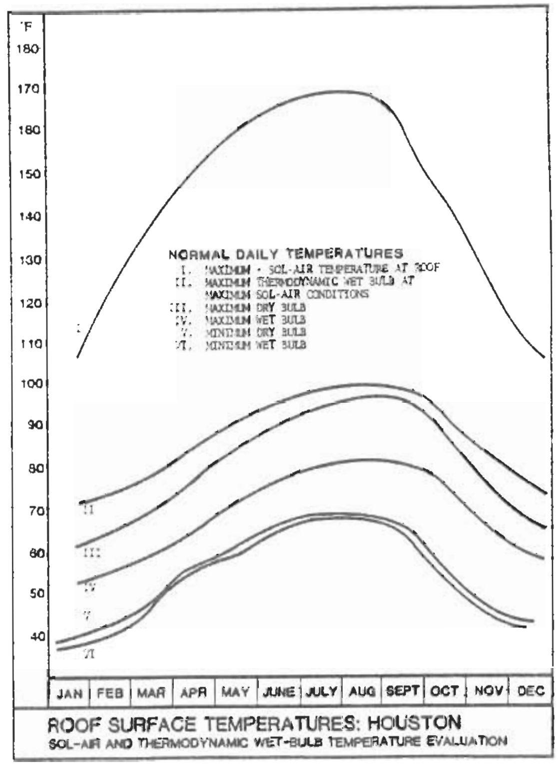


Figure 2. Roof Surface Temperatures. As a roof converts incident solar energy to heat, the surface temperature and the air film against it approach the theoretical sol-air temperature. Evaporative cooling can reduce these temperatures to something close to ambient temperatures by using the latent heat of evaporation to remove Btus from the roof. This "thermodynamic wet bulb" is the temperature achieved by saturating the air on a hot roof.

## PERFORMANCE

On a daily basis, a dry roof will cycle from a few degrees below the lowest night air dry-bulb temperature to a maximum temperature dependent on incident solar energy, roof mass, conductivity and absorptivity. A roof can easily reach an equilibrium temperature 65°-70°F above ambient dry-bulb temperature at peak conditions.

Wet roofs on the other hand should seldom exceed 100°F. The net reduction in peak cooling load then is the familiar:

$$uA(T_{dry} - T_{wet}) \text{ or } A(T_{dry} - T_{wet})/R \qquad (1)$$

For most roofs and in most warm/temperate climates a 60°F peak temperature difference is a safe assumption. For a more thorough analysis, it is necessary to calculate the theoretical sol-air temperature (an equivalent surface temperature which ignores radiative exchange with the surroundings) of the air at the roof surface:

$$t_s = t_a + aI/h - 7 \text{ (for horizontal surfaces)} \qquad (2)$$

where

$t_s$ = sol air temperature, F
$t_a$ = ambient air temperature, F
$a$ = roof surface absorptance, %
$I$ = total incident radiation, Btu/(hr. sq. ft.)
$h$ = coefficient of radiation and convection transfer
about 3.0)

Alternately, values of sol-air temperatures are listed for 30 and 40 degrees latitude in the ASHRAE Handbook of Fundamentals.

Having established the design conditions of temperature and humidity for the climate in question and found some idea of the temperature the roof might reach at these conditions, the peak temperature difference between a dry and a wet roof can be estimated graphically by following the wet bulb line to saturation. This does not account for cooling by convection, but wind velocity is generally inversely proportional to air temperature anyway and is likely as not to be stagnant during peak conditions. Refer to Figure 3.

| | |
|---|---|
| ROOF R-VALUE: 11 | COMPRESSOR HOURS: 1880 |
| ROOF SQ. FT.: 10000 | RAINMAKER COST: 3600 |
| SYSTEM EER: 6.5 | ENERGY ESCALLATION: .15 |
| COST PER KWH: .05 | OPORTUNITY RATE: .1 |
| COST PER KVA: 4.5 | |
| RACHET CHARGE: 0 | |

| HEAT GAIN REDUCTION PEAK BTU | A/C LOAD REDUCTION PEAK TONS | A/C COST REDUCTION $ | FIRST COST DIFFERENTIAL $ | ENERGY COST DIFFERENTIAL $/YEAR |
|---|---|---|---|---|
| 54545.00 | 4.55 | 3863.60 | 263.60 | 1036.89 |

| PERIOD | OPERATIONAL COSTS | | LIFE-CYCLE COSTS | | NET SAVINGS POTENTIAL | |
|---|---|---|---|---|---|---|
| YEARS | RAINMAKER | A/C | RAINMAKER | A/C | NEW | RETROFIT |
| 1 | 52.27 | 1084.02 | 3661.36 | 5071.59 | 1410.22 | -2577.35 |
| 2 | 106.92 | 2217.31 | 3724.28 | 6214.27 | 2489.99 | -1506.97 |
| 3 | 164.05 | 3402.11 | 3788.92 | 7407.61 | 3618.69 | -386.81 |
| 4 | 223.78 | 4640.77 | 3855.48 | 8654.03 | 4798.55 | 785.29 |
| 5 | 286.23 | 5935.73 | 3924.14 | 9956.05 | 6031.91 | 2011.59 |
| 6 | 351.51 | 7289.55 | 3995.06 | 11316.28 | 7321.22 | 3294.49 |
| 7 | 419.76 | 8704.91 | 4068.45 | 12737.47 | 8669.03 | 4636.46 |
| 8 | 491.12 | 10184.61 | 4144.46 | 14222.47 | 10078.00 | 6040.14 |
| 9 | 565.71 | 11731.56 | 4223.30 | 15774.24 | 11550.94 | 7508.26 |
| 10 | 643.70 | 13348.83 | 4305.14 | 17395.89 | 13090.75 | 9043.68 |

Table 1 - Houston example economics

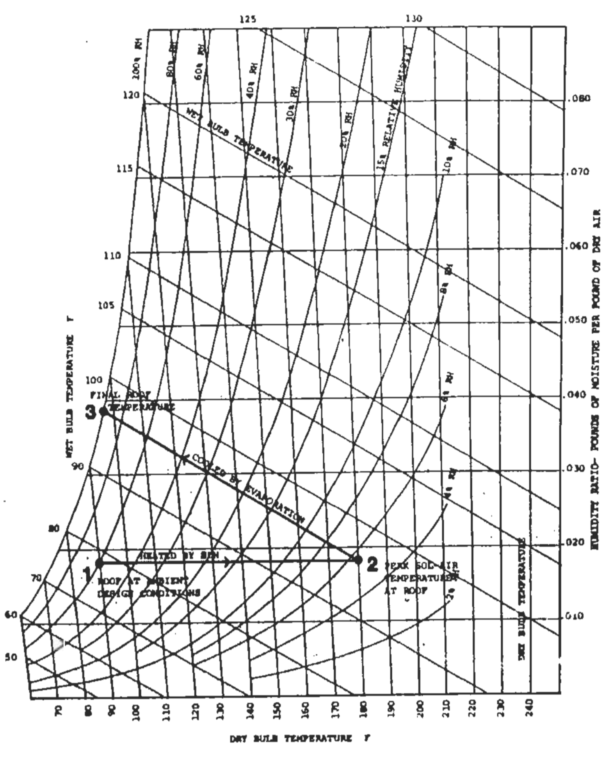


Figure 3. Using the high temperature psychrometric chart, the ESRC process can be examined graphically. From summer design conditions (1), (Houston example shown) the roof is heated by solar energy to the sol-air temperature (2), then cooled as roof heat is absorbed by evaporation to the thermodynamic wet bulb (3). In practice, the roof is never allowed to reach peak sol-air conditions and is normally maintained below 100°F.

LIFE CYCLE SAVINGS

Given a set of conditions and economic assumptions, the potential application of an ESRC system can be evaluated by applying the formulas above and analyzing cash flow for an extended period of time. The following example discounts future costs by assuming that energy will inflate at an average 15% per year while the cost of money or investment opportunity rate (for cash buyers) is 10%. The examples include additional assumptions as follows:

| | |
|---|---|
| Cost of water | 50¢/1000 gal. |
| Cost of a/c equipment | $850/ton |
| Compressor replacement | every 8 years |

The example building has a 10,000 sq. ft. roof, insulated to R-11. The life cycle cost analysis (table 1) was performed for Houston. The peak roof surface temperature reduction was assumed to be 60 degrees (see previous discussion). ESRC system and electrical costs structures are stated in the table. The studies evaluate the life cycle costs of a roof spray system versus avoided electrical costs of air-conditioning for a retrofit application or, for new construction, the combined avoided expense of a/c operating cost and a/c equipment costs (due to reduced peak cooling load). The "New" column under "Net Savings Potential" reflects the advantage of being able to down-size a/c equipment in new construction versus the "Retrofit" column.



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## BENEFITS AND ALTERNATIVES

Energy savings due to reduced roof temperatures are the central benefit of ESRC systems, at least in principle. But, before completing an evaluation of these systems, other advantages and some disadvantages should be pointed out.

First, consider the vast number of roof-top air-conditioners which must operate in the extreme roof environment temperatures. Keeping the roof cool can aid this equipment greatly. According to John Grimm, of compressor manufacturing Copeland Corporation in Sydney, Ohio: "There is no doubt that lowering the temperature environment of the condensing coil will reduce head pressure and extend both system efficiency and life expectancy" (11). The roof spray becomes a pre-cooler of condenser air.

Secondly, and very importantly, roof cooling can greatly extend the life expectancy of many roof materials. Because cooler roofs do not undergo the extreme daily temperature cycles of a dry roof (Fig. 3), they are not subjected to the constant thermal stress of expansion and contraction. And because the higher temperatures are never reached, the volatile oils that keep the roof membrane pliable and water-tight do not boil off. This combination of stress and drying (and sudden thermal shock from rain on a very hot roof) contributes to the premature demise of many roofs. Roof spray systems are often purchased to protect the major investment that larger roofs represent; and not infrequently this is as important a purchase decision as energy savings.

This roof life topic deserves extra clarification. There seems to persist, in the minds of cautious building owners and the hearts of careful, warranty offering roofers; the idea that roof spray results in standing water, roof ponds and subsequent rotting of the roof membrane. But while this was probably true of very early, irrigation technology systems, it is not the case today.

While no concise study has been done on wetted surface roof-life, some information does stand out. Edwin Rissmiller gives an excellent treatise on the relationship of roof temperature and roof life. He succinctly describes the torturous effects of the dry roof environment and goes into great depth on thermal shock, thermal stress, bonding to structure and chemical degradation. His paper ends with some roof savings suggestions including: "Evaporation of moisture from the surface of the roof can cool it significantly; this was the basis for "waterponding" years ago. Unfortunately, the dangers of ponding ... outweigh the benefits ... a light spray of water onto the surface of the roof will provide all the benefits of ponding without the dangers" (5).

Mr. Rissmiller retired from the Jim Walker Research Corp. last year (a subsidy of Cellotex, a large roofing product manufacturer). Contacted for comment, he stated that problems with early roof spray systems could have been solved if "the architects would have given us more roof incline".

Chuck Krupa, Regional Marketing Manager for GAF seems to agree. Mr. Krupa offered his personal opinion as: "There is no question that solar heating ages a roof by drying off volatile oils and subjecting it to thermal stresses driven by 100 degree daily temperature swings. This destroys the top pour and allows further damage to inner layers. If you can keep a roof cool without allowing standing water, there is no question that you can extend roof life" (8).

The only issue then, is control of spray sufficient to maximize evaporative cooling of the building skin yet not so much as to allow standing water. And this control is largely what distinguishes todays successfully marketed systems.

Of course, roof spray systems share advantages with some alternatives: they reduce peak loads and ratchet demand charges year-around, they lower radiant transfer from ceiling to inside spaces and maintain comfort levels, and they reduce the required equipment cooling capacity and hence first cost. Spray systems are inexpensive to purchase, maintain and operate, and are as readily retrofitted to existing structures as designed into new.

Evaporative roof systems are not without drawbacks however. Unlike insulation, roof spray contributes to comfort and energy conservation only during the cooling season. On a cost basis, roof spraying compares favorably to installed insulation, radiant barriers or reflective roof coatings. Final evaluation of the alternatives should take a life cycle look at all of the assumptions of cost and benefit, energy savings and roof life.

Perhaps the most important objection to roof spray systems is the attendant consumption of water, an increasingly depleted natural resource in its own right. While the best market for roof spray systems may be in the humid southeast, the fact that evaporative systems work best in areas where water is scarcest and most precious only accentuates these reservations.

According to Winston Chow at the Electric Power Research Institute, "a typical generating facility will evaporate about 450 gallons per megawatt-hour of electricity produced". Fully 80% of this electricity is lost in transmission and therefore 1800 gallons are consumed for each megawatt used. This equates to 1.8 gallons per kilowatt hour at the point of user. In other words, a ton of air-conditioning operating at a Seasonal Energy Efficiency Ratio of 7.0 (SEER = Btu/watt) "uses" about 3 gallons of water per hour (10).

Clearly, water consumption is not such a one sided argument as it might first appear; but roof spraying is not totally justified or a generating plant comparison basis. Perhaps the best point is that indirect evaporative techniques are best suited to more humid climates where humidity should be excluded from internal spaces. The arid, water scarce climates make better use of direct evaporative cooling from the typical "swamp coolers" and "water slingers". (But they do so at the expense of their roofs). Also, roof spray systems can conserve water anywhere by utilizing any available process water that is normally wasted. Warm condenser water is a popular source.

APPLICATIONS

The market resurgence of roof spray systems could be especially good news for those in the more humid eastern climates, who have heard much about night sky re-radiation and direct evaporative techniques so appropriate west of San Antonio. The lack of diurnal flux (daily temperature swing) in humid climates makes roof spray techniques all the more intriguing - for here it does not suffice to depend on the time lag characteristics of mass (and insulation) to offset heat loads into cooler evening hours.

Building type and load profile are more significant than climate criteria. Particularly appropriate are large roof area, single story, lightly insulated buildings such as air-conditioned schools, shopping centers or assembly plants. Many buildings of this type built before the mid-seventies have R-6 or less insulation; and many more facilities are still being built with R-11 or less roof insulation.

Other buildings, which have expanded or otherwise increased loads beyond existing cooling capacity may find that roof cooling would off-set the added requirement. And for buildings with temperature sensitive environments (i.e. refrigerated warehouses), roof cooling would not only reduce required capacity but also provide some back-up for partial or temporary failure of the mechanical refrigeration systems.

Non-air-conditioned spaces such as industrial facilities, farm structures and horsestables where cooling is desirable but not critical or worth the expense are also suitable. One of the current on market systems was developed following successful attempts to "temper" large work spaces in Canada.

CASE STUDIES

Houston Retrofits

Houston Lighting and Power has taken initial steps toward initiating a full roof spray monitoring program. For starters, they have surveyed the billing history of several buildings which have retrofitted roof cooling systems.

The residential example shown (Fig. 4), a surface load dominated building, illustrates a decrease from 3400 kWh to 2200 kWh per month for typical August weather (7793 degree hours) or a 21.4% savings in total electrical consumption (the a/c was not metered separately). For the restaurant, an internally load dominated building, the graph (Fig. 5) indicates an 8000 kWh or 15.4% reduction in consumption. Hopefully, HL&P will opt to do a full study- isolating a/c run time and water consumption.

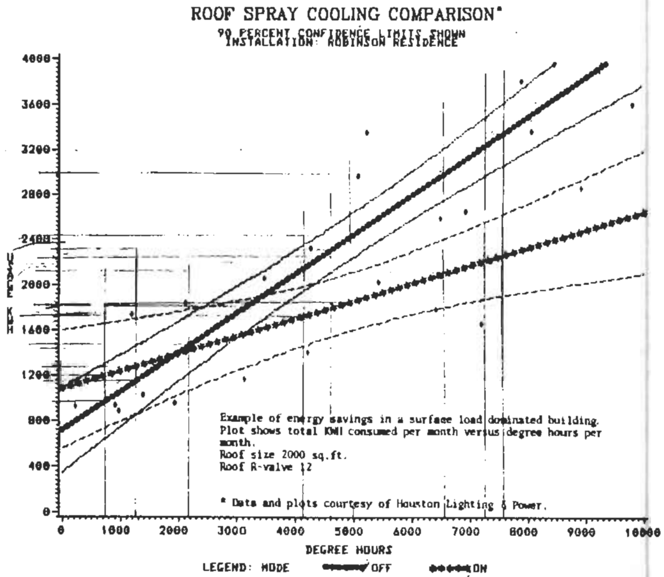


Figure 4. Roof spray cooling comparison of total kWh consumption before and after ESRC retrofit on a residence. Courtesy of Houston Lighting and Power.

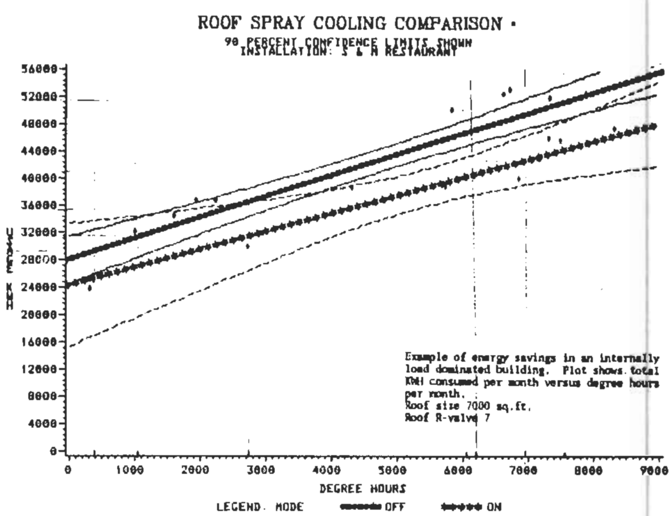


Figure 5. Total kWh consumption plot for an ESRC retrofit to a restaurant. Note the difference in savings profile between the internally load dominated restaurant and the surface load dominated residence (Fig. 4). Courtesy of Houston Lighting and Power.

Texas Instruments Calculator and Home Computer Assembly Plant, Abilene, Texas.

T.I.'s John Reed, P.E. presented his study (9) of an ESRC system at the 1983 conference on Industrial Energy Conservation (Houston, April '83). The facility involved is a 163,000 sq. ft manufacturing plant. The roof "R" value is 4.3 or "U" 0.24.

The T.I. plant used 9430 linear feet of copper pipe with 6600 spray orifices to spray 163,500 sq. ft. of roof in 12 separate zones. To measure the effectiveness of the systems, Reed set up a "dry" section on the windward side of the building and monitored roof temperatures there versus simultaneous temperatures in a sprayed zone. From July 23 to July 26, 1982, temperatures were recorded. The wet section was normally 40 to 55 degrees cooler than the dry roof during afternoon hours.

The installed cost of the ESRC was $56,000, or roughly 34¢/sq. ft. Reed calculates that the savings provided by the system were about $26,000/yr. in electrical demand charges and $17,800 kWh consumption during the 1982 cooling season. T.I. expects (expected) a 1.4 year payback.

Roof maintenance was treated more subjectively and the report only claims that the plant had far fewer leaks despite having added many roof penetrations. No build-up problems of solids at the spray orifice were noted and no other problems were reported. To quote From Reeds paper: "While many energy conservation measures do not work out in practice compared to what was advertised, our roof spray system is not one of these. In fact, it functioned better than advertised, and the savings obtained from our "wet/dry" comparison data exceeded those forecast by the vendor" (9).

Energy and Environmental Control Office, Armco Steel, Houston, Texas

This 3,000 sq. ft. engineering office in the more humid Houston climate was tested from August 31 to September 16, 1982, monitoring roof surface temperature, solar intensity and power consumption. Measurements were taken with and then without roof spray on alternate days, assuming that weather variations would "average out" (10).

The report concludes that the wet roof provided a 62% reduction in temperature differential and an average daily electrical consumption savings of 132.15 kWh (about 24%) during the late summer season.

Of particular note in this application is that the roof deck is insulated from below with R-19 batt and at the ceiling with R-11 batt to provide a return-air plenum and a well-insulated roof. Further, much of the 20 ton nominal cooling capacity is concerned with internal loads from computers and competes with the electrical re-heat used for humidity control.

Georgia Power Company Roof Spray System Test, Atlanta, Georgia

This test was conducted on a mobile home by a power company for a 20 day test period from August 11 11 to September 2, 1980. A "PVC" spray system with a 90 degree set-point was utilized. The energy research manager concluded that during the test period, kWh consumption by the 3 ton air-conditioner was reduced 35.6%, demand was lowered 4.1% and ESRC water consumption averaged 5.15 gallons per day.

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