THEORY VS. PRACTICE IN DIRECT EVAPORATIVE ROOF SPRAY COOLING

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ABSTRACT

This paper will examine in depth the development of roof spray cooling in this country and elsewhere, the theory and practice of roof cooling, and the limits of system application.

While this relatively simple method of air conditioning has been around for some time, and is being employed increasingly by large U. S. industrial firms, its operation, principles, and application, both empirically and practically, have not been widely discussed.

The impact of roofing construction, building location, and internal and external load on the effectiveness of roof cooling will be considered. Also discussed will be the theoretical and actual effect of roof cooling on a facility's energy consumption, and on internal temperature variations where there is no mechanical air conditioning.

A complete survey of most studies and findings to date will be presented. Guidelines for consideration of roof spray cooling systems will be developed incorporating ASHRAE methodology.

INTRODUCTION

Direct evaporative roof spray cooling systems are designed for installation on the roofs of industrial and commercial buildings. By means of a programmable controller, the system automatically and uniformly distributes very small amounts of water onto the building's roof, and, in some situations, a building's wall(s).

This is done in such a fashion as to optimize the heat dissipation qualities of the evaporating water film, and thereby to reduce air conditioning usage by the amount proportional to the external load contributed by the roof. In buildings without air conditioning, evaporative roof spray cooling systems will reduce the interior temperature of the facility by as much as 10°F. Evaporative roof spray cooling systems also have a positive impact on roof life and maintenance, as attested to by several roofing products manufacturers.

The roof surface to which the water is applied may be made of any type of material, and may be either flat or sloped. The water is distributed onto the roof by means of a series of copper pipes and low volume sprayheads.

The water used by the system may come from almost any source; typically, city, well, or waste water is used. The water pressure required (50 p.s.i.) is low enough to preclude the need for pressure-boosting pumps or holding tanks. The temperature of the water is of little importance, as it is the latent heat rather than the sensible heat that determines the cooling effect of the system.

The amount of water used by the system is controlled by sprayheads through varying their orifice sizes and spray angles, by various forms of temperature and climate sensors, and by the controller's sequence control panel.

During the installation of the piping system, the roof membrane should not be penetrated. In most situations, the system is attached to the roof by means of blocks and pipe hangers which are affixed to the roof by inorganic adhesive. This permits the entire system to be quickly and easily removed from the roof, if necessary.

The reduction in cooling load will vary from building to building, but generally is significant enough for buildings with roof to floor ratios of 1:1 to 1:2 and with roof insulation of less than R-10 to warrant examination and consideration.

The limits of the effect of a roof spray cooling system can be determined by isolating the roof (or wall) in question in a typical cooling load calculation. The most accurate method employed of determining potential savings can be found in the cooling load temperature differential calculations as set forth in the 1981 ASHRAE Fundamentals Handbook (2). While this is quite a laborious process, it yields excellent projections of benefits and costs. Simplified methods of estimating cooling load reductions are practicied, but these ignore the changing solar load over the course of the day and over the course of the cooling season.

THERMODYNAMIC PRINCIPLES

One attraction of roof spray cooling lies in its conceptual simplicity. Using water as a coolant is certainly neither mysterious nor unique; all of us perspire, and physiologically derive benefit from this effect. Moreover, most of us have experienced the chilling effect of direct evaporative cooling upon stepping out of a swimming pool or shower. It is the ability of water to absorb a large amount of heat during vaporization that creates this cooling effect, and, in fact, is the basis for the effectiveness of roof spray cooling.

When water changes from a solid to a liquid (the Latent Heat of Fusion), the amount of energy absorbed is only 80 calories per gram. At the other extreme, when the liquid is vaporized, the amount of heat absorbed in the transformation (the Latent Heat of Vaporization) is 537.7 calories/gram, or 7 times the heat absorbed during fusion.

Translating this into more familiar terms, at 212°F, the heat absorbed by 1 pound of water is 970 Btu's, or 8,080 Btu's per gallon. At lower temperatures -- for example, 120°F -- the heat absorption characteristics of water are amplified during a more gradual change of phase, and the heat exchange is increased to 1,025 Btu's/pound, or approximately 8,538 Btu's per gallon of water evaporated.

Rather than confining this physical phenomenon to the inside of coils and tubes, as with traditional mechanical air conditioning, roof spray cooling applies it directly to the largest source of external heat on a typical 1-2 story commercial/industrial facility by spraying the roof with a fine mist of water and allowing the water to evaporate completely.

The result, with proper design and application, is that a roof no longer acts as one huge solar heat absorption panel. Instead, roof spray cooling allows a roof to remain at or below the ambient temperature. This means that the heat load contributed by the roof is negated; moreover, at certain times of the day, the roof may actually absorb heat from the interior of a structure and release it to the outside.

As an example, a 10,000 square foot roof can evaporate approximately 1,000 gallons of water over the course of an 8-hour day, or 8,330 pounds of water. Assuming the lowest conversion value (120°F and 1,025 Btu's), this means that over 8.5 million Btu's (8,330 lbs. X 1,025 Btu's/1b) will be removed by this evaporation on the surface of the roof.

Note, of course, that these numbers do not imply that all of this heat would have penetrated into the building, if un-sprayed. Much of the heat would have been absorbed by the roof and roof insulation and/or reflected. However, it should also be noted that this heat absorption does have a deleterious effect on the roof structure itself.

HEAT FLOW

Heat always flows from a warmer to a cooler environment. Consequently, in summer, heat will flow into a building, while during the winter, heat will flow from the building to the outside. Such heat flow in summer will cause the temperature of the interior air to rise as long as it is not removed (through the use of mechanical air conditioning) as fast as it flows in.

The total rate of heat flow or heat gain depends on three factors:

1. The heat conducting properties of the material through which the heat is passing;
2. The total area of the material through which the heat is flowing; and
3. The difference in temperature between the warmer and cooler sides of the material.

These factors are expressed in the standard heat flow calculation:

$$q = AU(t_2 - t_1) \qquad (1)$$

where q = heat gain in Btu's/hour
A = area
U = conductance
$t_2 - t_1$ = the difference in temperature between the outside and inside surfaces

CONDUCTANCE

The insulating properties of a material are typically referred to as its U-value or R-factor.

The U-value signifies the conductance of heat through a non-homogeneous material (such as a roof) in terms of Btu's per hour through 1 square foot of that material (of specified thickness) for a 1 degree temperature differential.

The R-factor, or resistance factor, is simply the inverse of the U-value. For example, if the U-value is 0.20, the R factor is 5.0; a roof evaluated as R-10 means a U value of 0.10. Most roofs of industrial buildings have a U-value of between 0.30 and 0.10 by design. A bare metal roof will have an R-factor of 0, while this same roof with 1-1/16 inch of fiberglass insulation will have an R-factor of approximately 4.17.

AREA

The roof surface area of a one or two story building typically is the building's largest source of heat gain. This is easy to understand by considering the example of a building with the dimensions of 1,000 ft. long X 1,000 ft. wide by 20 ft. high. Each side of the building consists of 20,000 sq. ft., for a total wall area of 80,000 sq. ft. However, the roof area totals 1,000,000 sq. ft., or 12.5 times as much as the total wall area. Furthermore, the roof area, as a horizontal plane exposed to the sky, is substantially more affected than the walls by the impact of solar radiation.

TEMPERATURE DIFFERENTIAL

The heat flow through roofs (and walls) depends on the temperature difference across the roof (or wall) from outside surface to interior surface.

Surface Temperatures. The radiation impinging on the roof's surface is directly related to the angle of the sun's rays over the course of the day. As the sun's rays hitting the building's roof approach an angle of 90°, the amount of radiant energy is maximized.

By the same token, the latitude and the time of the year also have a bearing on the angle at which the sun's rays are hitting the roof.

Obviously, the solar radiation strikes more squarely on the roof at the lower than at the higher latitudes. In addition, the amount of radiation will vary as the earth revolves and changes its orientation (and tilt) in relation to the sun on a daily/monthly basis, which results in the various seasons.

The fact that the earth and a building's roof change their orientation to the sun on an hourly basis complicates the heat flow calculation considerably. However, for simple heat flow calculations, it is possible to assume that the sun's radiation is constant.

What is always considered a constant in both a simple and a more realistic heat flow calculation is the interior building temperature.

Interior Temperature. The interior design temperature is that temperature at which a facility operates at maximum comfort and efficiency. Generally, the design temperature is set at 78°F, although some operations may require much lower temperatures (such as computer rooms, cold storage areas, etc.), while other operations may be able to operate at interior temperatures higher than 78°F (warehouses, for example).

STATIC HEAT FLOW CALCULATION - A SIMPLE EXAMPLE

To show how much heat will enter a building during the course of just one hour, we can consider an example of a 50,000 sq. ft. light manufacturing faciliy, with roof construction having a U-value of .207. If the temperature of the top side of this roof is 140°F, and the temperature is 78°F on the inside, the amount of heat flowing through the roof in one hour is (from Eq. (1)):

$$q = AU(t_2 - t_1)$$
$$q = 50{,}000(.207)(140 - 78)$$
$$q = \underline{641{,}700 \text{ Btu's/hour}}$$

If 12,000 Btu's equal 1 ton of mechanical air conditioning, then it would require 53.5 tons of air conditioning to displace the amount of heat that enterns the example facility in one hour.

SOLUTIONS TO HEAT GAIN

The solutions to heat gain are: 1) increase the resistance to the heat flow through the use of additional insulation in the roof; 2) increase the amount of air conditioning, either through additional tonnage or lengthening the "on" times to pump out the heat faster than it can come in; 3) decrease the temperature differential from the outside of the roof to the inside by adjusting or allowing the internal temperature to increase, say, from 78°F to 85°F; or 4) decrease the temperature differential across the roof by letting the roof temperature to approach the ambient wet bulb temperature through the use of a roof spray cooling system.

Adding Roof Insulation. The purpose and function of insulation is to impede or slow the flow of heat from the outside surface to the interior. A wall (or roof, for that matter) with sufficient thermal mass would actually completely block the heat flow from the outdoors. This, however, is never done, simply because, structurally and economically, it would not make sense.

Using the previous example, it would take 64 feet of conrete, or 29 inches of fiberglass insulation in the roof to create sufficient resistance to completely block the incoming heat flow (or an R-factor of 62/U-value of 0.016).

The effect of insulation during the summer months is not to prevent all of the heat flow, but rather to delay it from entering the building's interior for a period of time.

Moreover, too much insulation in a facility with a large amount of operating equipment and machinery will serve to trap the internal heat load inside the building, causing increased strain on air conditioning equipment and reduced worker comfort.

Increasing Air Conditioning Use. Mechanical removal of heat through the use of air conditioning units is a method that does not involve the heat flow calculation itself, as does the determination of the amount of air conditioning tonnage required to do the job. Mechanical air conditioning involves the removal of heat at a rate equal to that which the heat enters or is generated within the building. In the above example, the amount of air conditioning required to displace the heat entering the buildingly only through the roof would be over 50 tons.

Increasing the Interior Design Temperature. This solution merits little discussion, as it is impractical and undesirable in most situations.

Reducing the Roof Surface Temperature. The final solution would be to reduce the temperature of the roof so that the temperature differential across the roof is reduced, and hence the heat gain, via the application of a roof spray cooling system. The effect of lowering the temperature differential from 62 degrees (140°F - 78°F) to 17 degrees (95°F - 78°F) is to virtually eliminate the heat gain. When viewed over the course of a 24-hour day, the roof spray cooling system, in addition to eliminating the heat gain, can actually draw heat from the interior of the building.

DEVELOPMENT OF ROOF SPRAY COOLING

Cooling the exterior of a roof through the evaporation of water has been around for some time. The Brazilians used a network of open conduit on their roofs through which water flowed, acting both as a simple air conditioner and as a water heater. The Indians cooled railway cars through the use of burlap placed on the train's roof, which was wetted from station to station.

In the U. S., the method has been employed, or rather, recognized, since the 1930's. Dr. Willis Carrier, the acknowledged father of mechanical air conditioning, was a proponent of the method. When asked why he did not use the idea himself, he replaied that his business was the manufacture of compressors and related equipment only; even so, Dr. Carrier encouraged the development of roof spray cooling (1).

Roof spray cooling's relative neglect over the years since the 30's can be attribued to what might be called a lack of elegance; and designers and manufacturers of roof spray cooling systems have only contributed to the problem by approaching it in a fairly crude and typically unsophisticated manner.

Initially, the method of distribution employed was impact sprayheads or lawn sprinkler heads, which, while more effective than nothing at all, resulted in roof water coverage that was both uneven and excessive. In addition, due to the amount of pressure required to charge such a system with water, pumps and storage tanks were required. The off/on control of these systems was either manual or a simple solenoid/thermostat mechanism, which typically sprayed either too much or too little water.

These findings led to the development of a "punched pipe" system. With punched pipe systems, holes are punched or milled into "sticks" of copper or pvc pipe. These holes generally are located 1 - 1½" apart along the length of the pipe at the 10 o'clock and 2 o'clock positions. When properly charged, these pipes spray water in much smaller droplets than the impact heads, and consequently have a better coverage pattern. Also, because less water per line is used, the use of a pump and storage tank is unnecessary. Until about two years ago, the control system on these punched pipe systems differed little from those used in the 30's and 40's. Some are still sold with a mechanical cam timer system, though, most often, today an electronic control system is employed.

There are two major drawbacks to these punched pipe systems, discounting completely the controls:

- First - The amount of water sprayed from the pipe is still excessive; studies have shown that approximately twice as much water is used as is necessary (4). Thus, usually the pressure drop across a line or an entire field (unless it is relatively small) causes "leakers". This occurs where the water pressure is not high enough to force the water out of the holes with enough force to cause the water to break into a mist. This results in uneven spray patterns and less than adequate coverage.

- Second - Maintenance of these systems is rather involved. The influx of any foreign matter, including such things as sand, clogs up the holes. In addition, because it is impossible to filter the water just prior to its issue from the holes, and because the holes are punched directly into copper pipe, which oxidizes and captures any precipitates from the water, the holes frequently need to be cleaned with a brush from the outside, and annually through swabbing the inside of each pipe.

MAKING ROOF SPRAY COOLING MOST EFFECTIVE

Two specific advances in roof spray cooling technology have served to optimize the effectiveness of roof cooling systems, while minimizing the cost of operation.

Sprayheads Designed for Roof Spray Cooling Alone. The design and manufacture of low volume sprayheads, developed specificially for roof spray cooling, solve a number of problems that plague systems utilizing older (circa 1930) punched pipe technology.

These new sprayheads are designed so that the volume of water and the direction of the water mist can be altered in a variety of ways. Each sprayhead can be modified so that it supplies the right amount of water in the correct pattern for its specific location on the system. Earlier roof cooling systems utilizing punched pipe permitted only one pattern and amount of water flow. Moreover, alteration of the spray pattern or water flow stoppage was often a problem caused by clogging or oxidation of the spray holes; the integrity of the hole could be damaged even during shipping. In addition, due to the fact that these punched holes were relatively large in diameter and only 12"-18" apart, the fall in pressure across a line and the amount of water used were great. Very seldom did a line spray uniformly across its length.

With the new roof spray cooling sprayhead, water can be directed away from any equipment on the roof top, and can be applied in varying amounts to the roof surface. The individual filters in each sprayhead inhibit clogging of the sprayhead orifice. Unlike the older systems, which often required regular and laborious brushing out of each spray hole, the sprayhead maintenance, if necessary, is as easy as unscrewing the head from its base and backflushing the filter. Finally, the construction of the sprayheads makes them sturdy enough to be guaranteed for the life of the roof spray system.

Microprocessor-Based Control System. Until recently, the typical roof spray cooling system not only was an arrangement of punched pipe, but also was controlled by a mechanical control that consisted of a number of cams that, once set, were exceedingly difficult to adjust; in fact, they had only one setting, meaning the water schedule stayed the same, not only throughout the day, but throughout the entire summer cooling season.

This situation caused considerable overspray and ponding in the relatively cooler months of May and September, or underspray and thus limited effectiveness in the hot months of June - August.

The use of advanced control systems has eliminated these problems by monitoring temperature variation throughout every day of the cooling season, and altering the amount of water as the conditions for optimal evaporation change. Thus, only that specific amount of water tha can be sprayed at a particular point in time will be sprayed by the system as it runs from day to day throughout the summer. This eliminates ponding and optimizes the cooling effect of the water.

ANALYSIS OF ROOF SPRAY COOLING SYSTEM TEST RESULTS

HOUGHTON, ET AL - ASHVE - PITTSBURGH, PA (1)

The research was conducted by Houghton, et al (1) at the ASHVE Research Lab in Pittsburgh, PA. A test building was constructed on which the heat flow through various types of roofs, with and without different types of treatment, was measured. The interior of the building was maintained at a constant 75°F and 50% relative humidity. The tests involving the sprinkled roof were conducted on September 8. The calculations were then corrected for the design day of August 1. The outdoor dry bulb temperature ranged from 77°F to 95°F (the design db temperature), while the wet bulb temperature ranged from 68°F to 75°F, and therefore the relative humidity varied from 64% to 40% during the day.

The summary of the studies indicated the following for roof spray cooling and a concrete asphalt roof, in terms of heat flow (Btu/sq. ft./hour):

TIME	WITHOUT SPRAY	WITH SPRAY
5 a.m.	-2.3	-4.0
6	-2.0	-3.8
7	-1.6	-3.2
8	-0.2	-2.0
9	2.0	-1.0
10	5.5	0
11	9.0	0.7
12 p.m.	12.2	1.1
1	15.3	1.7
2	17.5	2.0
3	15.5	2.1
4	17.0	2.0
5	15.5	1.8
6	13.1	1.0
7	10.1	0
8	7.0	-1.0
9	4.6	-1.8
10	3.0	-2.5
11	1.4	-3.0
12 a.m.	0.3	-3.5
1	-0.5	-3.8
2	-1.1	-4.0
3	-2.0	-4.0
4	-2.3	-4.1

Examination of these figures reveals the following:

<u>Maximum Heat Flow</u> (Btu/sq. ft./hour):

Without Spray	18.0
With Spray	2.1

<u>Minimum Heat Flow</u> (Btu/sq. ft./hour):

Without Spray	-2.3
With Spray	-4.1

<u>Length of Time with Zero or Negative Heat Flow</u>:

Without Spray	8 hours
With Spray	16 hours

<u>Average Heat Flow Over the 24-Hour Period</u> (Btu/sq. ft./hour):

Without Spray	5.81
With Spray	-1.22

According to Houghton, et al (1), the effect of water in the case of the sprinkled roof is to greatly reduce the rate of heat flow from that found for the same panels in dry conditions. Of greater interest, however, is the effect of the water to absorb a large part of the radiant heat, to retain it and dissipate it back to the air through the latent heat of evaporation (1).

YELLOTT - ASHRAE - PHOENIX, AZ (4)

Rather than build an entire structure and measure the reduction of heat flow through the roof into an air conditioned environment, Yellott constructed an open roof deck and measured the temperature of the deck itself, with and without water spray. These tests were conducted in Phoenix, AZ, and consequently the ambient conditions were much different from Houghton's Pittsburgh tests.

Fourteen tests were run between July 17 and August 4, and the August 3 test was designated by Yellott as typical.

TIME	TEMP. (°F) W/O SPRAY T_1	TEMP. (°F) W/ SPRAY T_2	$T_2 - T_1$ (°F)	AIR TEMP (°F) T_a	$T_2 - T_a$ (°F)	RELATIVE HUMIDITY
5 a.m.	74	74	0	80	-6	50%
6	75	75	0	82	-7	
7	98	90	-8	87	3	
8	120	98	-22	90	8	42%
9	145	106	-39	92	14	
10	160	110	-50	95	15	
11	172	110	-62	99	11	32%
12 p.m.	177	111	-66	100	11	
1	177	110	-67	100	10	
2	170	103	-67	100	11	20%
3	159	98	-61	103	-5	
4	143	90	-53	103	-13	
5	124	82	-42	102	-20	19%

These figures reveal the following:

<u>Maximum Temperature of the Roof Surface</u> (°F):

Without Spray	177
With Spray	111

<u>Average Hourly Temperature Difference Between Roof Surface and Ambient Air Over the 12-Hour Period</u> (°F):

Without Spray	40.92/hour
With Spray	1.69/hour

As is evident from the earlier study, the sprayed roof shifts from a heat panel to a cooling panel much sooner and to a greater degree than does the unsprayed roof. Unfortunately, Yellott did not continue to monitor this cooling panel effect over a 24-hour period.

SRIVASTAVA, ET AL - CENTRE OF ENERGY STUDIES, INDIA INSTITUTE OF TECHNOLOGY, JODHPUR, INDIA (3)

Srivastava, et al (3) designed a dormitory for students in Jodhpur, India, which incorporated a roof spray cooling system. Several methods of cooling the dormitory were considered, with the most effective being the use of evaporative roof spray cooling in conjunction with "desert cooling fans."

Below is represented the effect of merely the roof spray cooling system on the interior temperature of the un-cooled building (that is, operating without fans):

TIME	AMBIENT TEMP. (°F)	INTERIOR TEMP. ROOM W/O SPRAY (°F)	INTERIOR TEMP. ROOM W/ SPRAY (°F)	ROOM TEMP. DIFFERENCE (°F)
1 a.m.	87.8	97.2	91.6	5.6
3	85.6	96.4	90.5	5.9
5	81.7	95.4	88.7	6.7
7	85.1	94.1	87.4	6.7
9	91.9	95.0	88.2	6.8
11	96.6	96.3	89.6	6.7
1 p.m.	102.4	97.3	90.1	7.2
3	105.8	98.4	91.4	7.0
5	104.0	99.0	92.8	6.2
7	99.5	98.8	93.0	5.8
9	95.0	98.6	92.8	5.8
11	91.4	97.7	92.3	5.4
1 a.m.	87.8	97.3	91.4	5.9

ELECTRICAL COMPONENTS MANUFACTURING PLANT, RIO PIEDRAS, PR

This test was performed by company employees in order to evaluate the effectiveness of the roof spray cooling system recently installed on their facility. It was conducted on two consecutive days in Rio Piedras, PR. As can be noted, there was a slight variance in the ambient temperature from one day to the next; however, the results still conform closely to the studies previously discussed.

TIME	AMBIENT TEMP. DAY ONE (°F)	ROOF SURFACE TEMP. W/O SPRAY (°F)	AMBIENT TEMP. DAY TWO (°F)	ROOF SURFACE TEMP. W/ SPRAY (°F)
7 a.m.	78.8	78.1	80.6	80.6
8	82.4	83.8	84.2	81.7
9	86.0	95.0	85.1	80.8
10	86.0	105.3	83.3	82.8
11	86.0	106.3	84.0	83.1
12 p.m.	86.0	107.6	85.0	83.6
1	87.8	106.3	86.0	83.7
2	88.7	106.3	84.2	84.1
3	86.0	105.3	84.0	81.1
4	84.0	100.6	82.0	81.0
5	82.0	95.0	80.0	80.8

A portion of this building was air conditioned and maintained at a temperature ranging from 74.6°F to 80°F during the day, while the tool and stock rooms were un-air conditioned, and their temperatures varied more widely, dpending on the external load; a large part of this load naturally came from the roof.

The air conditioned portion of the plant was monitored for electrical consumption of the air conditioning units both while the roof spray cooling system was and was not being employed. The un-air conditioned areas were monitored for dry bulb temperatures on both days.

Again, because these tests were run in conditions that varied from one day to the next, a direct comparison cannot be made. However, the recorded data are as follows:

TIME	AVERAGE TEMP. (°F) UN-A/C'D AREA W/O SPRAY DAY ONE	AVERAGE TEMP. (°F) UN-A/C'D AREA W/ SPRAY DAY TWO
7 a.m.	78.8	78.8
8	81.5	82.4
9	84.2	83.8
10	89.6	89.6
11	93.7	87.6
12 p.m.	95.0	85.3
1	95.0	84.9
2	95.0	84.0
3	93.7	83.3
4	85.1	83.3
5	84.1	82.9

TIME	POWER CONSUMPTION (KVA) A/C'D AREA W/O SPRAY DAY ONE	POWER CONSUMPTION (KVA) A/C'D AREA W/ SPRAY DAY TWO
7 a.m.	128.9	128.9
8	170.4	164.6
9	187.1	173.8
10	188.7	173.8
11	191.2	174.6
12 p.m.	199.5	174.6
1	199.5	174.6
2	199.5	174.6
3	199.5	158.0
4	191.2	158.0
5	187.1	138.0
AVERAGE	184.9	163.0

As noted, while direct comparison of the data gathered from these tests must be undertaken with caution, the reduction in the interior temperature of the un-air conditioned area from Day One (without roof spray) to Day Two (with roof spray) of 10.5°F at 1:00 p.m. can be attributed in large part to the cooling of the roof.

The same can be said of the power consumption for the air conditioned area, which was an average of 21.9 kva/hour less over the test period with the application of the roof spray cooling system.

THE CALCULATIONS

The following is a summary of the calculations involved in utilizing the ASHRAE 1981 Fundamentals Handbook's (2) Cooling Load Temperature Differential Calculations, isolating the roof, to determine the savings afforded by the application of a roof spray cooling system for a typical facility.

VARIABLES INCLUDED IN THE COOLING LOAD CALCULATION

The factors involved are:

- The intensity of the solar radiation impinging on the roof's surface. This in turn depends on 3 factors:
  * The time of day;
  * The latitude; and
  * The time of year.
- The construction of the roof and its:
  * U-value;
  * Color; and
  * Rural or urban location.
- The interior of the building - its:
  * Design temperature; and
  * Ceiling, plenum or false.
- The efficiency of the present mechanical air conditioning equipment and its operating hours.

All of these factors are considered and given a value assigned by ASHRAE.

SUMMARY OF THE COOLING LOAD TEMPERATURE DIFFERENTIAL CALCULATION

In order to calculate the heat gain/cooling load that the roof contributes to a facility, the 1981 ASHRAE Fundamentals Handbook is employed. This method is used by all air conditioning manufacturers and contractors; it is known as the cooling load temperature differential method, or CLTD, for short.

This method begins with the heat flow through various sunlit roofs. The heat gain is converted to cooling load by using heat transfer functions for various types of roofs. All calculations are based on sol-air temperatures and interior air temperatures of a constant 78°F.

Sol-air temperature is that temperature of the outdoor air which, in the absence of all radiation exchange, would give the same rate of heat entry into the surface as would exist with the actual combination of solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air.

These calculations are then divided by the U-value for each different type of roof; the results thus obtained are in units of total equivalent CLTD. A specific roof's heat flow characteristics can be obtained by multiplying the CLTD's by the applicable U-value.

Since the sol-air and CLTD's vary depending on outdoor temperature as well as the intensity of the solar radiation, the month and latitude must be taken into consideration. Other factors involved are roof color, indoor design temperatures other than 78°F, and ductwork and ventilation below the roof but above the ceiling.

With this in mind, it is possible to calculate the roof cooling load. We will use the example of the 50,000 sq. ft. building with a built-up roof having a U-value of .207, used for light manufacturing, in the vicinity of Atlanta, GA. The facility operates 220 hours a month, and the air conditioning system in use has an EER of 7.0. The interior design temperature is 78°F.

ROOF COOLING ENERGY SAVINGS - STEP-BY-STEP

First, we must determine the appropriate outdoor design temperature. The base number of 85°F is based on a latitude of 40 degrees. The latitude of Atlanta, GA is 35 degrees, and the design temperature is 93°F, with a mean daily range of 22°F.

This means that the highest temperautre reached, on an average, over a 15 year period for July at 3 p.m. is 93°F, and that the lowest temperature on this day will be 93°F - 22°F or 71°F. During the daylight hours with which we are primarily concerned, the temperature will range from 77.4°F to 93°F at 3 p.m. and will fall to 88.4°F at 6 p.m.

By taking the average temperatures during a 10-hour period, we get 87.8°F. This will be used to correct the standard outdoor design temperature of 85°F.

HOURLY TEMPERATURE VARIATION

TIME	9	10	11	12	13	14	15	16	17	18	10 Hour Average
% RANGE	71	56	39	23	11	3	0	3	10	21	
db °F	93	93	93	93	93	93	93	93	93	93	
RANGE	22	22	22	22	22	22	22	22	22	22	
T_o	77.4	80.7	84.4	87.9	90.6	92.3	93.0	92.3	90.8	88.4	87.8

In order to ascertain the heat flow through a particular roof in Atlanta, we must take the rough, uncorrected CLTD for the roof and correct it for LM (latitutde month correction for a horizontal surface), K (color adjustment factor for roof, with 1.0 being dark or light colored in an industrial area), and f (a factor for attic fans and/or ducts above the ceiling, with 1.0 being no attic or ducts). We also correct for inside and outside temperature design differences. We then proceed to develop the corrected CLTD's on an hourly basis throughout an average day in June, per the following calculation:

$$\text{CLTD (corrected)} = \qquad (2)$$
$$[\text{CLTD} + \text{LM}) \text{ X } K + (78 - T_r) + (T_o - 85)] \text{ X } f$$

HOURLY COOLING LOAD TEMPERATURE DIFFERENTIAL

SOLAR TIME	[V]	9	10	11	12	13	14	15	16	17	18	10 Hr Av.
CLTD (uncorr.)		34	49	61	71	78	79	77	70	59	45	62.3
LM	1	1	1	1	1	1	1	1	1	1	1	
CLTD + LM		35	50	62	72	79	80	78	71	60	46	
K	1	1	1	1	1	1	1	1	1	1	1	
(CLTD + LM)K		35	50	62	72	79	80	78	71	60	45	
78°F - T_r	T_r = 78	0	0	0	0	0	0	0	0	0	0	
T_o - 85°F	T_o = 87.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	
f	1	1	1	1	1	1	1	1	1	1	1	
CLTD (corr.)		38	53	65	75	82	83	81	74	63	49	62.3

After completing this, we take this average daily CLTD and adjust it over the course of an entire summer, pulling out both the average CLTD and the peak CLTD for the various summer months.

AVERAGE MONTHLY COOLING LOAD TEMPERATURE DIFFERENTIAL

MONTH	[V]	April	May	June	July	Aug.	Sept.	Mo. Avg.
CLTD (uncorr.)	62.3	62.3	62.3	62.3	62.3	62.3	62.3	62.3
LM		-1	1	2	1	-1	-5	
CLTD + LM		61.3	63.3	64.3	63.3	61.3	57.3	
K	1	1	1	1	1	1	1	
CLTD + LM)K		61.3	63.3	64.3	63.3	61.3	57.3	
78°F - T_r	T_r = 78	0	0	0	0	0	0	
T_o - 85°F	T_o = 87.8	2.8	2.8	2.8	2.8	2.8	2.8	
f	1	1	1	1	1	1	1	
CLTD (corr.)	64.1	66.1	67.1	66.1	64.1	64.1	60.1	64.6

PEAK MONTHLY COOLING LOAD TEMPERATURE DIFFERENTIAL

MONTH	[V]	April	May	June	July	Aug.	Sept.	Mo. Avg.
CLTD (uncorr.)	79	79	79	79	79	79	79	79
LM		-1	1	2	1	-1	-5	
CLTD + LM		78	80	81	80	78	74	
K	1	1	1	1	1	1	1	
(CLTD + LM)K		78	80	81	80	78	74	
78°F - T_r	T_r = 78	0	0	0	0	0	0	
T_o - 85°F	T_o = 87.8	2.8	2.8	2.8	2.8	2.8	2.8	
f	1	1	1	1	1	1	1	
CLTD (corr.)		80.0	82.8	83.8	82.8	80.8	76.8	81.3

Once we have the heat flow through the roof per square foot, we translate them into kW and kWh through the standard heat flow formula:

$$Q = [UA \times CLTD(corr.)] \times hrs./mo. \times EER \times 1{,}000 \quad (3)$$

where U = U-value
A = Area of roof
CLTD(corr.) = Heat flow in BTU's/sq. ft./hr.
hrs./mo. = The number of hours per month the facility and air conditioning equiment are in operation
EER = Energy Efficiency Ratio of the mechanical air conditioning equipment in place (ranges from 6.0 to 9.5, in general, or an efficiency of 50-80%)

ENERGY REDUCTION & ELECTRICITY SAVINGS

MONTH	MO. AVG. CLTD(corr.)	MO. USAGE kWh/Mo. *	MO. PEAK CLTD(corr.)	MO. DEMAND kW/Mo. **
April	64.1	20,846	80.8	119.4
May	66.1	21,497	82.8	122.4
June	67.1	21,822	83.8	123.9
July	66.1	21,497	82.8	122.4
August	64.1	20,846	80.8	119.4
September	60.1	19,545	76.8	113.5
TOTAL		126,053		721.1

U = .207
A = 50,000 sq. ft.
EER = 7.0
Hrs./Mo. = 220.0

$$\text{* Monthly Usage (kWh/Mo.)} = \frac{[U \times A \times CLTD(corr.)] \times Hrs./Mo.}{EER \times 1{,}000} \quad (4)$$

$$\text{** Monthkly Demand (kW/Mo.)} = \frac{[U \times A \times CLTD(corr.)]}{EER \times 1{,}000} \quad (5)$$

Finally, we can translate the heat flow into equivalent air conditioning tonnage to show the amount of air conditioning tonnage required to provide comparable cooling capacity.

AIR CONDITIONING TONNAGE EQUIVALENCIES

Equation: $Q = U \times A \times CLTD(corr.)$ (6)
where U = .207
A = 50,000 sq. ft.
CLTD(corr.) 64.6 (Average)
83.8 (Peak)

AVERAGE SAVINGS:
Q = Avg. Btu/Hr. Reduction = 668,465.1
A/C Avg. Tonnage Equivalence
[Btu/hr.]/12,000 Btu's per Ton = 55.7

PEAK SAVINGS:
Q = Peak Btu/Hr. Reduction = 857,185.1
A/C Peak Tonnage Equivalence
[Btu/hr.]/12,000 Btu's per Ton = 72.3

EVALUATING ROOF SPRAY COOLING SYSTEMS

From these calculations, the value of roof spray cooling systems in various situations can be determined.

I. Existing Buildings
  A. Air Conditioned
    1. Sufficient mechanical air conditioning tonnage - will reduce energy consumption and cost
    2. Insufficient mechanical air conditioning - may eliminate need to purchase additional tonnage
  B. Un-Air Conditioned
    1. Purchase of air conditioning under consideration - permits purchase of fewer tons
    2. To remain un-air conditioned - will reduce interior temperature by 4-10°F, improving worker comfort and productivity or product integrity.

II. Proposed Buildings
  A. To Be Air Conditioned - requires less tonnage
  B. To Be Un-Air Conditioned - particularly valuable in warehouses where perishables are stored (see I.B.2., above).

ROOF SPRAY COOLING - A VIABLE ALTERNATIVE

The reason for the resurgence of interest in and use of roof spray cooling systems is their evolution over the past few years from inherent theoretical acceptance to effective practical application. Through advances in system engineering and design -- chief among them being the advent and utilization of microprocessor controls and low volume, low maintenance sprayheads -- the "low tech" idea of roof spray cooling has been adapted to fit the needs of a high tech world. Through sophisticated design, energy analysis, and system control, roof spray cooling has become an eminently viable cooling and energy conservation alternative for the 80's and beyond. Rather than acting as a mere add-on and in isolation, the roof spray cooling system can be integrated into a facility's complete HVAC system to increase building operating efficiency and to generate substantial cost savings.

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