Effect of Rooftop Exposure in Direct Sunlight on Conduit Ambient Temperatures

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***Abstract*—The interiors of electrical conduits located on rooftops in full sunlight become considerably hotter than those located in shaded areas. Differentials between these conduit interior temperatures and outside air temperatures (the latter always measured in the shade) can easily reach 39 °C (70 °F) for conduits lying directly on a dark roof. As the height of the conduit above the roof increases, this temperature differential decreases, to perhaps 15 °C (27 °F) at a height of 0.9 m (36 in) above the roof. Lighter-colored roofs, although they keep the interior of the buildings cooler, actually reflect more heat onto conduits located more than a few centimeters above the roof. This makes these conduit interiors hotter as compared to conduits located above dark-colored roofs. In practice, the actual temperatures inside conduits are seldom taken into account when electrical ampacity calculations are made. This can lead to serious overheating and even failure of electrical cables inside the conduits.**

***Index Terms*—Ampacity corrections, building wire, conduits, derating, National Electrical Code (NEC), solar effects, Thermoplastic High Heat-resistant Nylon coated (THHN), wire and cable.**

I. Introduction

When electrical conductors are placed in conduits located in sunlight, the interiors of those conduits can reach quite high temperatures. The temperature of the air inside a conduit is the "ambient temperature" that should be used for sizing the cables. In practice, temperature corrections are seldom made, due in part to a lack of knowledge on what those ambient temperatures actually are.

A. Ambient Temperature Corrections

As the temperature of a metallic conductor increases, its ampacity, or current-carrying capacity, decreases due to the accompanying rise in electrical resistance. Certain tables and equations in the U.S. National Electrical Code (NEC)—particularly Table 310–16—are intended to make the necessary ampacity corrections for elevated temperatures, known as derating the cable [1]. These tables take into account the additional I^2R heat added to the conductor by the current flowing through it. A danger point is reached when the ambient plus the I^2R heating exceeds the temperature rating of the cable insulation or other covering, which is often 90 °C (194 °F).

Conduits in direct sunlight on the flat rooftops of industrial and commercial buildings are a common occurrence in many areas. Since many variables might influence conduit temperatures, such as the color and texture of the roof, how high above the roof the conduit is placed, the type of conduit, the geographical location of the building in question, and the time of year, research was needed to determine the influence of these factors.

B. Outdoor Temperatures

Since the main purpose of this research was to determine the temperature adjustment that needs to be added to the expected outdoor temperature for a given location, it is important to use an accepted number for the outdoor air temperature itself.

Fortunately, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) deals with outdoor temperatures in order to design air-conditioning and heating systems [2]. An ASHRAE weather database for 753 locations in the USA, and 4422 worldwide, includes summer design temperatures. The temperature data are based on 30 years (1972–2001) of hourly readings from weather stations of the National Climatic Data Center, a subsidiary of the National Oceanic and Atmospheric Administration, and both are part of the U.S. Department of Commerce [3].

It is quite important to use appropriate design temperatures to properly size a building's air-conditioning system. Undersizing the system will not provide sufficient air conditioning on hot days, while oversizing causes the system to run too little, resulting in insufficient dehumidification as well as wasted energy when it does run.

However, the consequences of improperly sized air conditioning are only poor economics or uncomfortable days in the summer. The consequences of an undersized electrical distribution system may be more severe—failure of cable insulation leading to shorts or other problems. Note that these failures may occur at currents below those protected by circuit breakers when derating has not been done, removing any automatic protection afforded by the breaker.

Table I shows design temperatures for 16 locations from the ASHRAE database. Since hottest temperatures almost

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TABLE I
OUTDOOR AIR TEMPERATURES FOR SELECTED U.S. CITIES

City	2% Design Temp., °C	1% Design Temp., °C	Max Temp., °C *
Phoenix, AZ	43	44	49
Las Vegas, NV	42	43	48
Wichita, KS	38	39	45
Houston, TX	36	36	42
Atlanta, GA	34	35	41
New Orleans, LA	34	35	39
Denver, CO	34	35	41
Miami, FL	33	33	38
New York, NY	33	34	40
Chicago, IL	33	34	40
Minneapolis/St. Paul, MN	32	33	41
Boston, MA	32	33	40
Pittsburgh, PA	31	32	39
Los Angeles, CA	26	27	42
San Francisco, CA	25	28	40
Fairbanks, AK	24	28	36

*Maximum temperature recorded over last 50 years
Source: 1% and 2% design temperatures derived from ASHRAE 1% and 2% design data for the months of June, July and August. Maximum temperature derived from ASHRAE design tables. [2]

TABLE II
SOLAR RADIATION FOR SELECTED U.S. CITIES

Location	June Global Horizontal Radiation cal/cm²-day	June Clear Air Radiation cal/cm²-day	March Clear Air Radiation cal/cm²-day
Phoenix, AZ	719	749	540
Las Vegas, NV	719	759	529
Wichita, KS	575	722	496
Houston, TX	518	697	545
Atlanta. GA	553	703	524
New Orleans, LA	526	689	540
Denver, CO	586	751	496
Miami, FL	480	681	570
New York, NY	526	700	453
Chicago, IL	540	705	445
Mpls/St. Paul, MN	526	719	434
Boston, MA	526	700	437
Pittsburgh, PA	521	705	456
Los Angeles, CA	567	708	505
San Francisco, CA	616	716	477
Fairbanks, AK	483	678	220

Source: Solar Radiation Data Manual for Buildings, National Renewable Energy Laboratories [4]

everywhere in the northern hemisphere can be found between June 1 and August 31, those three months are considered. Thus, the three months constitute a total of 2208 hourly readings for each year.

The 2% readings in Table I represent a percentile approach. Thus, in a typical year, it would be expected that 44 of the 2208 readings for Phoenix would be above 43 °C (110 °F). A more severe design criterion sometimes used is 1%, in which case 22 readings in Phoenix should be above 44 °C (111 °F). As a comparison, the highest temperatures for the last 50 years are also shown. In the case of Phoenix, it is 49 °C (121 °F).

It is recommended that the 2% criterion be used to determine the applicable summer outdoor temperature for a given location for design purposes. The average differential between the 2% level and the maximum is about 8 °C (15 °F), with Miami the lowest at 5 °C (9 °F). However, because of local climate peculiarities, for Los Angeles it is a much larger 16 °C (29 °F) and for San Francisco 15 °C (27 °F). For those cities, it may well be prudent to use a higher design temperature than the 2% level.

Others have argued that absolute maximum temperatures on record for a given region should be used, because of the serious consequences of cable failure. The counterarguments to this are threefold: 1) The economic consequences of sizing cable to a once-in-a-lifetime occurrence could be severe; 2) the ampacity tables such as NEC Table 310–16 supposedly already have some safety factor built in; and 3) since derating for overheating in conduits in direct sunlight is, by and large, not being done now, any improvement is better than the status quo.

It is likely that the design outdoor temperature for a given area, to which the appropriate temperature adjustment identified later in this paper should be added, will be decided at the local level. ASHRAE data are available for all major population centers in the USA, and temperatures can be estimated in all other locations based on nearby data.

C. Solar Radiation

The work reported on in this paper was carried out in Las Vegas, NV. Since Las Vegas is one of the hotter sites listed in Table I, it has been suggested that these data are not typical of other cooler locations.

In fact, Las Vegas is a particularly good test site because of its high number of clear days per year, and broad range of solar radiation intensities in different seasons, allow for good correlation of data with cities throughout the USA.

The relevant climatic property is solar radiation. Data are available for various orientations of solar collectors for various stations from the National Renewable Energy Laboratories [4]. Collectors are oriented at various angles to the sun but, since industrial and commercial roofs are nearly flat, the relevant orientation for the collector for this purpose is horizontal.

Table II shows solar radiation data for the same cities, in the same order, as shown in Table I. Actual data for June are shown, averaged over a 30-year period, followed by the "clear-air" values for June and for March as a comparison, when the sun is lower in the sky. All units are in calories per horizontal square centimeter per day.

Fig. 1. Roof surfaces cover range of reflectivity from very white to black.

Examination of Table II shows that the variation between U.S. cities on a clear day in June, when the sun is highest in the sky, is remarkably small (759 for Las Vegas, 678 for Fairbanks, AK). During other months, the differences are much greater. For March, for instance, Las Vegas measures 529 on a clear day, while Fairbanks is only 220. Second, Las Vegas in March has a much lower value than any city in the table in June. This tends to support the conclusion that tests run in Las Vegas in the spring involve less heating from solar radiation than many other cities in the summer on a clear day.

Of course, not all days are clear, and this is shown by the actual June readings versus the clear air reading for cities like Miami (480 versus a theoretical 681). Nevertheless, all cities have many clear sunny days during the summer months, and proper design must account for this.

1) Related Design Applications: Formulas exist in other electrical applications, such as in the design of overhead cable to IEEE standards, to use solar radiation data to determine ampacity [5], [6]. These standards and methodologies all assume constant solar radiation conditions anywhere in the USA. One such paper [7] states that the use of 900 W/m^2 "... is typical of conditions that exist on a bright, sunny mid-summer day throughout most of the United States..."[1]

2) Wind: One concern that has been expressed to the use of data derived in Las Vegas for other locations was that some locations experience significant winds a good percentage of the time. However, the wind is not always blowing on a hot day in any location, so this argument should be rejected. The IEEE working group for Standard 738, in fact, recommended that wind not be taken into account in designing overhead cable, because of its sporadic nature [5].

II. Experimental Procedure

The experiments are being conducted at a Las Vegas, NV, test site consisting of three simulated roof sections (Fig. 1). The sections were covered with three types of roofing surfaces: black mineral roll roofing, white mineral roll roofing, and mineral roll roofing painted with a white elastomeric coating. The latter is a brighter, more reflective roof surface than the uncoated white roofing.

Three-quarter-inch electrical metallic tubing (EMT) was used as conduit in the experiments. Each contains three AWG 12 Thermoplastic High Heat-resistant Nylon coated (THHN) copper conductors—one with either black, blue, or red insulation, one with white insulation, and one with green insulation. The conduits were arranged at seven different heights above the black and white roll roofing (Fig. 2). These heights were directly on roof, on struts 1.6 cm (5/8 in) above the roof, and at heights of 3.8 cm (1–1/2 in), 9 cm (3–1/2 in), 15 cm (6 in), 30 cm (12 in), and 91 cm (36 in). The white elastomeric-coated roof had samples only at the 9-cm height.

[1]The 900 W/m^2 converts directly to 77 cal/cm^2 · h. Clear-air June data for most of the cities in Table II are about 700 cal/cm^2 · day, or about 9 h at that high level of intensity. This comparison confirms that [7] and the NREL data [4] are consistent.

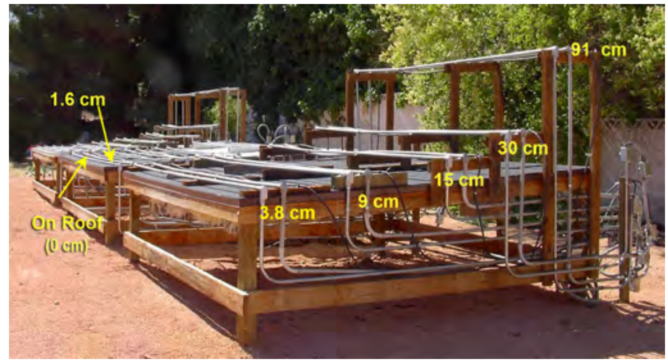

Fig. 2. Conductors situated in conduits lying on roof surface and incrementally above roof to 91 cm.

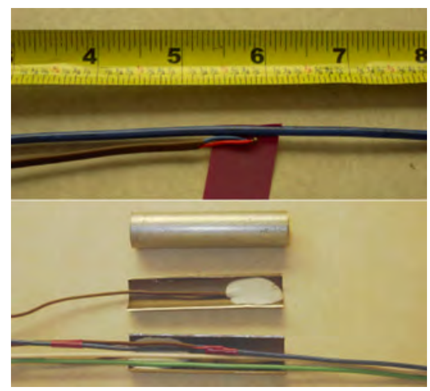

Fig. 3. (Top) Copper–constantan thermocouple being applied to outer insulation of THHN conductor. (Bottom) Cutaway of EMT conduit showing placement of thermocouples on phase conductor and on top and bottom inside surface of conduit.

Experiments were also conducted with rigid nonmetallic conduit (RNC) and earlier with a small number of intermediate metallic conduit. The RNC tended to run a bit hotter than EMT because its surface darkened considerably over the course of the experiment. Since all the conduits showed the same qualitative effects, for simplicity, only the results of the EMT experiments are reported here.

All the conductors were electrically unloaded. Type T copper–constantan thermocouples were used as temperature sensors. Fig. 3(a) shows a thermocouple ready to be taped to the insulation of a length of THHN phase conductor. Fig. 3(b) shows a cutaway of a conduit section with a phase conductor with sensor attached, a white neutral, and a green grounding conductor. Sensors attached to the inside bottom and top of the conduit itself are also shown.

The sensors were positioned at the center of each length of conduit, as shown in Fig. 2. These sensors were then routed

TABLE III
TEMPERATURE RISE INSIDE EMT CONDUIT OVER BLACK ROOF FROM SOLAR RADIATION

Example:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Outdoor Temp, °C:	14	16	20	22	24	30	36	38	43	47
Day of reading:	31-Jan	31-Mar	22-Jan	14-Apr	15-Apr	12-Jun	21-May	22-May	16-Jul	17-Jul
Time of reading:	11:30	12:00	12:15	1:00	1:00	12:00	12:30	2:00	12:45	2:15
	Temperature Differentials, °C*									
ON roof surface	32	36	29	39	35	36	39	36	36	36
1.6 cm above roof	23	26	21	27	24	25	27	26	26	24
3.8 cm above roof	19	21	15	23	18	20	21	18	21	20
9 cm above roof	18	19	14	21	17	19	21	18	20	18
15 cm above roof	17	18	13	19	16	17	18	16	17	14
30 cm above roof	16	17	11	17	14	16	17	15	16	13
91 cm above roof	13	14	10	15	13	14	14	13	14	12

*Sample of midday temperature differentials—between air in conduit and outside temperature; 3/4" EMT, AWG12; unloaded, as measured on insulation.

back to a multiplex unit and computer located in a climate-controlled building adjacent to the experiment. Temperatures were recorded at 1-min intervals throughout the day and night. However, 15-min averages were calculated, and only those data were permanently retained and used.

For comparison purposes, temperatures were also measured on the top and bottom inside surfaces of some conduits [Fig. 3(b)] and, in some samples not containing conductors, in the free air space in the center of the conduit. All temperature readings in these instances were within a degree or two of each other and of the temperature on the sensor attached to the conductor. Therefore, the temperature readings on the phase conductors were accepted as an accurate representation of the ambient temperature in the conduit. Of course, this would not have been the case had the conductors been electrically loaded.

Outdoor temperatures were measured using a standard six-plate solar radiation shield containing multiple thermocouple sensors installed in a housing. The temperatures of the various thermocouples were averaged.

The experiment was carried out between May 2004 and August 2005. Further details of the experimental procedure are available on request.

III. RESULTS

Note that the rooftop data reported in this paper in most cases represent temperature *differentials*, not actual temperatures inside the conduits. The differential is derived by subtracting the measured outdoor temperature from the measured temperature inside the conduit for each sample for each time recorded (to avoid any confusion between temperature differentials and measured temperatures, note that conversions from °C to °F are a straight 5/9 ratio for temperature differentials, not involving the $\pm 32^\circ$ used when converting measured temperatures).

The database was first "cleaned" by eliminating all outdoor temperatures under 21 °C (70 °F), since the experiment is intended to measure effects at high summer temperatures. Next, cloudy periods were eliminated. These could be easily identified by sudden drops in the temperature differentials from one 15-min period to the next. Again, this is justified since the purpose of the experiment was to study only the effects of direct sunlight on temperatures inside conduits. Since only about 17% of the data were eliminated by this latter exercise, it further illustrates the advantage of using Las Vegas as a test site. A nondesert location would have produced far fewer usable data points.

A. *Solar Effect*

During the time of the experiment, outdoor temperatures ranged from 10 °C to 47 °C (50 °F to 116 °F). Under all conditions tested, temperatures inside EMT conduits in direct sunlight are considerably higher than outdoor temperatures. To illustrate this, a random compilation of midday temperature-rise data under a wide variety of outdoor temperatures and seasons is shown in Table III for a black roof. In all cases, the sun was unobscured by clouds when the readings were taken.

The temperature-differential data show a high degree of consistency at the different times of year, whether the outdoor temperature is 14 °C or 47 °C. Temperature differentials on the roof surface are all in the range of 29 °C–39 °C, and even at 91 cm above the roof the range is narrow, from 10 °C to 15 °C.

B. *Statistical Basis*

The statistical approach used by ASHRAE to determine design temperatures would seem to apply as well to temperature-rise data derived in this experiment. However, the 2% figure used for the outdoor temperature would seem to be a bit "tight" for this data set. The reasons are the following: 1) The data from this experiment are focused only on the midday period from 11 A.M. to 3 P.M. (daylight savings time), as opposed to all 24 h of the day in the ASHRAE database; 2) only times when the sun is unobscured are considered; and 3) the database is considerably smaller than the 30-year ASHRAE temperature

TABLE IV
TEMPERATURE RISES INSIDE EMT CONDUITS IN FULL SUNLIGHT AT VARIOUS HEIGHTS ABOVE ROOF, BASED ON PERCENTILE OF READING

	Temperature Rise Above Outdoor Temperature, °C*						
Percentile**	**On Roof**	**1.6 cm above**	**3.8 cm above**	**9 cm above**	**15 cm above**	**30 cm above**	**91 cm above**
0% (max.)	40	27	26	24	23	21	17
1%	39	27	25	23	22	20	16
2%	38	26	25	23	22	20	16
5%	37	26	25	22	21	19	15
10%	**37**	**26**	**24**	**22**	**20**	**18**	**15**
50% (median)	34	24	22	20	18	16	14

* Average values for light and dark roofs..
** Measured from top.

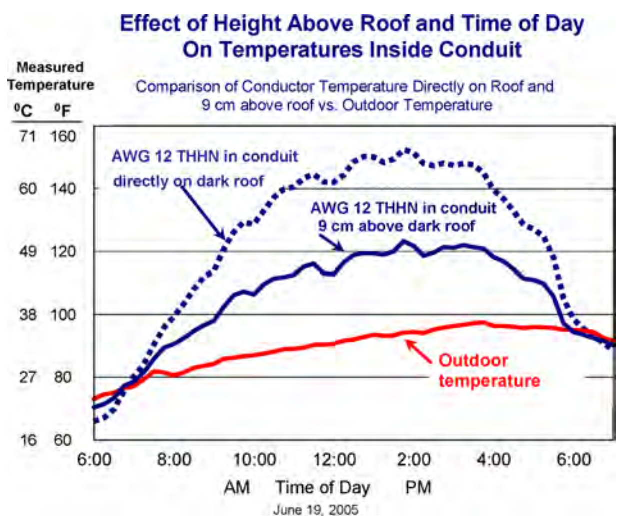

Fig. 4. Effect of height above roof and time of day on temperatures inside conduit.

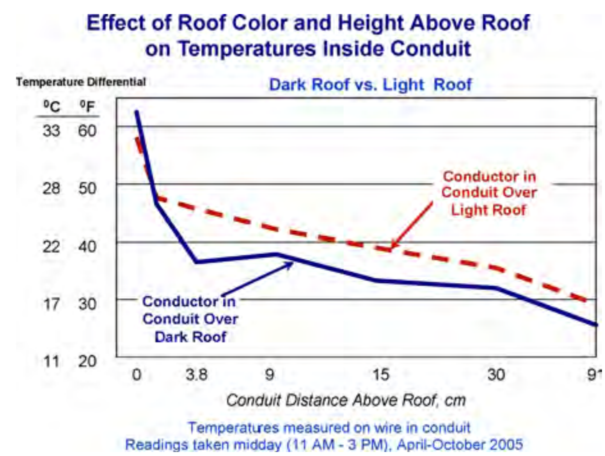

Fig. 5. Effect of roof color and height above roof on temperatures inside conduit.

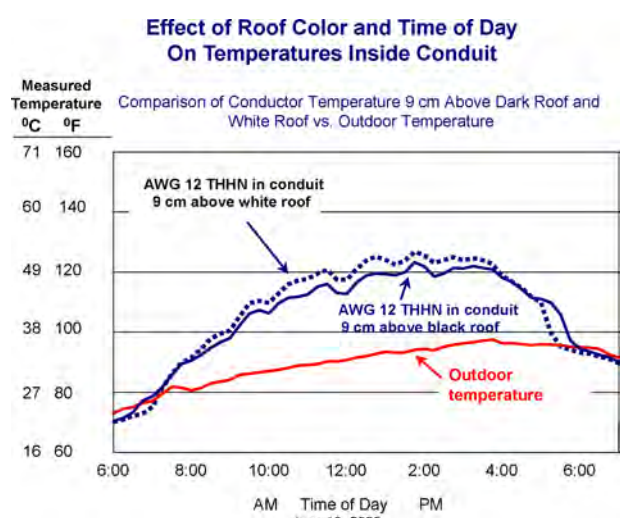

Fig. 6. Effect of roof color and time of day on temperatures inside conduit.

database. For these reasons, a 10% cutoff point is suggested, and the data that follow are at this level.

Table IV illustrates temperature rises at various heights above the roofs at different percentile levels, from 0% (highest number in data set) to 2%, 5%, the recommended 10%, and, finally, 50%, the median figure. The 10th percentile in all cases is roughly halfway between the highest number and the median, and so seems a reasonable compromise. Please note that all data to follow represent the 10th percentile measured from the top (hot) end.

C. *Distance Above Roof*

The temperature rise within a rooftop conduit in full sun decreases as the distance above the roof surface increases. The most dramatic temperature increase takes place for conduits lying directly on the roof, which had solar increases as high as 40 °C (Table IV). The 10th percentile used for design purposes is 37 °C (67 °F).

As the height above the roof increases to the 1.6 cm of a standard type of roof strut, the temperature rise drops by 11 °C to 26 °C above the outdoor temperature. For 9 cm (a 2 × 4 placed on edge, which is also commonly used), the differential compared to outdoor temperature is 22 °C. Moreover, for the highest elevation above the roof surface—91 cm—the differential is still 15 °C (27 °F).

Fig. 4 shows this phenomenon from another perspective time of day. The change in measured temperature (not the temperature differential) inside conduits over the course of a

TABLE V
TEMPERATURE RISES INSIDE EMT CONDUITS IN FULL SUNLIGHT AT VARIOUS HEIGHTS ABOVE ROOF, BASED ON OUTDOOR TEMPERATURE RANGE—10th PERCENTILE

Outdoor Temperature		Temperature Rise Above Outdoor Temperature, °C *						
°C	°F	On Roof	1.6 cm above	3.8 cm above	9 cm above	15 cm above	30 cm above	91 cm above
21 – 26.5	70 – 79.9	37	26	24	22	21	18	15
27 – 31.5	80 – 89.9	36	26	24	22	21	19	15
32 – 37.5	90 – 99.9	37	26	24	21	20	18	15
≥ 38	≥ 100	37	25	24	21	20	17	14
All temps	All temps	37	26	24	22	20	18	15

* Average values for light and dark roofs.

midsummer day is shown for two heights above the dark roof: 9 cm and directly on the roof. For comparison, the outdoor temperature is also shown. The gap between outdoor and conduit temperatures starts at about 7 A.M. and builds quickly by mid-morning. The differential is wide until after 4 P.M., disappearing at about 7 P.M. This figure is shown to illustrate that heating inside conduits is not limited only to high noon.

Because of the large difference in temperature rises depending on height above roof, this paper's recommendations suggest that electrical designers take this factor into account.

D. *Roof Color*

Temperatures inside conduits over dark-colored roof surfaces are higher than over light-colored surfaces if the conduits are on or quite close to the roof, as shown in Fig. 5. However, for distances greater than about 2 or 3 cm above the surface, and continuing until at least 91 cm, conduits over light surfaces are hotter, due to the higher reflection of heat from the light surface.

Fig. 6 shows this from the time-of-day perspective, using data from the same day, as shown in Fig. 4. Again, the temperature differential between outdoor temperature and temperatures inside conduits 9 cm above the roofs rises rapidly and stays high throughout the day.

However, the relatively small gap between the upper lines does not lead to the conclusion that any distinction be made between roof colors for design purposes.

It should be noted that, particularly in hotter climates, light-colored roof surfaces are recommended because of their ability to keep a building's interior cooler [8]. This has the unintended effect of increasing the temperature burden on conductors in rooftop conduits in locations with the most severe summer temperatures.

The combination of the two previous factors—distance above roof and roof color—means that temperatures inside conduits over light-colored roofs are consistently higher than over dark-colored roofs, from about 2 to 91 cm above the roof.

E. *Outdoor Temperature Range*

Table V shows the data arranged by outdoor temperatures. It shows a remarkable consistency in temperature rise, no matter what the outdoor temperature is, over the full range studied. In fact, *the data indicate that outdoor temperature is a minor factor in determining what temperature adjustment to make to arrive at ambient temperature inside a conduit in full sunlight.*

TABLE VI
RECOMMENDED ADJUSTMENTS (ADDITIONS) TO OUTDOOR TEMPERATURES TO DETERMINE AMBIENT TEMPERATURES INSIDE CONDUITS

Distance Above Roof	Temperature Adjustments	
	°C	°F
On roof, up to and including 1.3 cm. above roof	33	60
Above 1.3 cm, up to and including 9 cm. above roof	22	40
Above 9 cm, up to and including 30 cm. above roof	17	30
Above 30 cm, up to and including 91 cm. above roof	14	25

IV. CONCLUSION AND RECOMMENDATIONS

Attention should be paid by those designing electrical systems for industrial, commercial, and other flat-roofed buildings to potential problems caused by the presence of conductors inside conduits located outside in direct sunlight.

The air inside conduits in direct sunlight gets significantly hotter than the surrounding air, and designers need to make appropriate ampacity corrections. Although light-colored roofs reflect more heat than dark roofs and keep their buildings cooler, some of the heat is reflected to the conduit above the roof, making the air in the conduit generally hotter. Data from the experiment suggest that temperature rises in conduits over roofs of any color can be considered roughly equivalent, so there is no need to make distinctions for design purposes.

Neither is there a need to make distinctions based on the level of outdoor temperatures. Temperature rises are remarkably constant no matter what the outdoor temperature is during summer conditions.

It is suggested that the temperature adjustments shown in Table VI be used to convert outdoor design temperatures for a given area to temperatures inside conduits in direct sunlight.

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AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

AQ1 = The acronym “THHN” was defined as “Thermoplastic High Heat-resistant Nylon coated”. Please check if correct.
AQ2 = Pls. provide page range in Ref. [7].
AQ3 = Please provide the educational background and photograph of author David Brender.
AQ4 = Please provide the educational background and photograph Travis L. Lindsey.
AQ5 = “TLCS, Inc.” was changed to “TLC Consulting Services”. Please check if correct.
AQ6 = The acronym “IAS” was defined as “Industry Applications Society”. Please check if correct.
AQ7 = The acronym “PES” was defined as “Power Engineering Society”. Please check if correct.
AQ8 = The acronym “IAEI” was defined as “International Association of Electrical Inspectors”. Please check if correct.

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