OUTDOOR DESIGN CRITERIA:
For the Central Phoenix/East Valley Light Rail Transit System

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INTRODUCTION

Outdoor shading structures such as walkways, bus stops and car park canopies, have not been appropriately designed in hot arid climates like Phoenix. Many of these structures use dark single-ply light gauge metal as the primary shading surface. Activities under these structures fall off sharply during hot summer days. This author has made field measurements of a number of these structures and found that it is not uncommon to have on a summer day surface Sol-air temperatures of 150ºF (65ºC). Such a high temperature on such a large radiative plane six to eight feet above a user creates significant thermal discomfort.

The Central Phoenix/East Valley Light Rail Transit (CP/EV LRT) is currently in the process of designing a system that will offer riders a comfortable and speedy link between the cities of Phoenix, Tempe and Mesa. It is also expected that this system will become the spine, with each station acting as a critical transfer point, in a comprehensive Valley-wide transit system. Being cognizant of the harsh Phoenix summer climate and previous problems, the CP/EV LRT knew that the success of the overall system would be in jeopardy if the stations were not properly designed. Thus, the CP/EV LRT asked a research team at Arizona State University's School of Architecture to conduct a comprehensive study of outdoor design criteria for the twenty-two light rail stations being planned for metropolitan Phoenix.[1] While this study addressed a host of station design issues, only the outdoor design criteria and the associated methodology for testing the performance of station canopies will be discussed in this paper.

ESTABLISHING A REFERENCE

While there is considerable research on the use of thermal comfort models for indoor spaces very little exists for outdoor spaces. However, after reviewing the literature, our research team chose the standard effective temperature (SET) index as the most appropriate way of comparing thermal sensation, discomfort and physiological effect of a wide range of environmental situations, clothing and activity levels – including outdoor and extreme combination of conditions.[2] SET uses operative temperature (t_o) which is an average of ambient (t_a) and mean radiant temperature (MRT), weighted by air velocity and activity level to provide a dynamic equivalent index.

The mean radiant temperature is a metric that takes into account thermal exchange between the body and surrounding surfaces by way of radiation. Our research has found that controlling the surrounding surface temperature (i.e., MRT) is the most important mechanism for addressing thermal comfort as far as station design is concerned. Although the MRT calculation can be complex, we believe that simplifications can be introduced that would make the MRT calculation easily utilized by any of the station design teams. An example of the MRT calculation is presented in the Case Study Section.

Once the ambient and MRT are known the operative temperature (t_o) can be determined. This was done by generating a chart (see Figure 1.) which determines operative temperature as a function of air velocity and activity level.[3] In generating Figure 1., we assumed an air velocity of 25 fpm (still air conditions) and an activity level of 1.6 met for an average person who has arrived on foot and is now standing on a CP/EV LRT station platform on a summer day. The operative temperature is found by cross-referencing the ambient and the mean radiant temperature and reading between the curved lines.

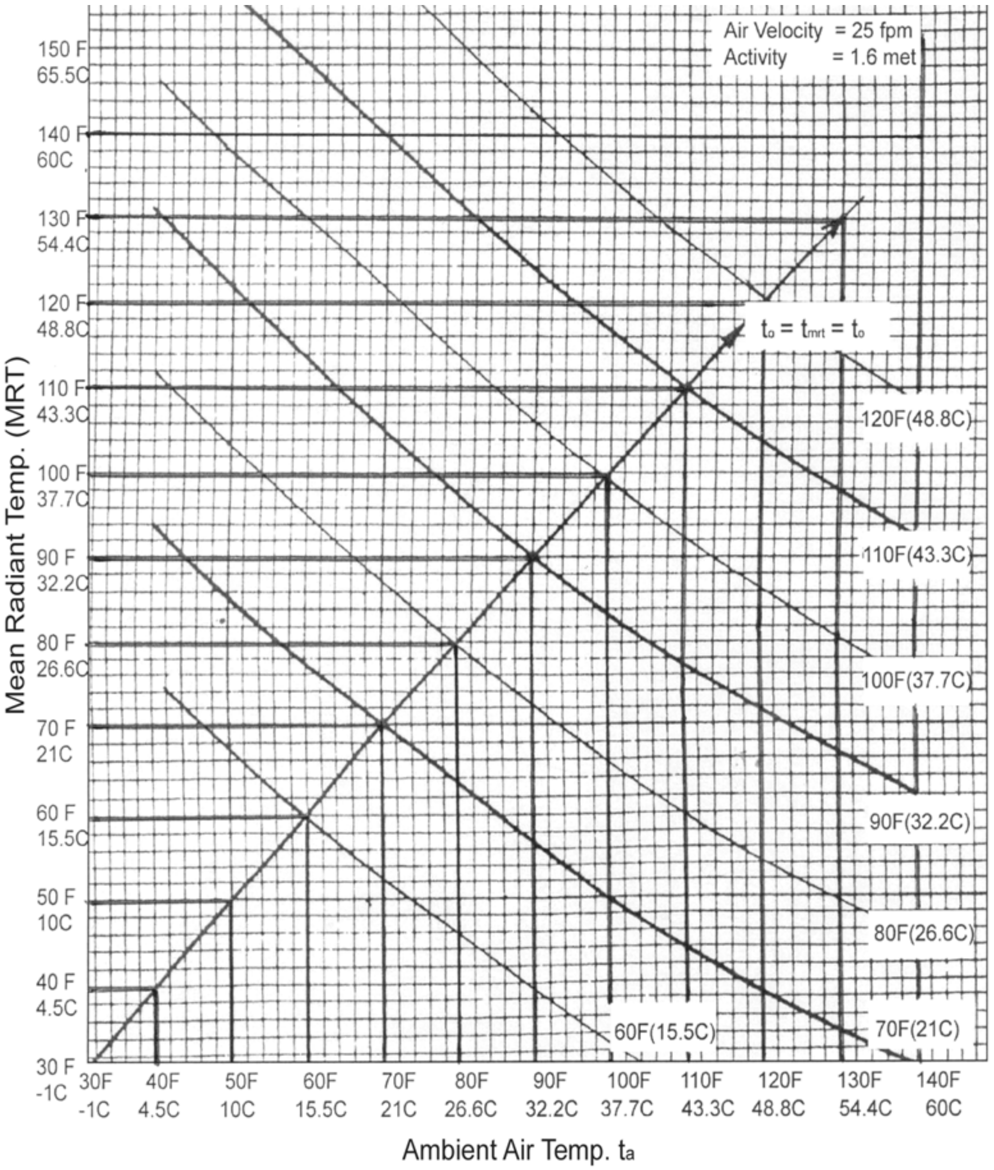

Fig. 1 Operative Temperature Conditions

After Fanger, P. O., Thermal Comfort: Analysis and Applications in Environmental Engineering. McGraw-Hill Book Company, New York, 1972.

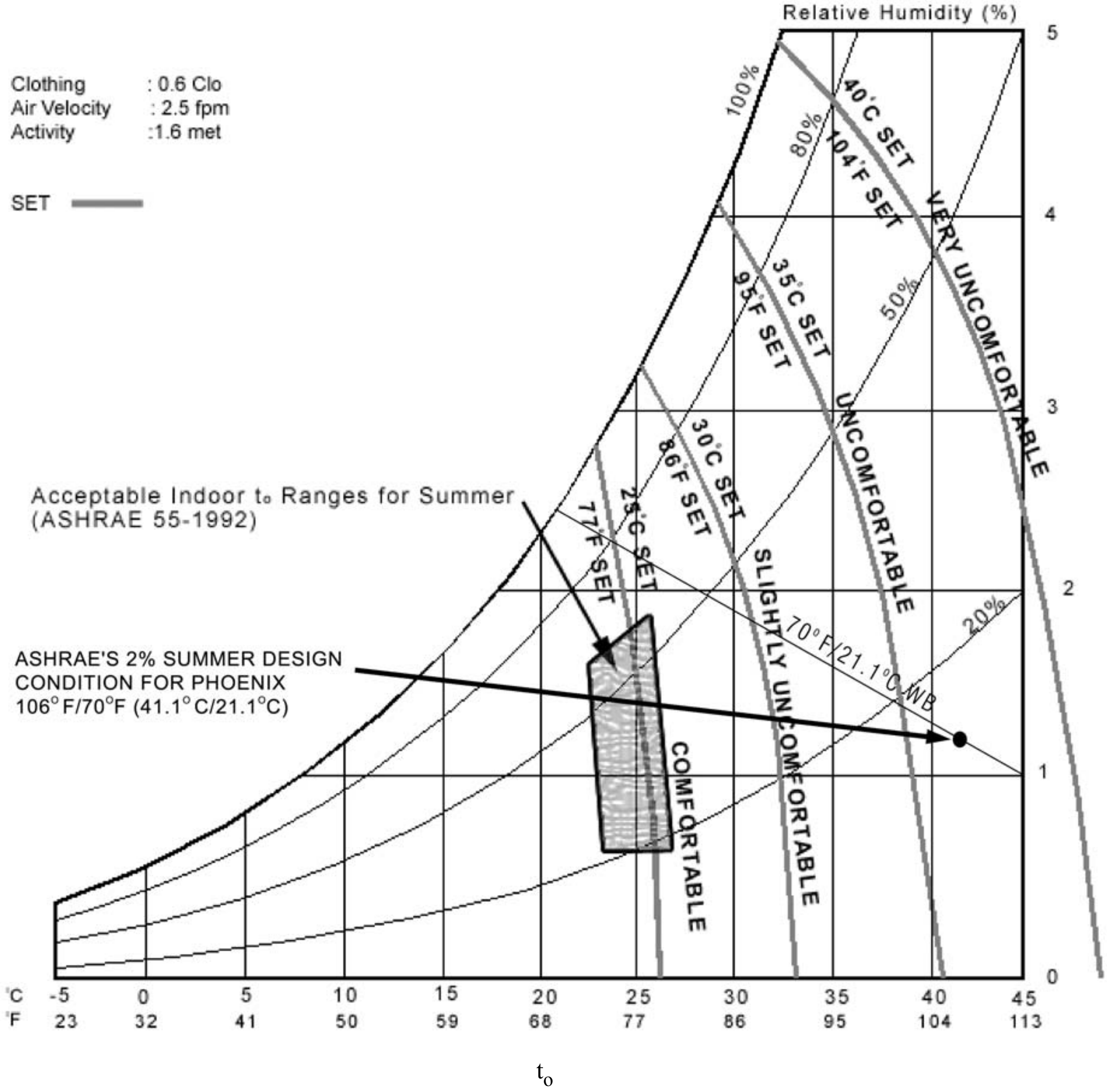

Fig. 2 Standard Effective Temperature (SET)

The next step was to establish the thermal comfort requirements for this project. This was done by plotting a series of SET values on the psychrometric chart. In generating this chart (see Figure 2.) we again assumed an air velocity of 25 fpm, an activity level of 1.6 met and added summer dress of 0.6 clo. The formulas used to generate Figure 2. are based on the ASHRAE Thermal Comfort Tool (a computer program which was developed and is made available though ASHRAE).[4]

SET values can be obtained from Figure 2. for a combination of conditions. Once a SET has been determined, the human thermal response for that condition can be ascertained by referencing Table 1. Here the relationship between thermal sensation (also called TSENS), and discomfort (also called DISC) can also be determined as a function of SET. It has been determined that there is a danger of suffering heat stroke if one is exposed to a prolonged SET of above 95°F (35°C). Thus the research team recommended that the maximum outdoor design criteria for all CP/EV LRT stations be a SET of 95°F (35°C). The outdoor ambient temperature was selected to be 106°F DB/70°F WB (41.1°C DB/21.1°C WB), which is the ASHRAE 2% summer design condition for Phoenix.[5]

Table 1. Human Response to varying SET*

SET (ºF)	**SET (ºC)**	**Temperature Sensation (TSENS)**	**Discomfort (DISC)**	**Regulation of body temperature**	Health
			Limited Tolerance	Failure of free skin evaporation	
104	40	Very Hot	Very Uncomfortable		
		Hot	Uncomfortable		Increasing danger of heat stroke
95	35		Slightly Uncomfortable	Increasing vasodilation sweating	
		Warm			
86	30				
		Slightly Warm			
77	25	Neutral	Comfortable	No registered sweating	Normal Health
		Slightly Cool			
68	20			Vasoconstriction	
		Cool	Slightly Uncomfortable		Complaints from dry mucosa
59	15			Behavioral changes	Impairment
		Cold		Shivering begins	Peripheral circulation
50	10	Very Cold	Uncomfortable		

*Source: Gagge, A. P., Nishi, Y. and Gonzlez, R. R. Standard Effective Temperature- a single index of temperature sensation and thermal discomfort. In proceedings of the CIB Commission W45 (Human Requirements) Symposium at the Building Research Station, 13th-15th September, 1972. Building Research Establishment Report 2. HMSO, London, 1973, 229-250.

CASE STUDY

The following example illustrates how the design team for one of the CP/EV LRT stations can perform an outdoor design criteria calculation. Here an operative temperature and MRT calculation will be performed for both a before and after case study. Since we are assuming a linear station platform and canopy configuration (16 by 300 feet) the spherical or three-dimensional properties of an MRT calculation can be neglected. Thus a simplified or two-dimensional MRT equation is sufficient for determining our outdoor design criteria. Figure 3. illustrates the simplified or two-dimensional MRT equation that we are proposing to use for determining our outdoor design criteria. Figure 4. illustrated the Before Case Study.

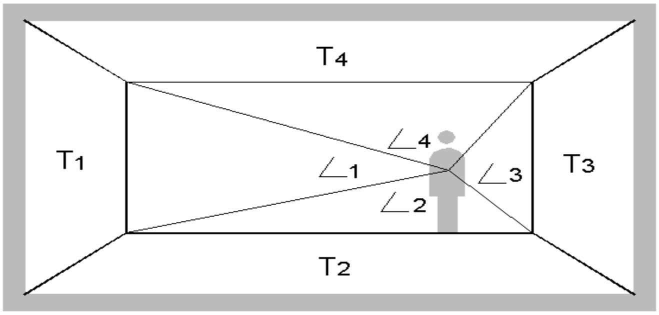

Fig. 3. Definition of Mean Radiant Temperature (T: Temperature, ∠: Angle)

$$\text{Mean Radiant Temperature (MRT)} = \frac{\Sigma t\theta}{360^{\circ}} = \frac{(T1\angle 1) + (T2\angle 2) + (T3\angle 3)\ldots\text{etc}}{360^{\circ}}$$

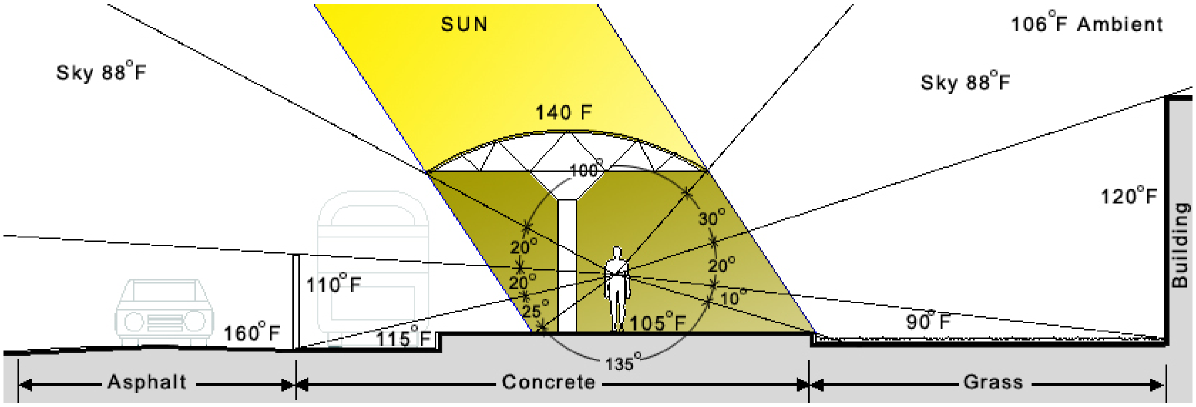

Fig. 4. The effect of radiant fields on a person – Before Case Study

$$\mathrm{MRT} = \frac{(140^{\circ}\mathrm{Fx}100^{\circ})+(88^{\circ}\mathrm{Fx}30^{\circ})+(120^{\circ}\mathrm{Fx}20^{\circ})+(90^{\circ}\mathrm{Fx}10^{\circ})+(105^{\circ}\mathrm{Fx}135^{\circ})+(115^{\circ}\mathrm{Fx}25^{\circ})+(110^{\circ}\mathrm{Fx}20^{\circ})+(88^{\circ}\mathrm{Fx}20^{\circ})}{360^{\circ}} = 114^{\circ}\mathrm{F}$$

Once the MRT has been calculated the operative temperature (t_o) can be determined by using Figure 1. To determine t_o we need to read along the 114° MRT horizontal line and along the 106°F ambient air temperature line (the 2% ASHRAE Summer Design Condition for Phoenix). The intersection of these two lines is the t_o which is read or interpolated between the two adjacent curved diagonal lines, for this case t_o = 111°F.

To determine if this t_o is acceptable from a thermal comfort standpoint (is it within the 95° SET) we need to use Figure 2. We read along the 111°F vertical line until we reach the 70°F wet bulb line; this point is to the right of the 95° SET line, thus this outdoor design condition would not be acceptable.

We need to make several material changes in order to reduce surface temperature, which would result in a lower MRT for the station design. Figure 5. illustrates the After Case Study which are also summarized as follows:

- Change canopy from an exposed metal to a highly reflective white metal with 1" of insulation, this would effectively reduce the surface temperature from 140°F to 116°F.
- Change concrete platform pavers to a more highly reflective material; this would effectively reduce the sunlit surface temperature to 105°F and the shaded surface temperature to 95°F.
- Block the 120°F adjacent building surface temperature by placing a row of trees along that edge of the platform; this would effectively reduce the surface temperature of that view to 90°F.
- Block the 110°F fence surface temperature by placing vegetation along that fence; this would effectively reduce the surface temperature of that view to 90°F.

These modified surface temperatures are based on a series of material temperatures that have been published and documented by the Lawrence Berkeley National Laboratory Cool Roof Program's,[6] a portion of which is summarized in Table 2.

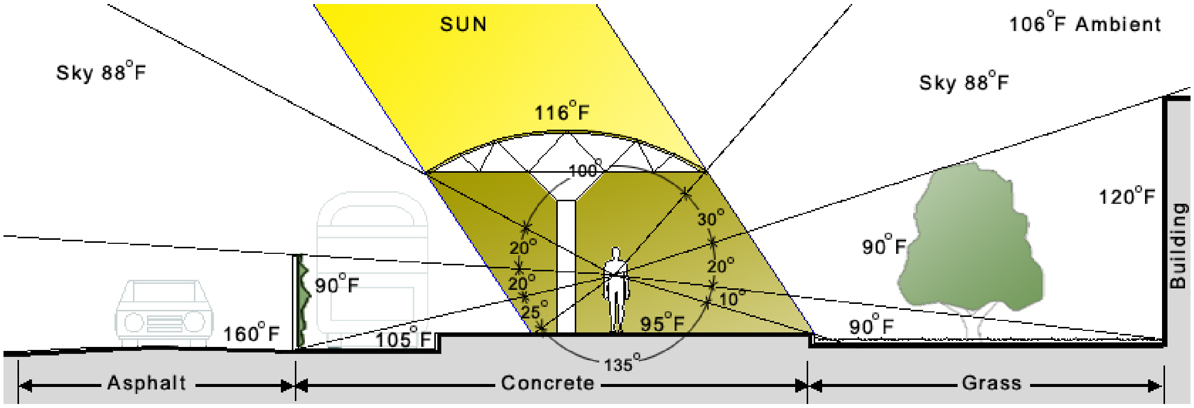

Fig. 5. The effect of radiant fields on a person – After Case Study

$$\text{MRT} = \frac{(116^{\circ}\text{F}\times100^{\circ})+(88^{\circ}\text{F}\times30^{\circ})+(90^{\circ}\text{F}\times20^{\circ})+(90^{\circ}\text{F}\times10^{\circ})+(95^{\circ}\text{F}\times135^{\circ})+(105^{\circ}\text{F}\times25^{\circ})+(90^{\circ}\text{F}\times20^{\circ})+(88^{\circ}\text{F}\times20^{\circ})}{360^{\circ}} = 100^{\circ}\text{F}$$

Figure 1. is again used, by reading along the 100°F MRT horizontal line and along the 106°F ambient air temperature line we determine the t_o to be 102°F. To determine if this t_o is acceptable from our outdoor design criteria, we again use Figure 2. We read along the 102°F vertical line until we reach the 70° F wet bulb line, this point is right on the 95° SET line, thus this outdoor design condition would be acceptable.

CONCLUSION

We believe that our proposed outdoor design criteria and the associated testing methodology is relatively simple and easy to use. It provides a consistent and verifiable benchmarking tool to compare the radiative properties of various station canopies. Designers can utilize this methodology to make quick comparisons of various material options as well as surface and landscape treatment. While limitations exist, particularly with the thermal comfort criteria that we assumed and with the limited number of materials for which we presently have data. However, as more data becomes available improvements to this methodology can be made.

In the next phase of this project we plan to perform detailed technical reviews on each of the twenty-two CP/EV LRT stations. In this phase performance will be estimated by a much more robust radiative analysis tool, for example a radiative simulation program such as RadTherm might be used.[7] Such a tool would allow us to not only validate our simplified methodology but to determine detailed performance characteristics for each of the station designs. After these stations are built, in-situ measurement will also be undertaken and compared to earlier estimates. It is our hope that the methodology outlined here will make an important contribution to our understanding as to how outdoor shading structures perform and how they can be better designed.

Table 2. Partial Summary of Roof Materials [6]

Product	Solar Reflectance	Infrared Emittance	Temperature Rise	Solar Reflectance Index
KoolSeal Elastometric on Shingles	0.71	0.91	22 F	88
Henry White Coating on Shingle	0.71	0.9	23 F	87
Aged Elastometric on plywood	0.73	0.86	21 F	89
Flex-tec Elastometric on Shingles	0.65	0.89	28 F	79
New Insultec on wood, thickness 0.5mm	0.841	0.89	10 F	106
Insultec on metal swatch	0.78	0.9	16 F	97
Enerchron on metal swatch	0.77	0.91	17 F	96
White Coating (1 coat, 8 mils)	0.8	0.91	14 F	100
White Coating (2 coats, 20 mils)	0.85	0.91	9 F	107
Triangle Coatings, Toughkote	0.85	0.91	9 F	107
Triangle Coatings, Trilastic	0.83	0.91	11 F	104
Triangle Coatings, high reflectance 7	0.84	0.91	10 F	106
National Coatings, Acryshield	0.83	0.91	11 F	104
Utrecht acrylic, titanium white	0.83	0.91	11 F	104
Guardcoat, white	0.74	0.91	20 F	92
Koolseal elastomeric	0.81	0.91	13 F	102
MCI, elastomeric	0.8	0.91	14 F	100
Nexus/Visuron elastomeric	0.851	0.9	9 F	107

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