



Window Performance for Human Thermal Comfort

Final Report – November 2005



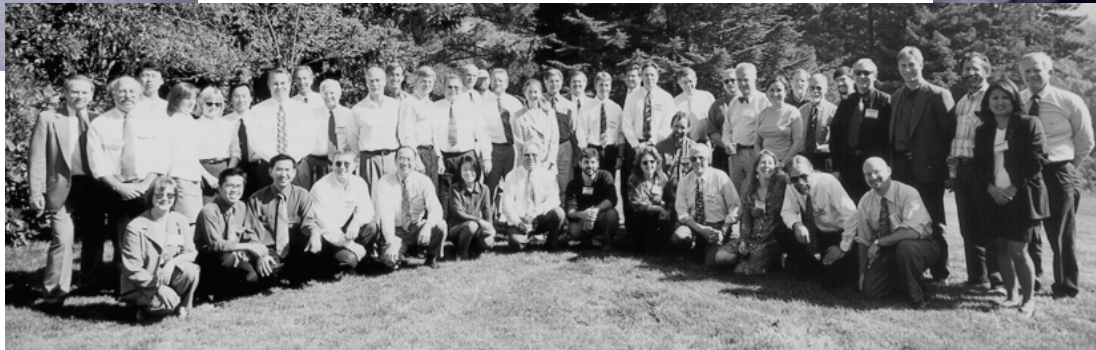
Charlie Huizenga
Hui Zhang
Pieter Mattelaer
Tiefeng Yu
Edward Arens

University of California, Berkeley

Peter Lyons
Arup Façade Engineering
Melbourne, Australia

Center for the Built Environment (CBE)

Our Mission: To improve the design, operation, and environmental quality of buildings by providing timely, unbiased information on building technologies and design techniques



CBE Industry Partners

Armstrong World Industries

Arup*

California Department of
General Services (DGS)

California Energy Commission

Charles M. Salter Associates

Flack + Kurtz

HOK

Pacific Gas & Electric Co.

Price Industries

RTKL

Skidmore Owings and Merrill

Stantec

Steelcase

Syska Hennessy Group

Tate Access Floors*

Taylor Engineering Team:

- Taylor Engineering
- The Electrical Enterprise
- Guttman & Blaevoet
- Southland Industries
- Swinerton Builders

Trane

U.S. Department of Energy (DOE)*

U.S. General Services Administration
(GSA)*

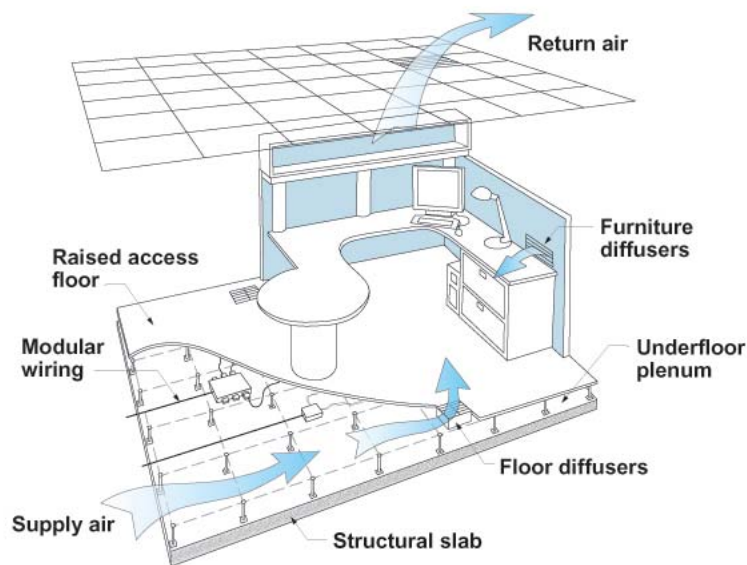
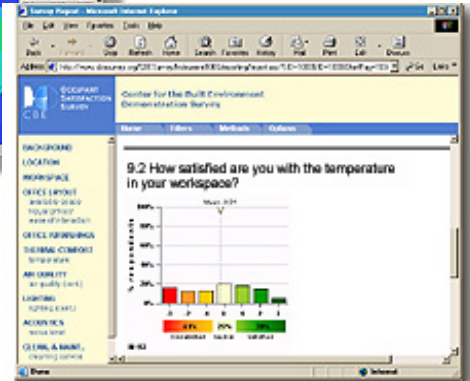
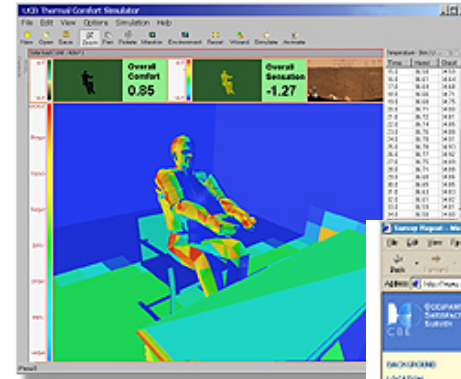
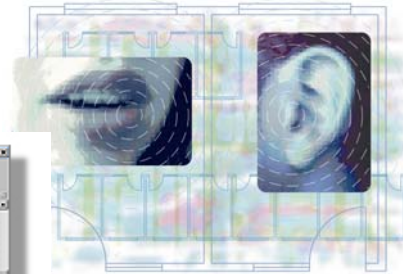
Webcor*

York International Corporation

*founding partner

CBE research programs

- Indoor Environmental Quality
- Envelope and Façade Systems
- Workplace Design
- Underfloor Air Distribution (UFAD)
- Building Information Technology



National Fenestration Rating Council Study

Objective:

Develop a technical basis for a method to rate the thermal comfort performance of windows.

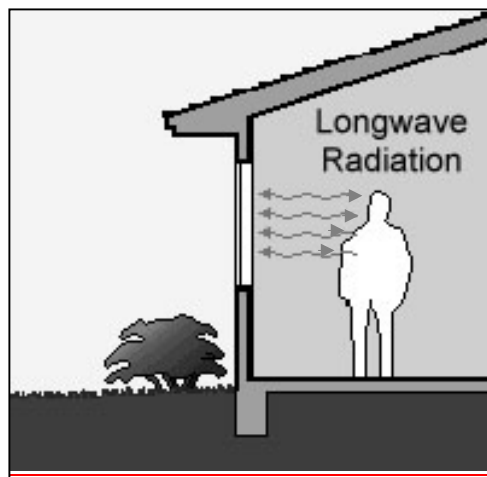
Phase I Literature review of thermal comfort studies related to windows, asymmetrical thermal environments, and draft.

Phase II Develop the technical basis and propose a rating method.

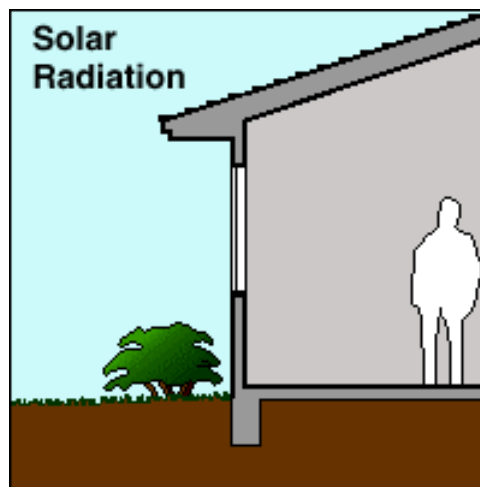
Literature review

- **20 page overview of the literature**
- **~175 relevant papers identified**
- **~40 papers summarize**

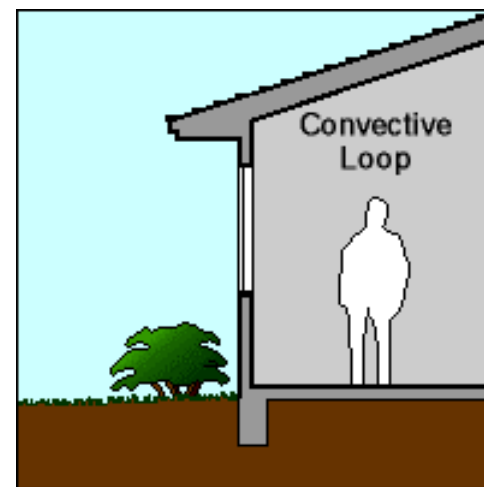
How windows influence comfort



Long wave radiation exchange is the dominant mechanism by which windows influence thermal comfort.



Solar radiation absorbed by the window increases the interior window surface temperature. Transmitted solar radiation that reaches the body has a significant impact on comfort.



A cold inside surface temperature can induce a convective draft in a room.

Predicted Mean Vote (PMV) comfort model

The PMV model (Fanger, 1970) is the standard method used to evaluate comfort in buildings.



However, it was based on data from uniform thermal environments (comfort chambers) rather than typical office environments



Local discomfort

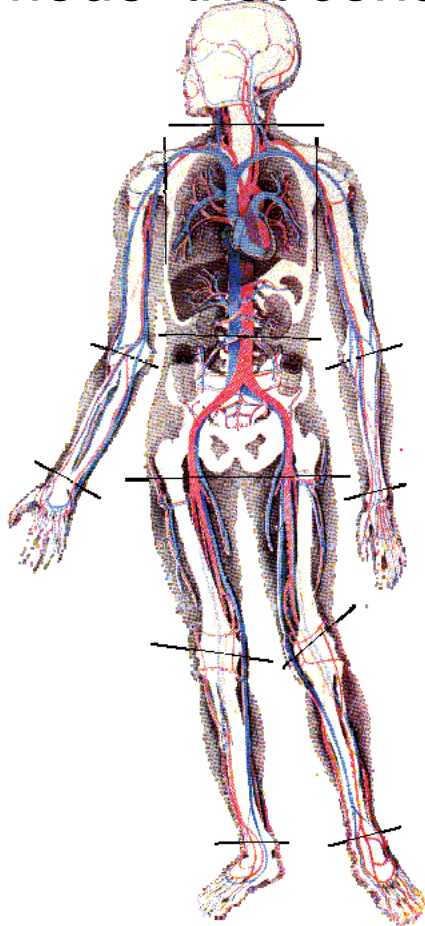
- Most thermal comfort complaints are a result of *local* discomfort rather than overall comfort
- Windows often cause local discomfort because they affect one side of the body
- PMV predicts overall comfort but is not able to assess local discomfort
- The CBE model comfort model is able to predict local discomfort

My
hands
are cold



UC Berkeley Comfort Model

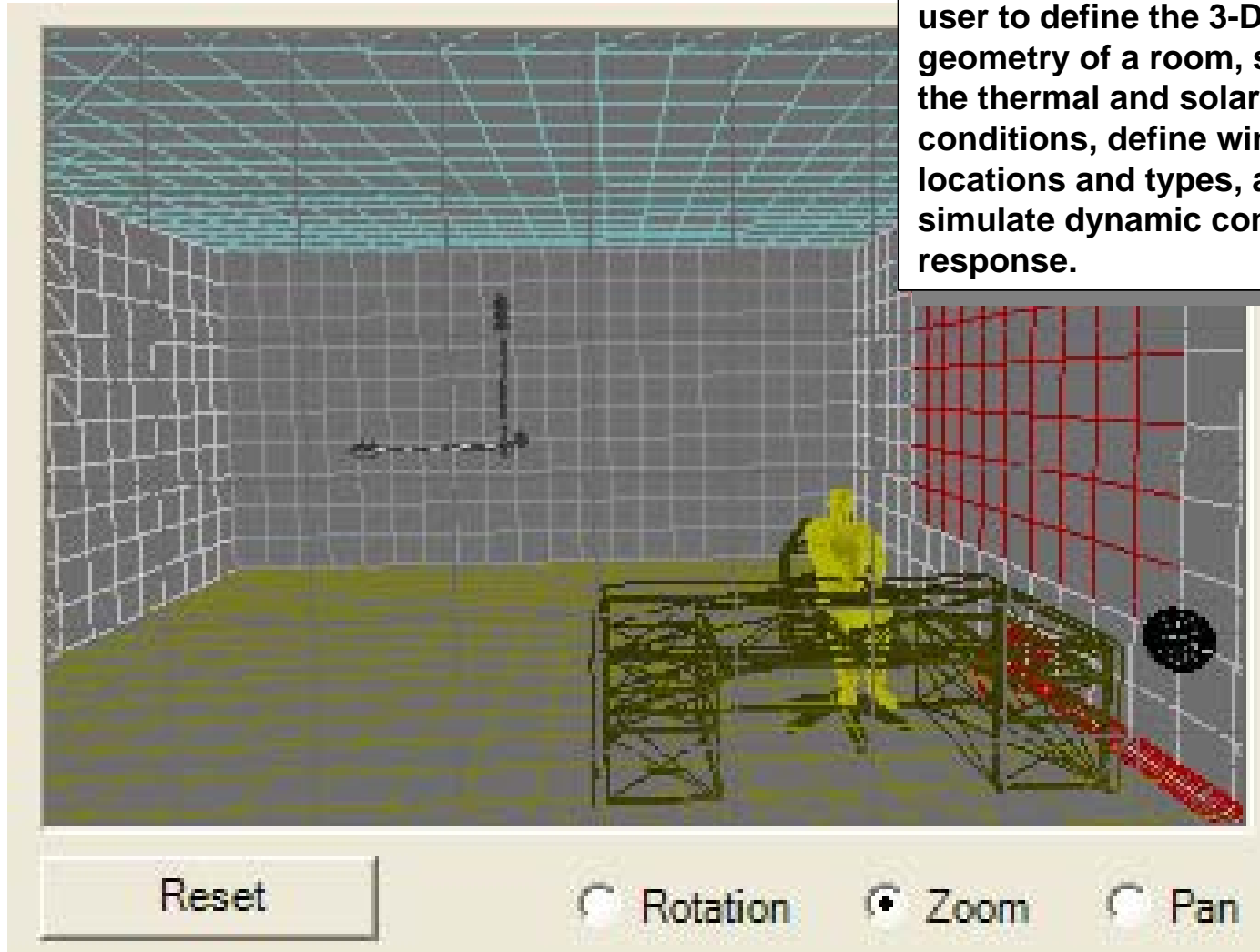
The UCB Comfort Model is a much more sophisticated model that considers non-uniform thermal environments.



- 16 body segments, 4 layers (core, muscle, fat, and skin)
- Transient
- Blood flow model
- Heat loss by evaporation(sweat), convection, radiation, and conduction
- Clothing model (including heat and moisture transfer)

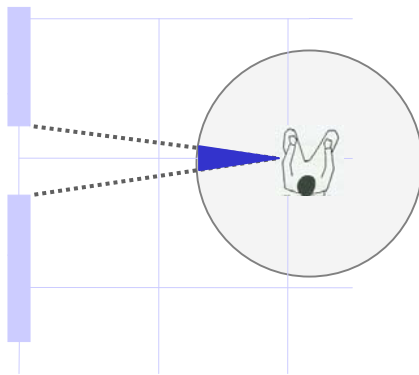
UCB Comfort Model interface

The UCB model allows the user to define the 3-D geometry of a room, specify the thermal and solar conditions, define window locations and types, and simulate dynamic comfort response.

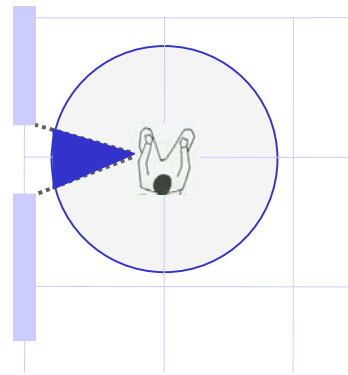


View factor

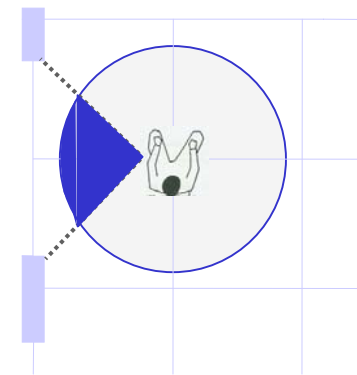
The view factor is a function of window size, room geometry, and occupant location



View factor is used to quantify the amount of radiation energy leaving the body that reaches the window.



View factor is increased by moving closer to the window.

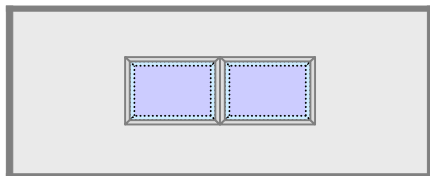


View factor is increased with a larger window.

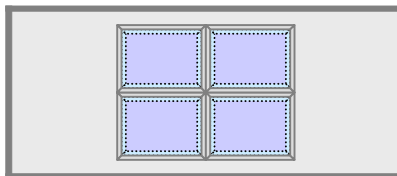
Sample window simulations

Window to wall ratio (WWR)

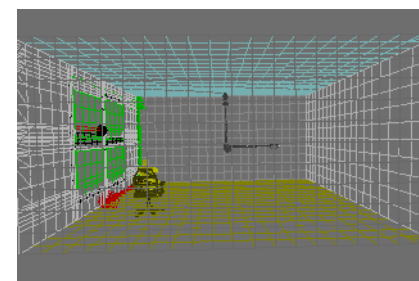
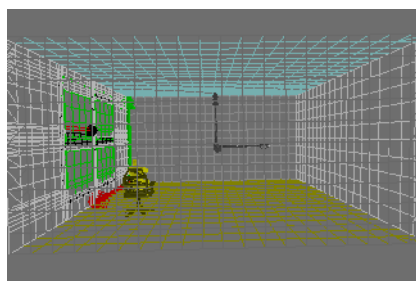
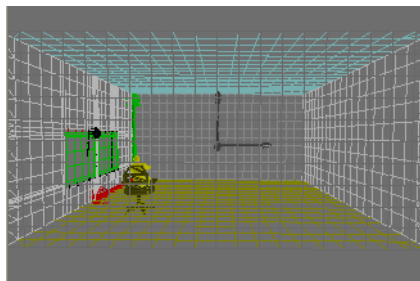
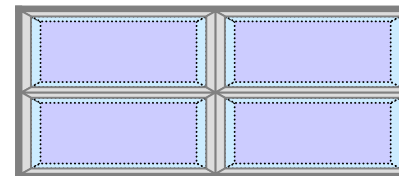
WWR=20%



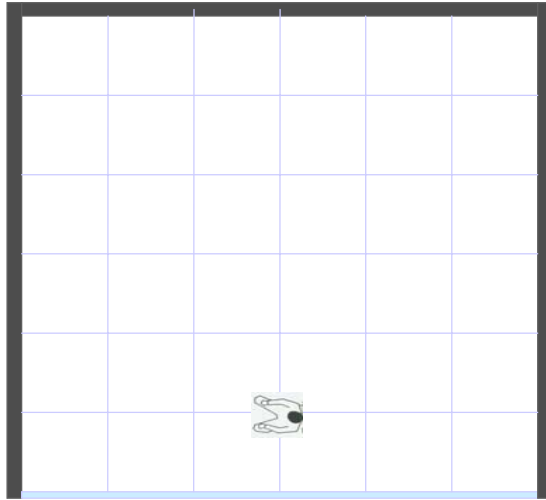
WWR=40%



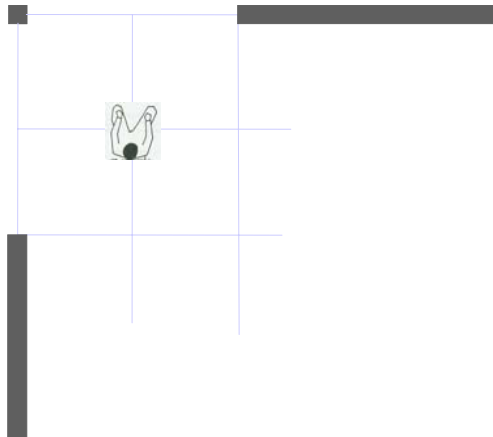
WWR=100%



Example simulation geometry



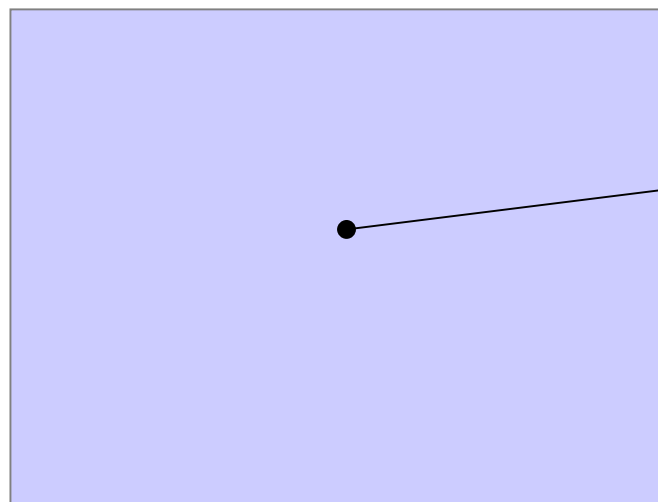
- 100% Window to wall ratio (WWR)
- Occupant sitting 1 meter from the window
- 6m x 6m x 3m room



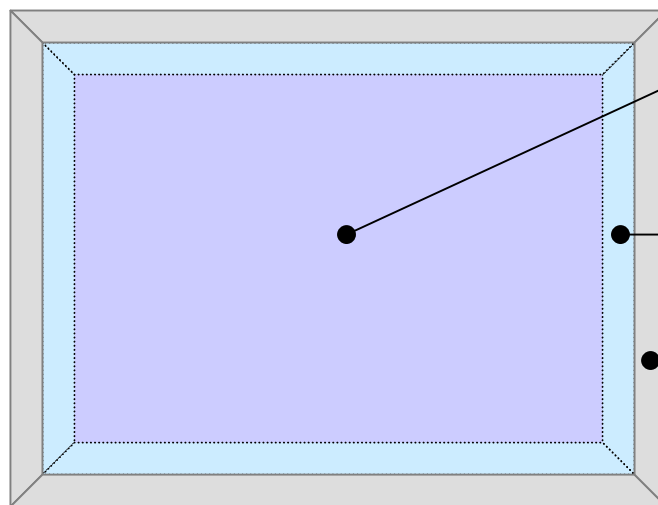
- Corner office

Window temperature distribution

Comfort results from area-weighted window temperature are very close to those using actual temperature distribution.



Idealized uniform window temperature (area-weighted)



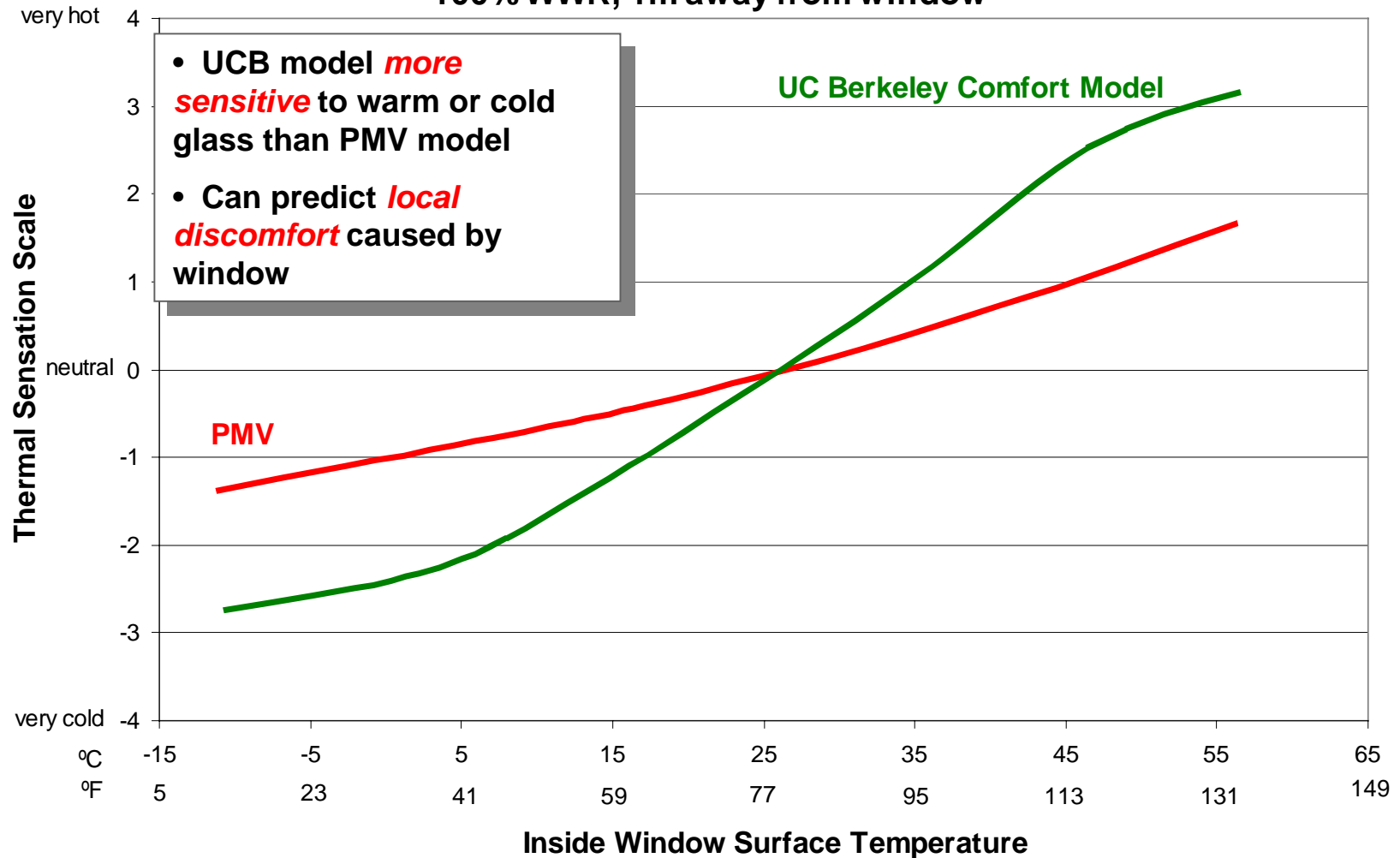
Center of glass

Edge of glass

Frame

Comparison of PMV and UCB Comfort Model

Sedentary, summer clothing, neutral air temperature,
100% WWR, 1m away from window



Spatial distribution of comfort

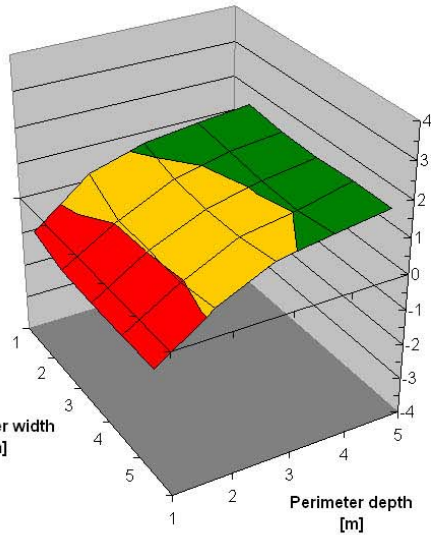
24°C (75°F) inside air temperature

40°C (104°F) inside window surface temperature, single tinted glass, ASHRAE summer condition

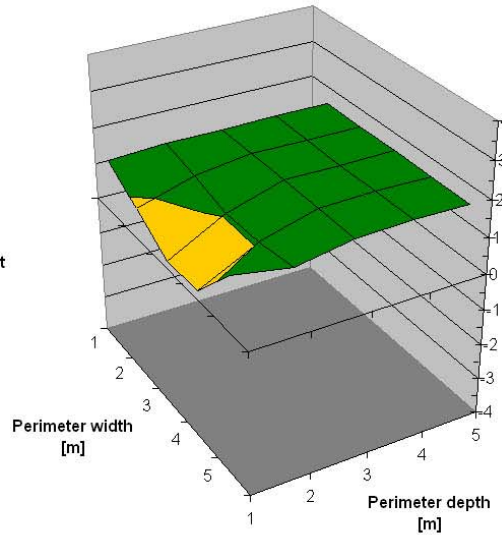
WWR = 100%

WWR = 40%

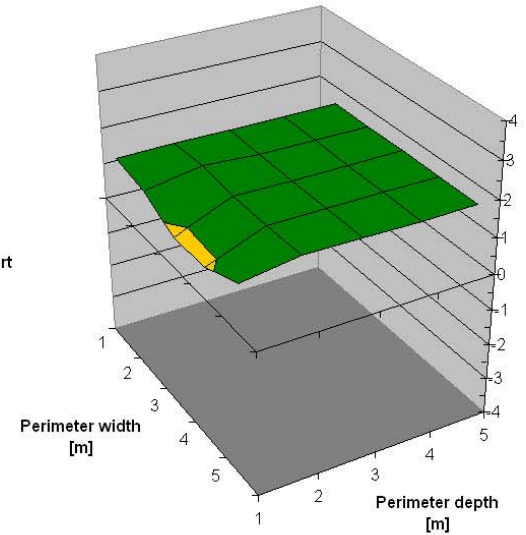
WWR = 20%



Overall Comfort
[-4;+4]



Overall Comfort
[-4;+4]



Overall Comfort
[-4;+4]

- Comfortable
- Just comfortable
- Uncomfortable

Possible indices of window thermal comfort

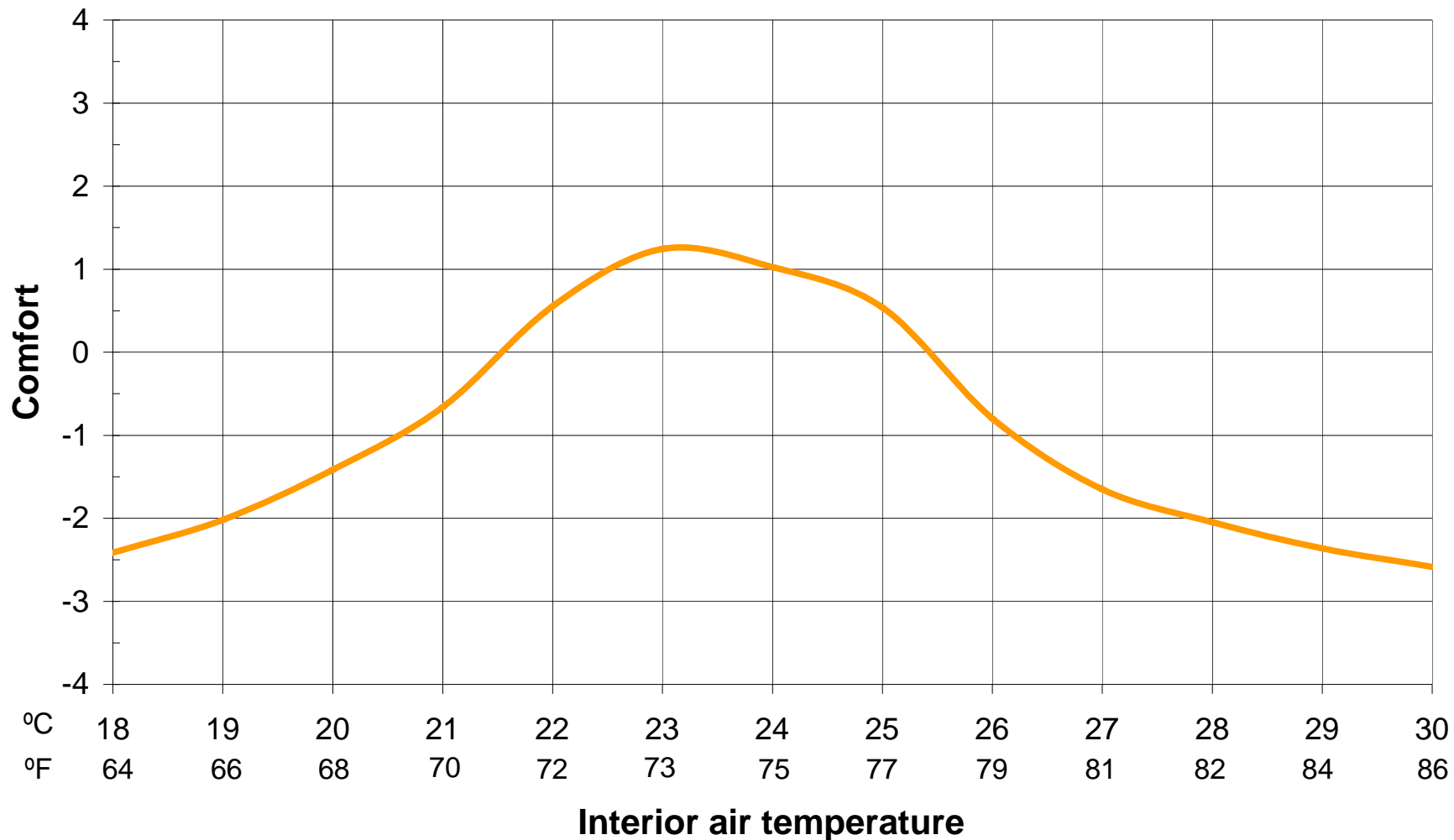
- **Point-in-time indices (NFRC winter *and* summer conditions)**
 - Thermal comfort index
 - Required indoor air temperature conditions to achieve comfort
 - Minimum distance from the window that is comfortable
 - Minimum outside temperature that remains comfortable

- **Annual indices**
 - Annual average comfort index
 - Number of hours outside the comfort zone
 - Annual energy required to maintain comfort
 - Percent of floor area that remains comfortable

Comfort vs. interior air temperature

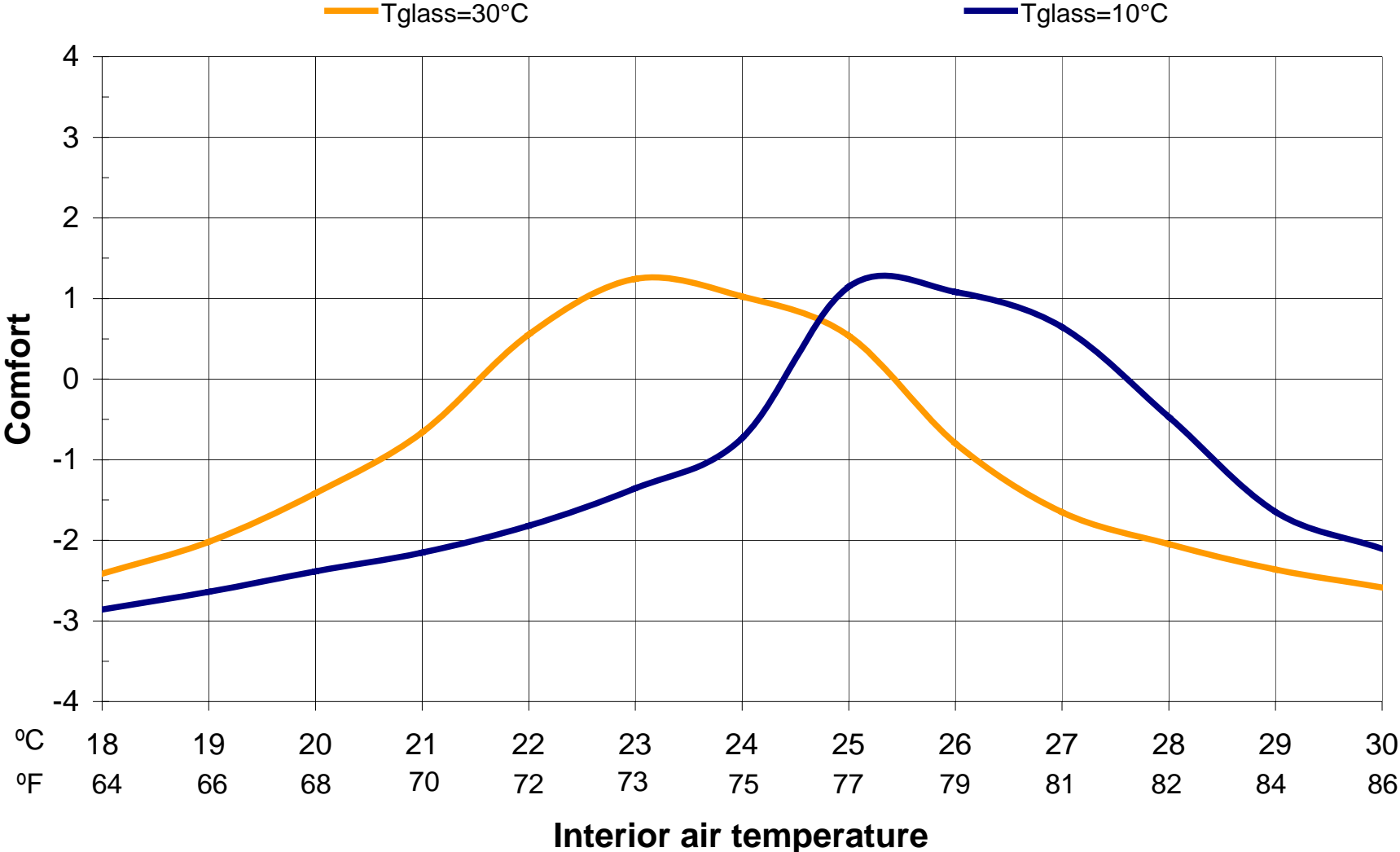
100% WWR, office work activity, summer clothing

— $T_{\text{glass}}=30^{\circ}\text{C}$



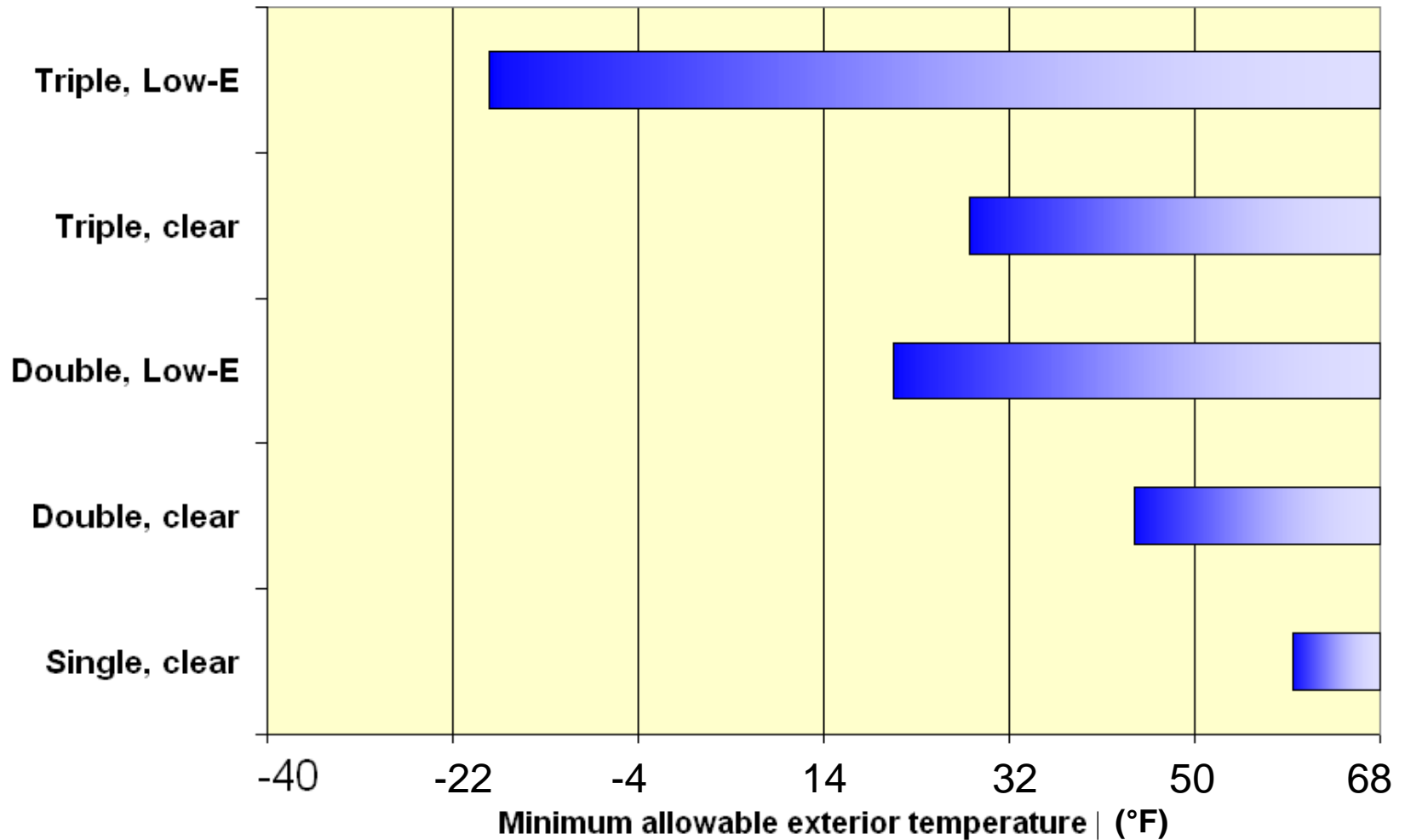
Comfort vs. interior air temperature

100% WWR, office work activity, summer clothing



Example winter comfort ratings

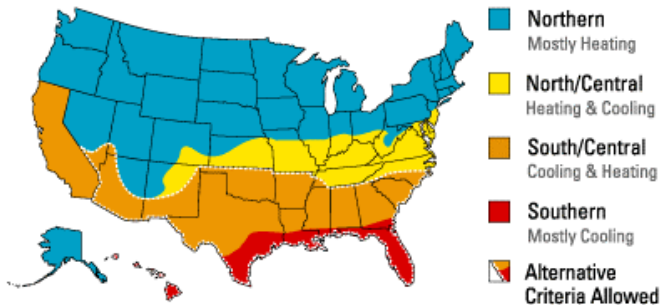
Ti = 23.5°C, 1.2 met, 0.57 clo, 100% WWR, 1 m from window



Winter rating

$$T_{\min} = 74.3^{\circ}F - \frac{8 \text{ Btu} / \text{hr} - \text{ft}^2}{U - \text{factor}}$$

Recommended U-factors

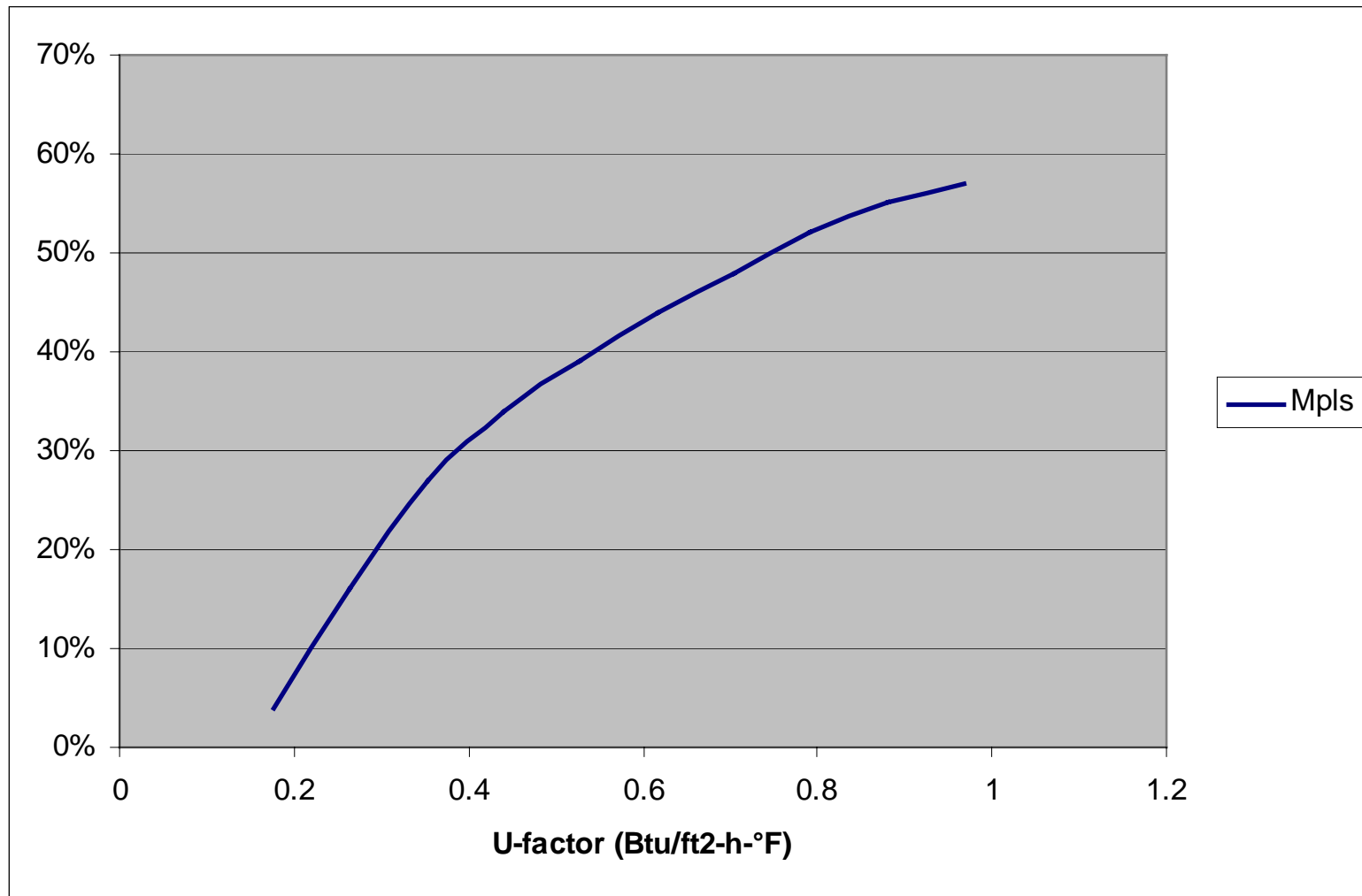


Zone	Energy Star	Present study (2.5% design DB)
Northern	<0.35	0.14 to 0.23
North/Central	<0.40	0.20 to 0.28
South/Central	<0.40	0.26 to 0.46
Southern	<0.65	0.31 to 0.83

U-factors in Btu/h-ft²-F

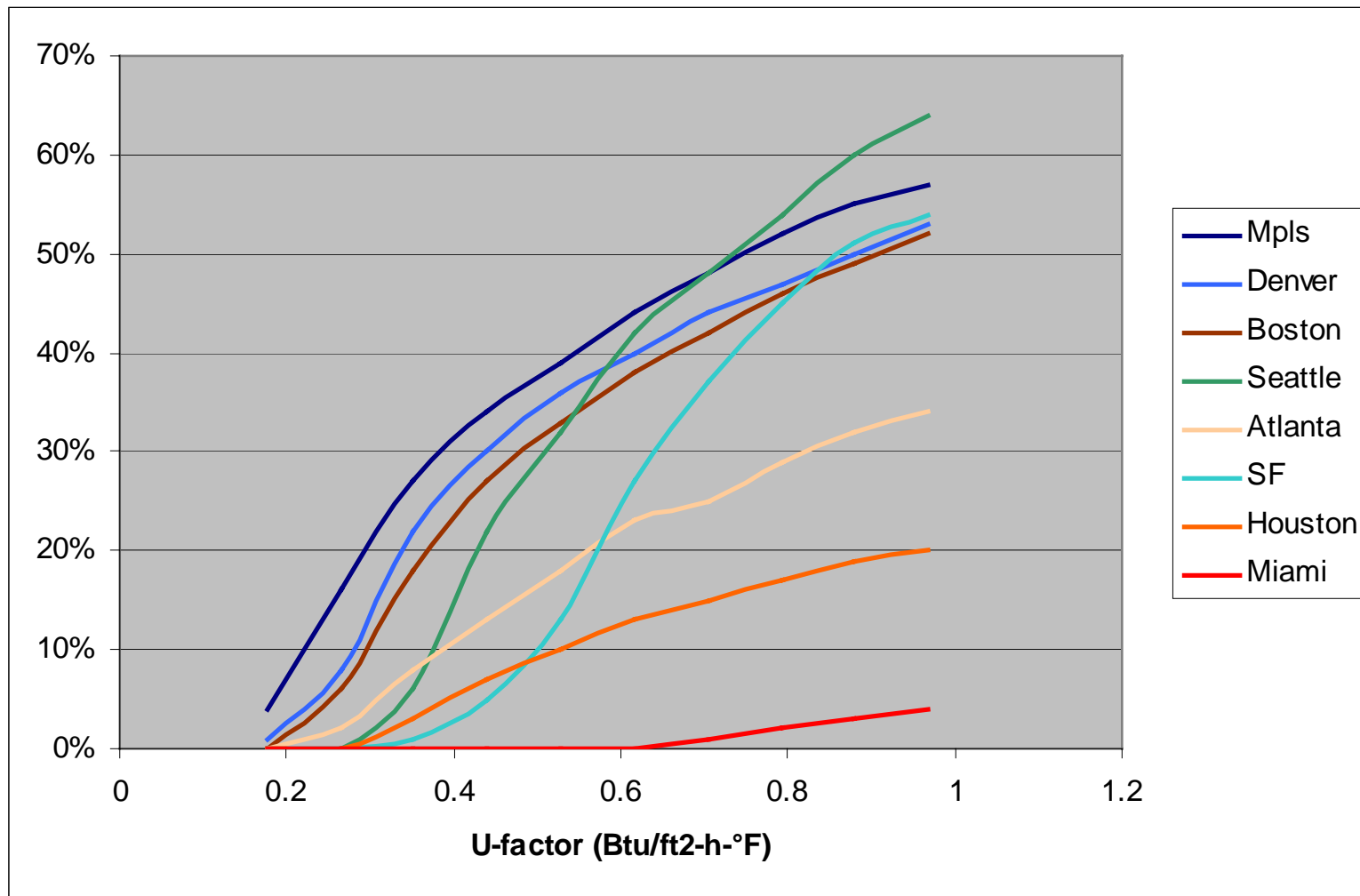
Winter rating: Annual comfort analysis

Percentage of uncomfortably cool hours vs. U-factor for Minneapolis
(1m from 100% glazed façade)



Winter rating: Annual comfort analysis

Percentage of uncomfortably cool hours vs. U-factor
(1m from 100% glazed façade)



Summer rating

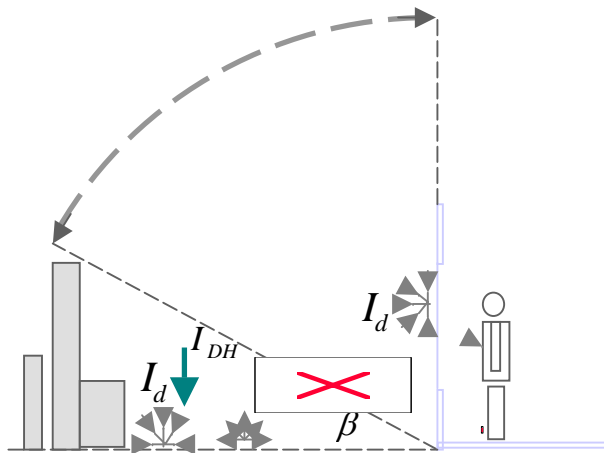
Two major impacts:

1. Inside window surface temperature
2. Transmitted solar radiation
(we are assuming no *direct* solar on the body)

U-factor is relatively unimportant in most cases

Impact of diffuse solar radiation

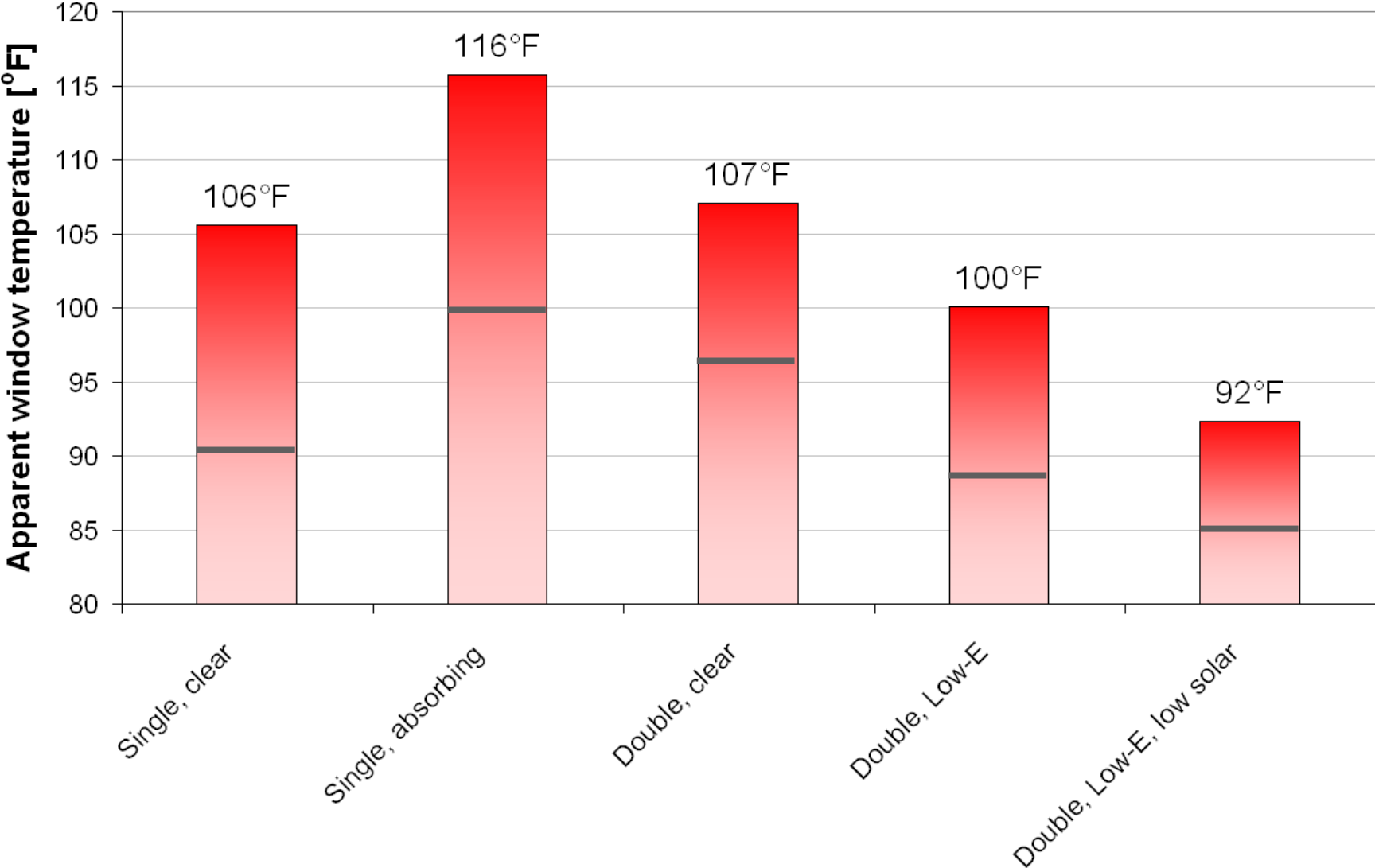
Some amount of the diffuse radiation incident on the window is transmitted and a portion of that is absorbed by the person, increasing their thermal sensation.



Apparent window temperature

- **Apparent window temperature:**
 - The temperature of a window in the same environment but without the transmitted solar radiation that would result in the same thermal comfort as the actual window.

Summer solar rating



Inside surface temperature...

Can be predicted using SHGC and T_{sol} :

$$Q_{total} = Q_{direct} + Q_{indirect}$$

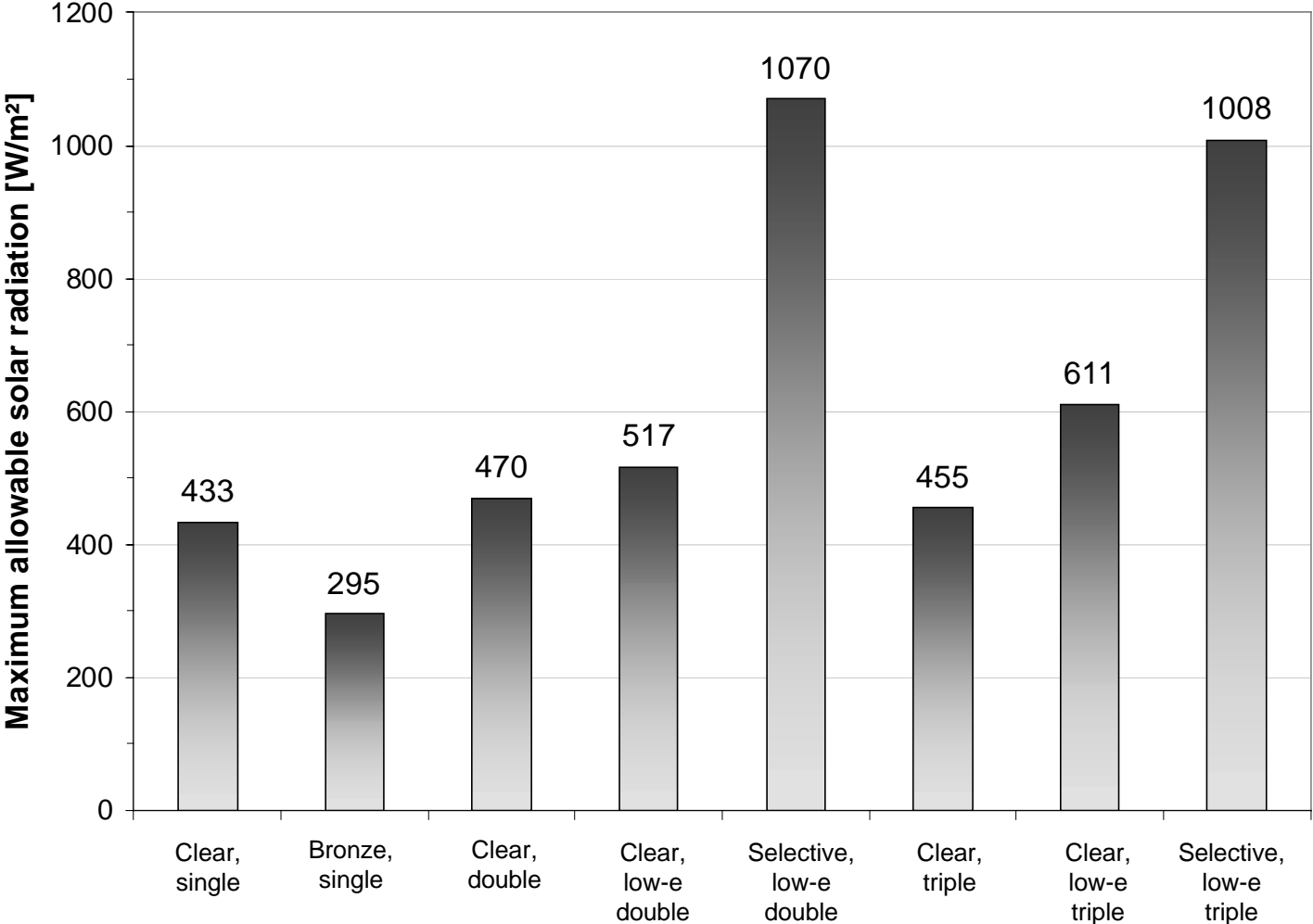
Direct component of SHGC is T_{sol}

Indirect component is $(SHGC - T_{sol})$ or $SHGC_{indirect}$

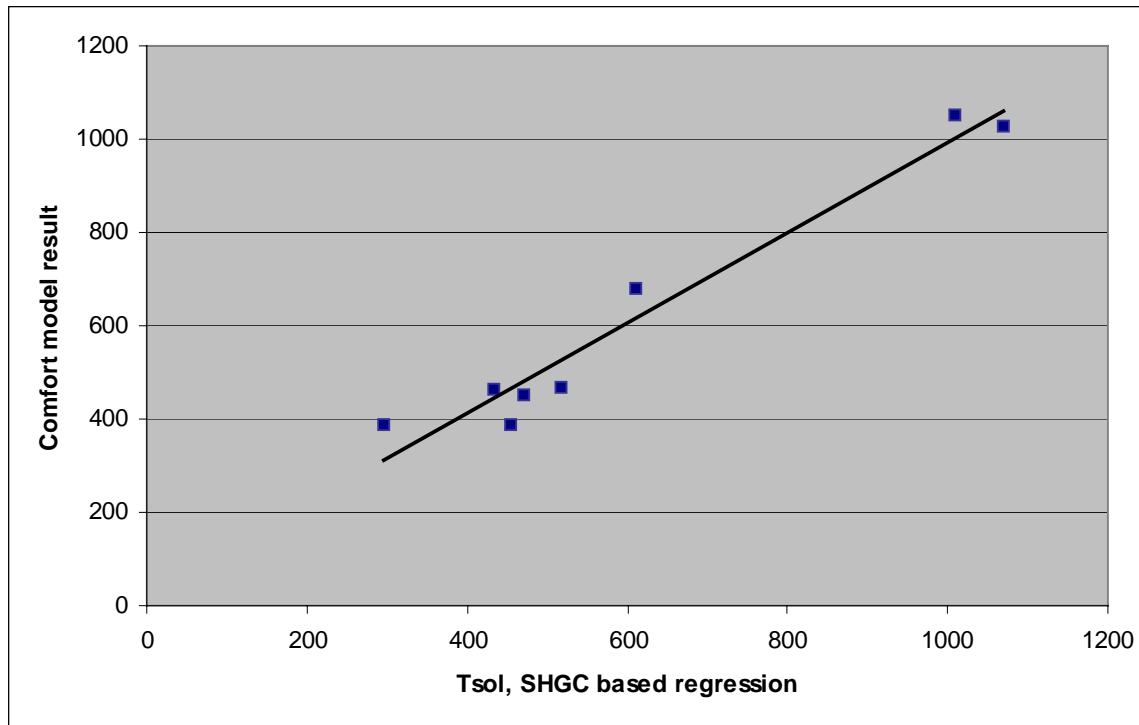
$$Q_{indirect} = Q_{solar} * SHGC_{indirect} = h_i * (T_{inside\ surface} - T_{inside\ air})$$

$$T_{inside\ surface} = Q_{solar} * SHGC_{indirect} / h_i + T_{inside\ air}$$

Maximum allowable solar radiation



Regression of maximum allowable solar



$$\text{Maximum solar} = 1600 \text{ W/m}^2 * (1 - 0.75 * T_{\text{sol}} - 3.3 * \text{SHGC}_{\text{indirect}})$$

Solar Comfort Coefficient

$$\text{SCC} = T_{\text{sol}} + \sim 5 * (\text{SHGC} - T_{\text{sol}})$$

	Tsol	SHGC	SCC
clear, single	0.77	0.82	1.02
bronze, single	0.49	0.72	1.64
clear, double	0.61	0.70	1.06
low-e, double	0.47	0.59	1.07
low-e, selective, double	0.31	0.36	0.56
clear, triple	0.49	0.62	1.14
low-e, triple	0.34	0.45	0.89
low-e, selective, triple	0.25	0.31	0.55

Questions?

Charlie Huizenga
huizenga@berkeley.edu

