An Investigation of Solar Reflectivity of Exterior Architectural Coatings

Zachary Danega, Olivia Everitt*, Lia Roccucci*, Soroush Arjomandi*, Wally Kesler#, and Ray Fernando**

Contact: rhfernan@calpoly.edu

**California Polytechnic State University, San Luis Obispo, CA*

#Dunn-Edwards Corporation, Commerce, CA

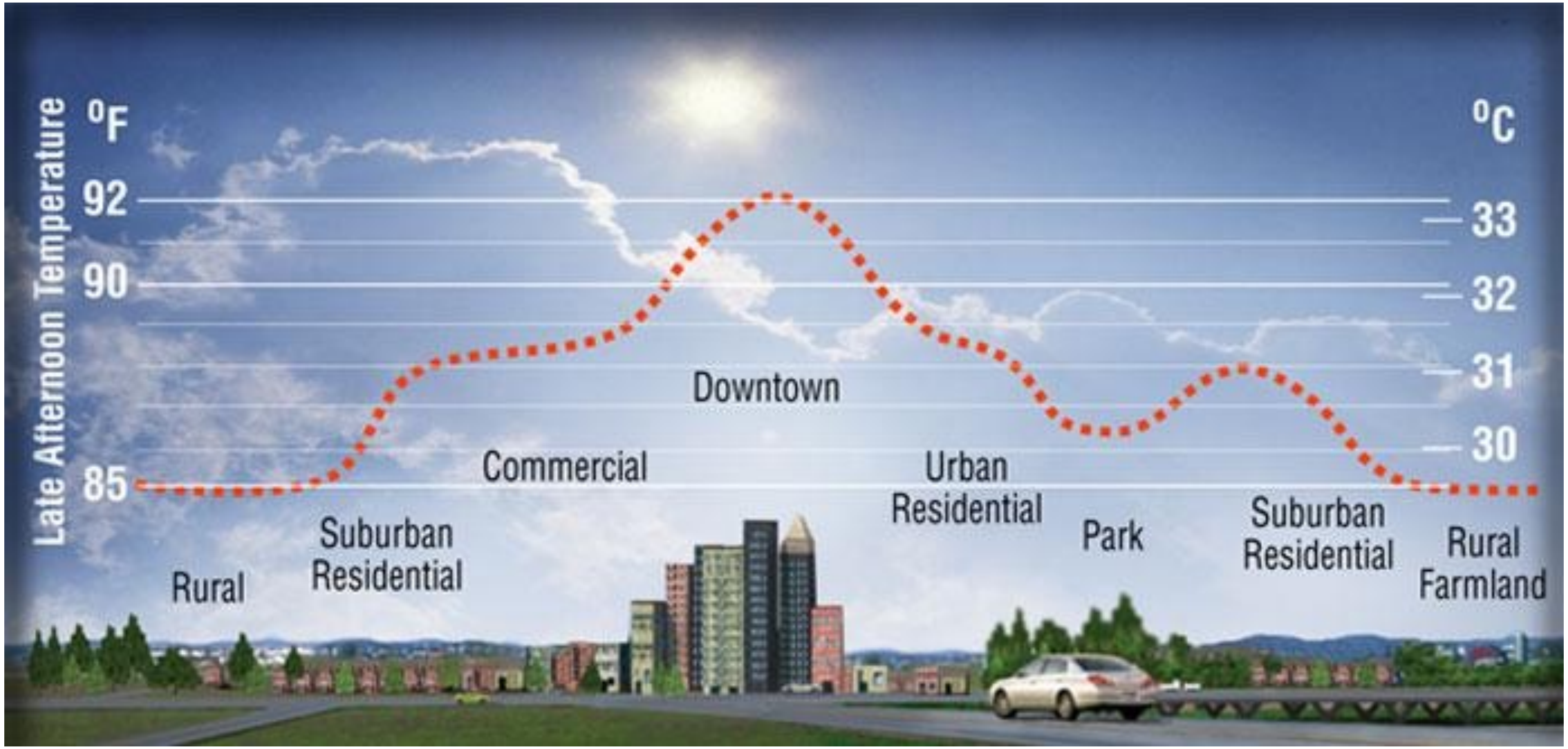
Outline

- Introduction
  - Urban heat island
  - Solar Reflectance and IR Emittance
- Basic principles of cool materials
- Experimental exterior wall coatings
- Appearance and solar reflectance results
- Conclusions and future directions

Urban Heat Islands

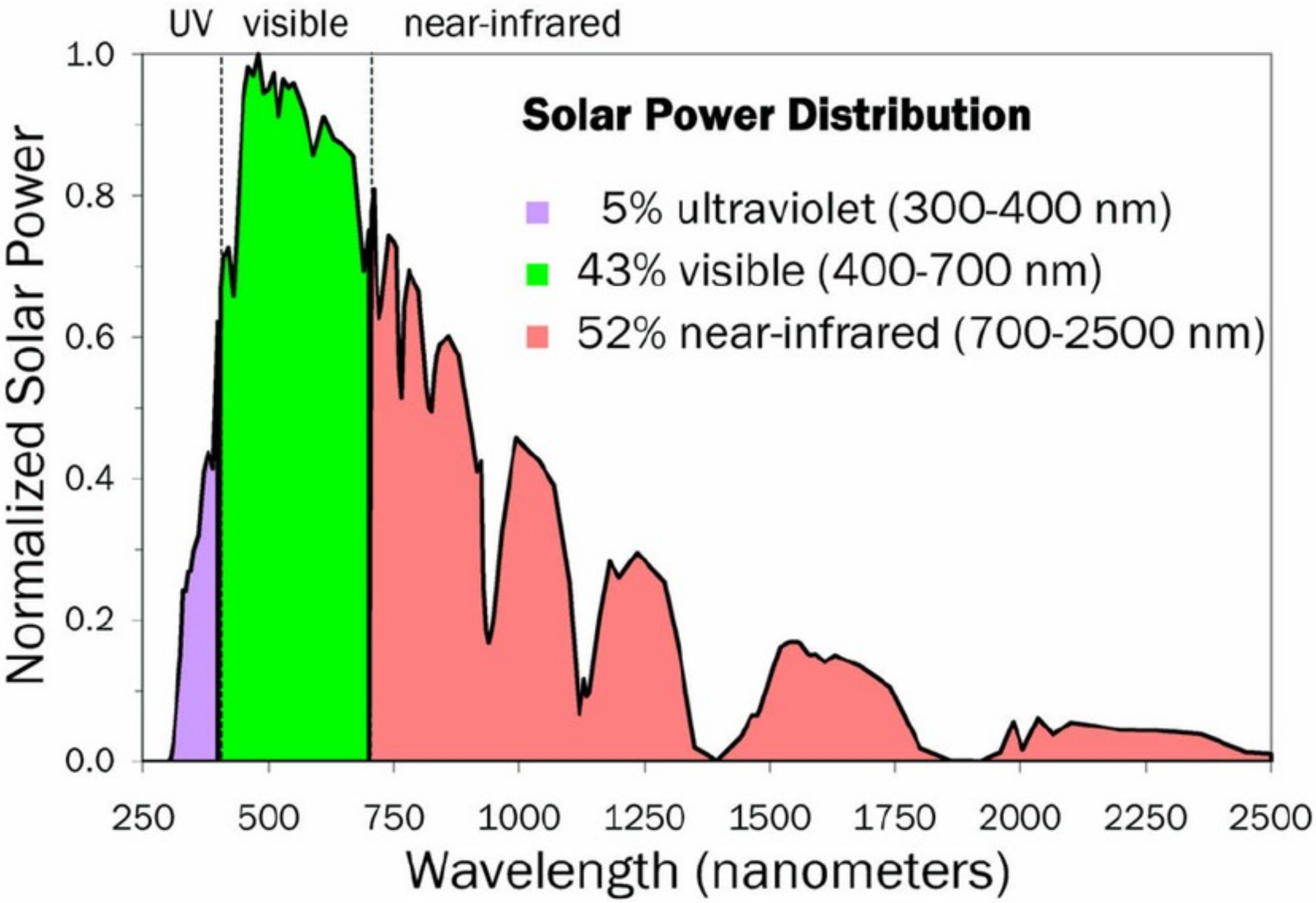
- Daytime elevation in outdoor urban air temperature as a result of the replacement of trees with heat-absorbing infrastructures such as buildings and roads
- Caused by urban surface properties & human activity
  - Dark colors and pavements can absorb 80% of sunlight
  - Transportation, manufacturing, etc. release heat
- Effect
  - Increases energy consumption
  - Decreases air quality
    - Increase production of smog (VOC's and nitrogen oxides)
    - Increased emissions (air pollutants and green house gases)
  - Illness and reduced productivity

Heat Island Effect

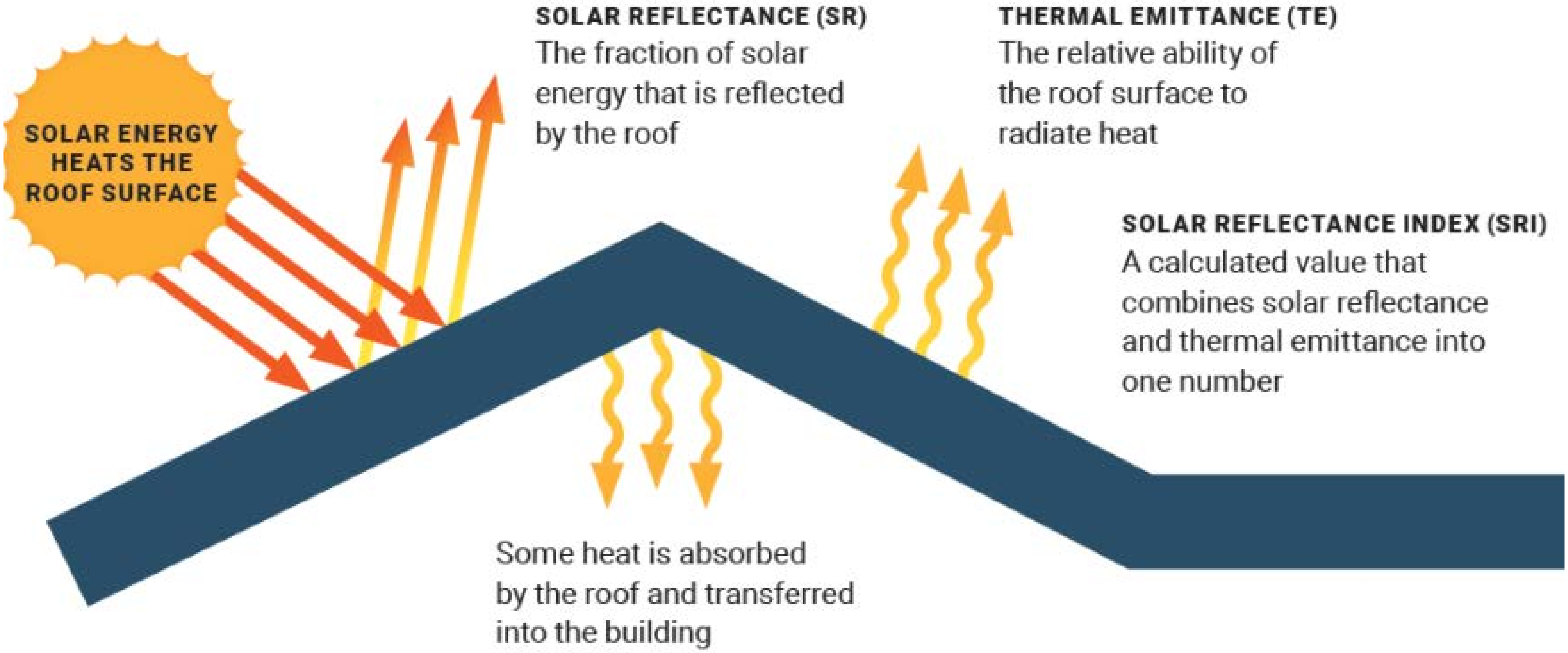


- Buildings
- Automobiles
- Pavements

https://heatisland.lbl.gov/coolscience



Cool Roofing Material, Akbari, et al., LLNL & ORNL, 2006



https://coolroofs.org/

Definitions: TSR & e

- TSR: Total Solar Reflectance
  - Between 0 and 1
  - Can be measured
    - Devices and Services3 SolarSpectrum Reflectometer Model SSR
    - Surface Optics 410-Solar-i Solar Reflectometer
- Infrared emittance (e)
  - Infrared emittance is a measure of the ability of a surface to release, absorbed heat.
  - Specifies how well a surface radiates energy away from itself as compared with a black body operating at the same temperature.
  - Infrared emittance is measured on a scale from 0 to 1.

SRI calculators

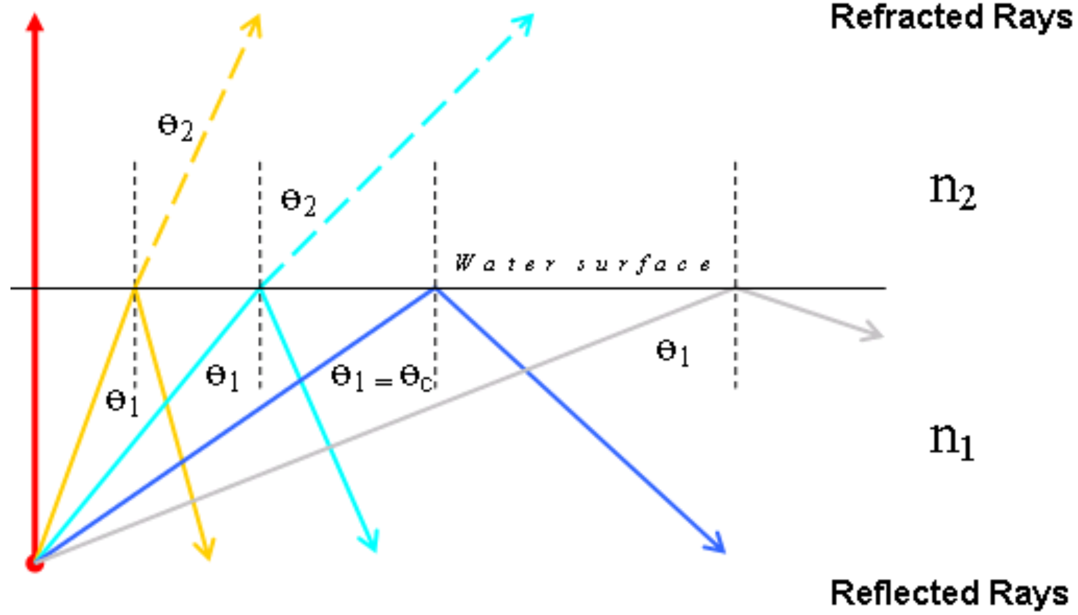
- Several SRI calculators have been developed and available online
  - ORNL SRI Calculator
  - LBNL Heat Island Group SRI calculator Excel sheet
  - LEED’s SRI Calculator

“Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions”, M. Santamouris, A. Synnefa, T. Karlessi, Solar Energy 85 (2011) 3085–3102

Mechanisms

- One mechanism parallels the hiding mechanism applicable to visible range
  - Refractive index difference
  - Particle size

	Refractive index
Vacuum	1.00
Air	1.00
Water	1.33
Binders	1.50
Calcium carbonate	1.63
Antimony Oxide	2.20
Titanium dioxide (anatase)	2.55
Titanium dioxide (rutile)	2.73
Silicon	4.01



390 COLOR AND APPEARANCE

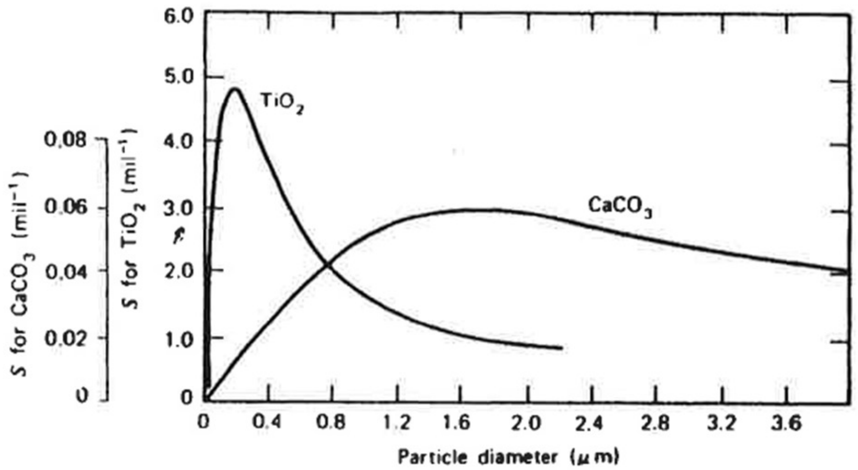


Figure 19.8. Scattering coefficients as a function of particle size for rutile TiO_2 and $CaCO_3$. (From Ref. [6], with permission.)

Wicks, et al., Organic Coatings: Science and Technology (4th Ed), 2018

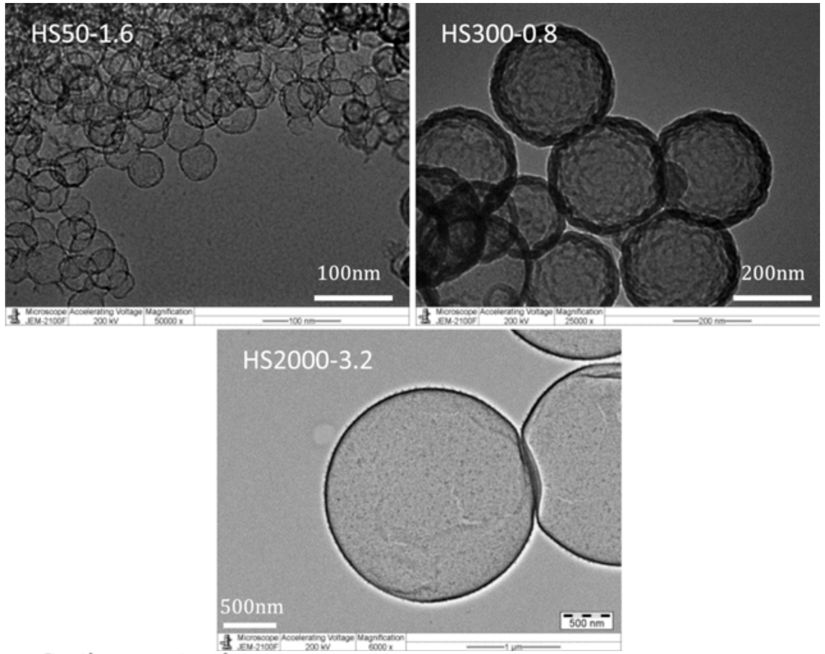
Product Opportunities – Exterior Walls

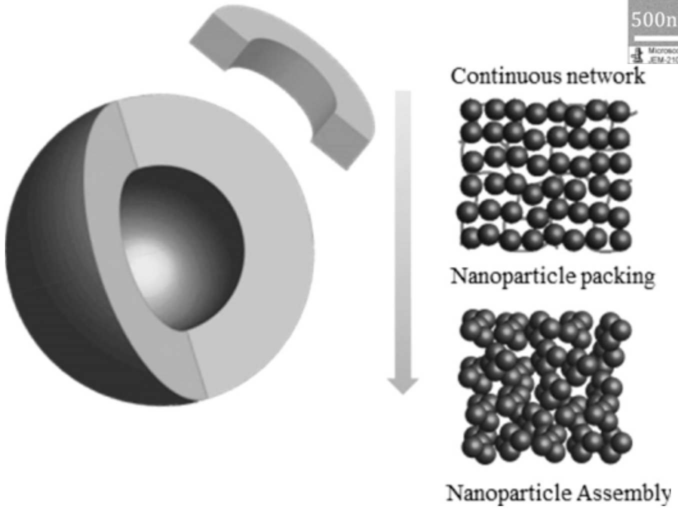
- 2019 Report by LBNL, USC, & UCSD
  - Solar-Reflective "Cool" Walls: Benefits, Technologies, and Implementation (About 1000 pages, 22 Authors)
  - "Potential benefits of cool walls on residential and commercial buildings across California and the United States: Conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants", Rosado, P.J. and Levinson, R., Energy & Buildings, 199 (2019) 58-607
- The Cool Roof Rating Council (coolroofs.org)
  - Roof Rating Program
    - More than 3000 products
  - Wall Rating Program (June 17, 2019)
    - Rated Wall Products Directory (January 17, 2022)
    - Less than 100 products
  - Opportunities for raw material development
  - Need to expand the knowledge base
    - Coatings for walls are not optimized for solar reflection and IR emission

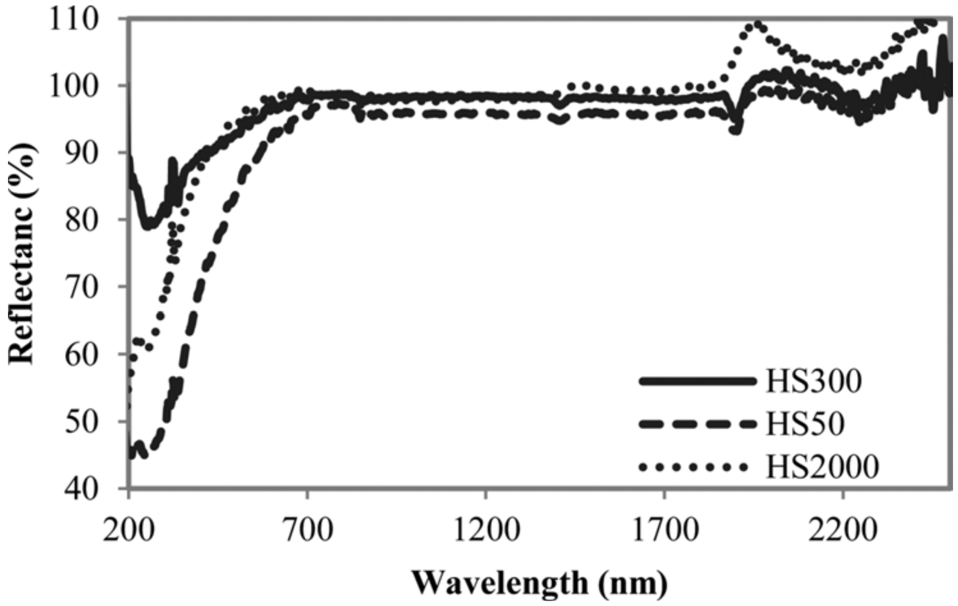
Project Objective

- Understand and quantify the heat reflective performance of conventional exterior architectural coatings
- Optimize such formulation for solar reflectance, without compromising other performance traits
- Quantify solar reflectance of specialty reflective materials
  - Hollow spherical material (polymer, glass)
  - IR reflective color pigments
  - Determine potential energy savings

Hollow Spherical Microspheres







MMA/EA copolymer matrix in a 1:1 volume ratio in the form of a coating film; toluene solvent

"Porous SiO_2 Hollow Spheres as a Solar Reflective Pigment for Coatings", Xing, Tay, Ng, and Hong, ACS Appl. Mater. & Interf., 2017, 9, 15103-15113

Experimental Exterior Wall Coatings

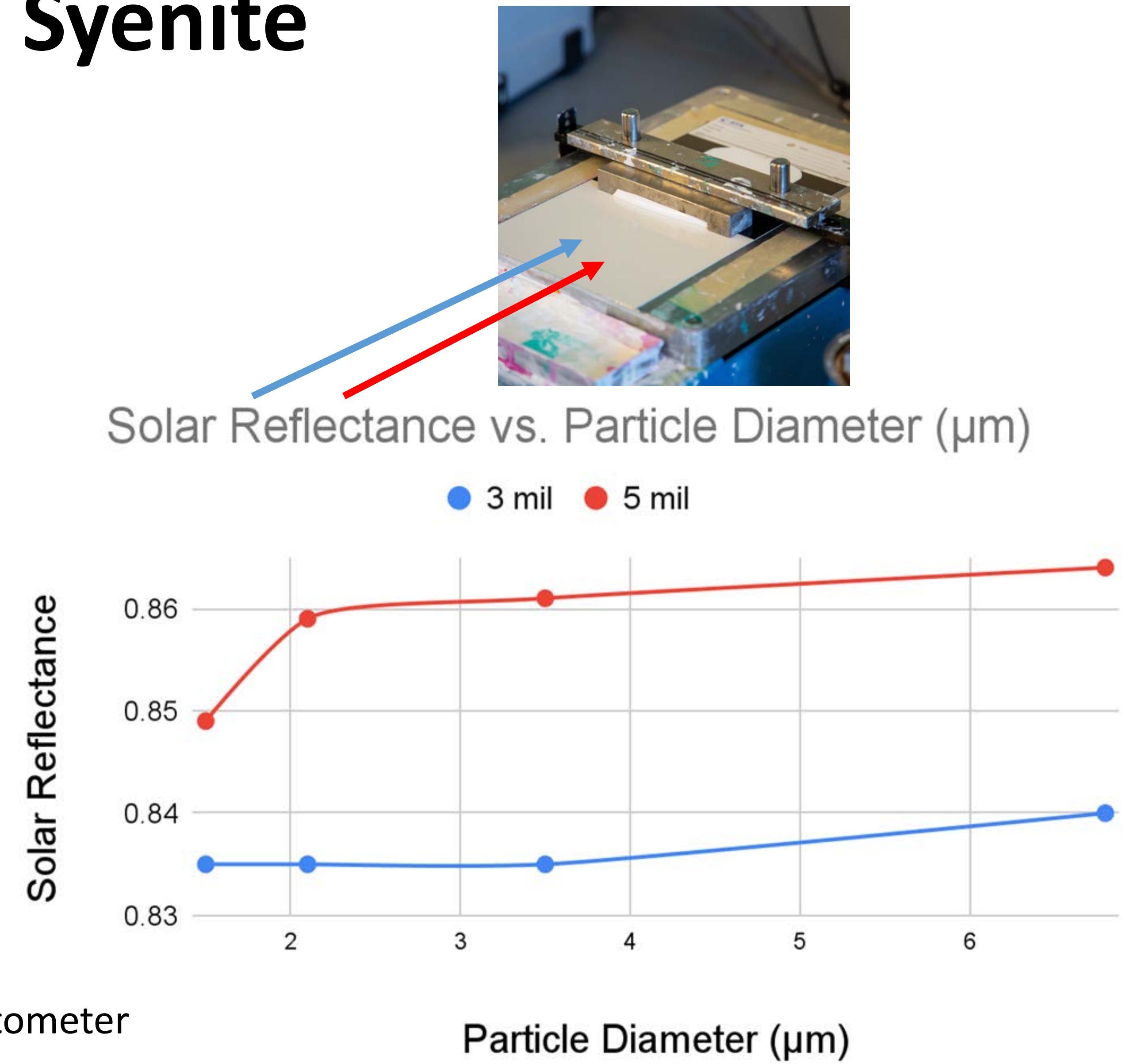
- Base formulation BF1
  - Acrylic latex & TiO_2 slurry
  - 40 %NVV
  - 43.4 PVC [TiO_2-17 & Filler-26.4]
  - Filler variations
    - Nepheline Syenite 1.5, 2.1, 3.5, 6.8 micrometer [NS 1, 2, 3, &6]
    - Calcium Carbonate 3.0, 5.5, 12 micrometer [CC 3, 5, & 12]

- Base formulation BF2A
  - Acrylic latex & TiO_2 powder
  - 32 %NVV
  - 25 PVC [TiO_2-15 & CC3 Filler-10]
  - Filler variations
    - 25 PVC [TiO_2-15 & Filler-10]
      - CC3 & TiO_2 hybrid, 1 micrometer (CT4)
    - 25 PVC [TiO_2-5, CC3-10 & CT4-10]
    - 25 PVC [TiO_2-5, CC3-5 & CT4-15]
    - 25 PVC [TiO_2-5, CC3-0 & CT4-20]
- Base formulation BF2B
  - Acrylic latex & TiO_2 powder
  - 32 %NVV
  - 25 PVC [TiO_2-10 & CC3 Filler-15]

	Base Formulation 2A		Exterior Semi-Gloss			
GRIND:			Formula		Non-Volatile	
% NV	lbs/gal	**Material**	Lbs	Gal	Lbs	Gal
0	8.33	**Water**	44.18	5.30	0.00	0.00
25	9.19	**Pigment Dispersant**	1.77	0.19	0.44	0.03
98.5	8.35	**Antifoamer**	0.15	0.02	0.15	0.02
9.25	8.80	**Biocide**	0.18	0.02	0.02	0.00
25	8.26	**High-Shear PU Thickener**	3.53	0.43	0.88	0.11
100	33.33	**Titanium Dioxide**	61.86	1.86	61.86	1.86
100	22.70	**Calcium Carbonate**	28.81	1.27	28.81	1.27
0	8.66	**Propylene Glycol**	3.53	0.41	0.00	0.00
75	9.07	**Non-Ionic Surfactant**	2.74	0.30	2.05	0.23
Grind Total			146.75	9.80	94.21	3.51
Pigment Total			90.66	3.12	90.66	3.12
LET-DOWN			Formula		Non-Volatile	
% NV	Lbs/Gal	**Material**	Lbs	Gal	Lbs	Gal
		Grind	146.75	9.80	94.21	3.51
0	8.33	**Water**	57.08	6.85	0.00	0.00
98.5	8.35	**Defoamer**	0.09	0.01	0.09	0.01
50	8.85	**Acrylic Latex**	167.72	18.95	83.86	8.88
25	8.26	**Low-Shear PU Thickener**	2.83	0.34	0.71	0.09
0	8.33	**Water**	21.21	2.55	0.00	0.00
0	7.93	**Coalescing Aid**	4.33	0.55	0.00	0.00
TOTAL			400.00	39.05	178.86	12.49
Paint properties						
Weight per gallon		**10.24**	**% NV by volume**		**32.00**	
% NV by weight		**44.71**	**PVC**		**25.01**	

Results – BF1, Nepheline Syenite

Filler	60° Gloss	85° Gloss	Contrast Ratio (3-mil)	Contrast Ratio (5-mil)
NS1	4.6	14.8	0.97	0.98
NS2	3.4	10.7	0.97	0.99
NS3	3.8	6.0	0.97	0.99
NS6	3.4	2.2	0.97	0.99



Surface Optics 410-Solar-i Reflectometer

Results – BF1, Calcium Carbonate

Filler	60° Gloss	85° Gloss	Contrast Ratio (3-mil)	Contrast Ratio (5-mil)
CC3	5.9	15.7	0.96	0.99
CC5	5.4	7.1	0.95	0.99
CC12	5.4	4.1	0.95	0.99

Filler	SRB (3-mil)	SRB (5-mil)	SRW (3-mil)	SRW (5-mil)
CC3	0.742	0.836	0.854	0.869
CC5	0.735	0.836	0.852	0.867
CC12	0.729	0.828	0.851	0.868

SRB – Solar Reflectance over black
SRW – Solar Reflectance over white

Formula ID List: BF2, $CaCO_3$ / TiO_2 Hybrid

Formulation ID	TiO_2 PVC	3μ $CaCO_3$ PVC	CT4 Hybrid PVC	Total PVC
T15CC310 [A]	15	10	0	25
T10CC315 [B]	10	15	0	25
T15CT410	15	0	10	25
T5CC310CT410	**5**	**10**	**10**	25
T5CC35CT415	**5**	5	**15**	25
T5CT420	**5**	0	**20**	25

Results – BF2, $CaCO_3$ – TiO_2 Hybrid

Formulation	L*	a*	b*	60	85	Contrast ratio
T15CC310 [A]	96.3	-0.35	3.7	34.6	65.0	0.96
T10CC315 [B]	96.1	-0.36	3.6	34.0	60.8	0.81
T15CT410	96.3	-0.36	3.7	22.3	62.5	0.97
T10CT415	96.0	-0.50	3.4	9.6	40.9	0.95
T5CC310CT410	95.0	-0.31	3.9	10.0	36.4	0.89
T5CC35CT415	95.0	-0.32	3.7	21.4	60.6	0.96
T5CT420	95.3	-0.29	3.8	10.6	38.3	0.92

Results – BF2, $CaCO_3$ – TiO_2 Hybrid

Formulation	SRB (3-mil)	SRB (5-mil)	SRW (3-mil)	SRW (5-mil)
T15CC310 [A]	0.736	0.823	0.861	0.877
T10CC315 [B]	0.712	0.802	0.863	0.875
T15CT410	0.758	0.829	0.864	0.879
T10CT415	0.721	0.856	0.808	0.872
T5CC310CT410	0.622	0.735	0.838	0.849
T5CC35CT415	0.633	0.742	0.839	0.855
T5CT420	0.668	0.762	0.844	0.859

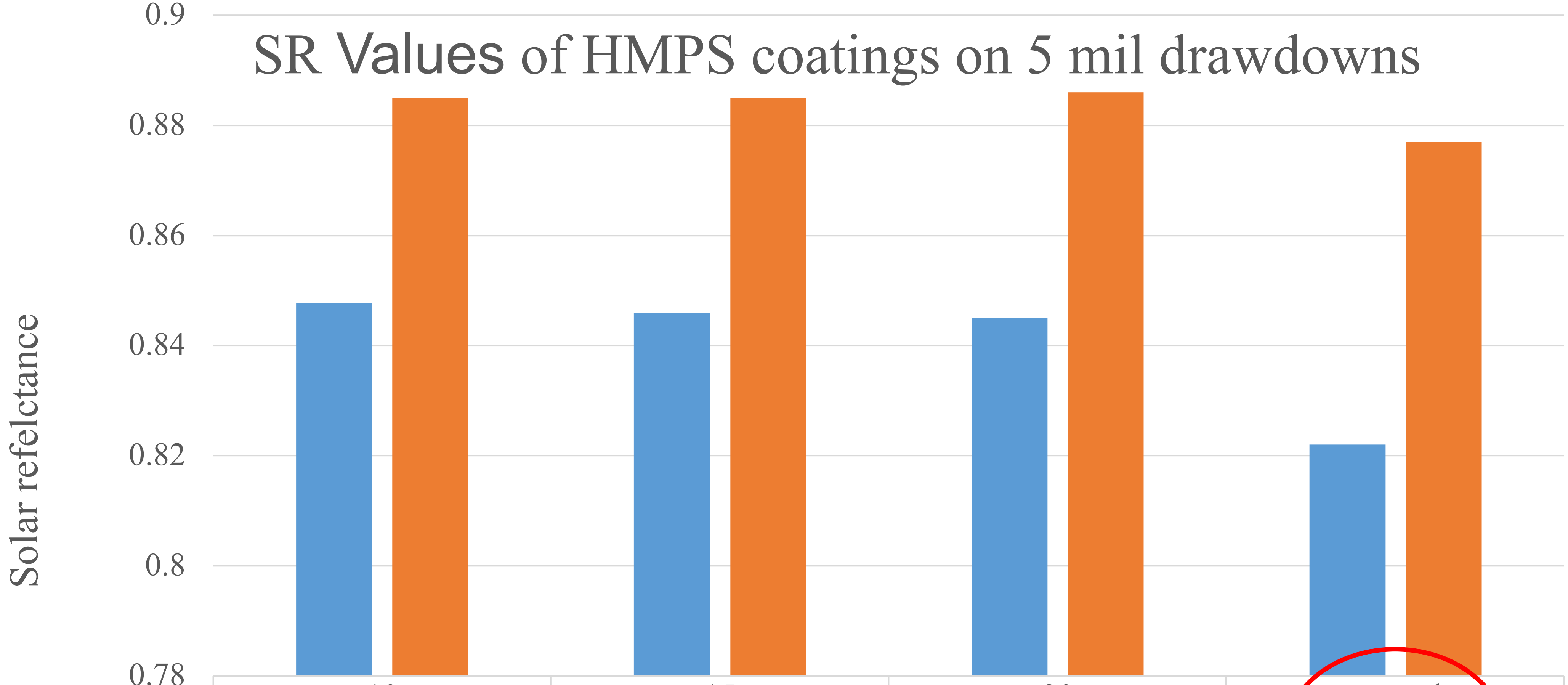
SRB – Solar Reflectance over black
SRW – Solar Reflectance over white

Results – BF2, $CaCO_3$ – TiO_2 Hybrid

Formulation	SRB (3-mil)	SRB (5-mil)	SRW (3-mil)	SRW (5-mil)
T15CC310 [A]	0.736	0.823	0.861	0.877
T10CC315 [B]	0.712	0.802	0.863	0.875
T15CT410	0.758	0.829	0.864	0.879
T10CT415	0.721	0.856	0.808	0.872
T5CC310CT410	0.622	0.735	0.838	0.849
T5CC35CT415	0.633	0.742	0.839	0.855
T5CT420	0.668	0.762	0.844	0.859

SRB – Solar Reflectance over black
SRW – Solar Reflectance over white

Hollow Microscopic Plastic Spheres



	10	15	20	control
SR over black	0.8477	0.846	0.845	0.822
SR over white	0.885	0.885	0.886	0.877

SR over black   SR over white

Hollow Plastic Microspheres

Formulation BF2	Solar Reflectance			
	3 mil films		5 mil films	
	Over Black	Over White	Over Black	Over White
T15CC310 [A]	0.735	0.861	0.822	0.877
T10CC315 [B]	0.712	0.863	0.802	0.875
10 PVC HMPS	0.756	0.864	0.847	0.885
15 PVC HMPS	0.754	0.864	0.846	0.885
20 PVC HMPS	0.749	0.864	0.845	0.886

BF2A: TiO_2 PVC=15 & $CaCO_3$ PVC = 10; BF2B: TiO_2 PVC=10 & $CaCO_3$ PVC = 15

Hollow Plastic Microspheres

Formulation BF2	Solar Reflectance			
	3 mil films		5 mil films	
	Over Black	Over White	Over Black	Over White
T15CC310 [A]	0.735	0.861	0.822	0.877
T10CC315 [B]	0.712	0.863	0.802	0.875
10 PVC HMPS	0.756	0.864	0.847	0.885
15 PVC HMPS	0.754	0.864	0.846	0.885
20 PVC HMPS	0.749	0.864	0.845	0.886

BF2A: TiO_2 PVC=15 & $CaCO_3$ PVC = 10; BF2B: TiO_2 PVC=10 & $CaCO_3$ PVC = 15

Hollow Glass Spheres

Formulation BF2	Solar Reflectance			
	3 mil films		5 mil films	
	Over Black	Over White	Over Black	Over White
T10CC315 [B]	0.712	0.863	0.802	0.875
30μ HGS	0.715	0.853	0.804	0.871
25μ HGS	0.711	0.852	0.841	0.878
20μ HGS	0.713	0.852	0.841	0.879

BF2B: TiO_2 PVC=10 & $CaCO_3$ PVC = 15

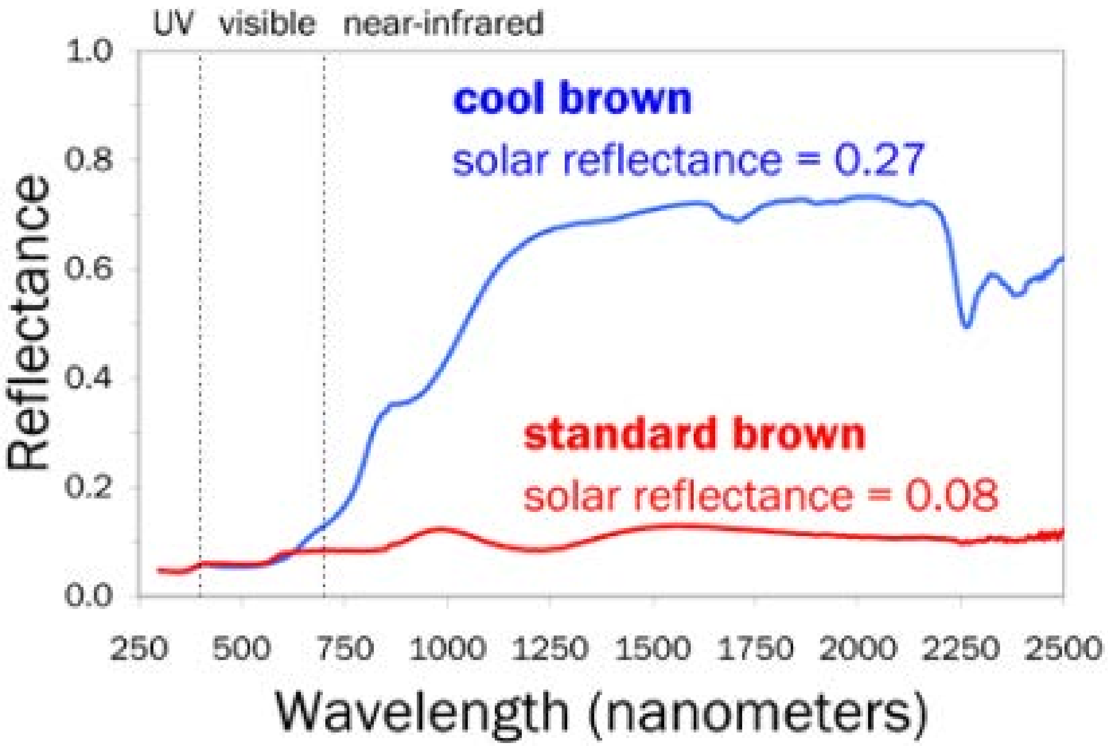
Hollow Glass Spheres

Formulation BF2	Solar Reflectance			
	3 mil films		5 mil films	
	Over Black	Over White	Over Black	Over White
T10CC315 [B]	0.712	0.863	0.802	0.875
30μ HGS	0.715	0.853	0.804	0.871
25μ HGS	0.711	0.852	0.841	0.878
20μ HGS	0.713	0.852	0.841	0.879

BF2B: TiO_2 PVC=10 & $CaCO_3$ PVC = 15

Black Pigments

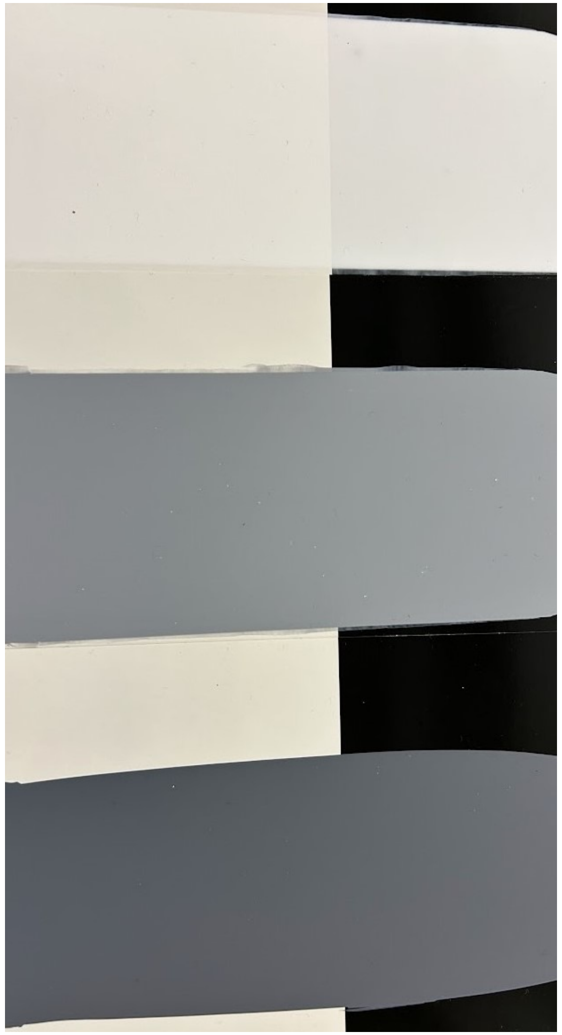
Pigment	Density (g mL^{-1})	Surface Area (m^2 g^{-1})
Carbon Black (CB)	1.4	
Calcium Titanium Manganese Oxide (CTMO)	4.1	2.7
Chromium Iron Oxide (CIO)	5.2	2.6



2006 "Cool Color Roofing Materials" H. Akbari, P. Berdahl, R. Levinson, S. Wiel, Heat Island Group, LBNL & B. Miller, A. Desjarlais, ORNL

Preparation of Tinted Films

Pigment	Grams per 100 g of tint base BF2[B] (PVC: 10 TiO_2 +15 $CaCO_3$)				
Carbon Black (CB)	1.25	2.5	5.0	-	-
Calcium Titanium Manganese Oxide (CTMO)	-	2.5	5.0	7.5	10.0
Chromium Iron Oxide (CIO)	-	2.5	5.0	7.5	10.0



Results: Carbon Black (CB)

Tint Base: BF2[B]

Grams of CB per 100g Tint Base	Wet Film Thickness (mil)	SRB	SRW	60°	85°	L*	a*	b*	CR
0	3	0.712	0.863	33.4	60.0	96.1	-0.4	3.6	0.81
	5	0.802	0.875	34.0	60.8	96.1	-0.4	3.6	0.86
	10	0.845	0.881	25.6	56.9	96.3	-0.4	4.2	0.99
1.25	3	0.306	0.309	18.9	45.8	65.9	-1.5	-1.5	1.00
	5	0.307	0.308	20.5	50.1	65.9	-1.5	-1.5	1.00
	10	0.308	0.307	21.5	50.9	65.9	-1.5	-1.5	1.00
2.50	3	0.226	0.226	19.8	51.0	60.4	-1.6	-2.2	1.00
	5	0.226	0.225	20.5	52.2	57.6	-1.6	-2.5	1.00
	10	0.226	0.226	21.4	52.5	57.7	-1.6	-2.5	1.00
5.00	3	0.151	0.151	16.7	47.4	47.1	-1.7	-3.5	1.00
	5	0.151	0.150	17.8	50.4	47.1	-1.7	-3.5	1.00
	10	0.151	0.151	18.6	51.7	47.2	-1.7	-3.5	1.00

Results: Calcium Titanium Manganese Oxide (CTMO)

Grams of CTMO per 100g Tint Base	Wet Film Thickness (mil)	SRB	SRW	60^o	85^o	L*	a*	b*	CR
2.50	3	0.420	0.484	17.9	48.9	58.0	-1.3	-3.6	1.00
	5	0.453	0.478	18.8	51.2	57.8	-1.3	-3.6	1.00
	10	0.465	0.470	19.4	52.3	57.8	-1.3	-3.6	1.00
5.00	3	0.372	0.414	15.7	48.1	48.8	-1.2	-4.4	1.00
	5	0.396	0.409	16.2	51.3	48.7	-1.2	-4.4	1.00
	10	0.406	0.408	16.9	52.4	48.6	-1.2	-4.5	1.00
7.50	3	0.355	0.386	13.9	47.4	44.4	-1.1	-4.7	1.00
	5	0.373	0.381	14.5	50.0	44.3	-1.1	-4.7	1.00
	10	0.380	0.381	15.0	50.3	44.3	-1.1	-4.7	1.00
10.0	3	0.339	0.363	12.4	45.5	40.8	-0.9	-4.7	1.00
	5	0.354	0.359	12.7	47.2	40.6	-0.9	-4.8	1.00
	10	0.360	0.360	13.4	48.5	40.6	-0.9	-4.8	1.00

Results: Chromium Iron Oxide (CIO)

Grams of CIO per 100g Tint Base	Wet Film Thickness (mil)	SRB	SRW	60°	85°	L*	a*	b*	CR
2.5	3mil	0.426	0.478	17.1	49.2	63.9	-1.4	-3.4	0.98
	5mil	0.455	0.473	17.3	50.0	64.0	-1.4	-3.3	0.99
	10mil	0.468	0.474	18.6	49.2	64.2	-1.4	-3.3	0.99
5	3mil	0.363	0.396	14.5	46.4	55.2	-1.4	-4.4	1.00
	5mil	0.383	0.394	14.8	48.1	55.4	-1.4	-4.3	0.99
	10mil	0.393	0.395	15.3	47.8	55.6	-1.4	-4.3	1.00
7.5	3mil	0.332	0.359	12.9	45.5	50.3	-1.4	-4.8	1.00
	5mil	0.349	0.356	12.8	46.2	50.5	-1.3	-4.7	1.00
	10mil	0.355	0.357	13.4	46.3	50.7	-1.4	-4.7	1.00
10	3mil	0.311	0.333	11.3	43.3	46.9	-1.3	-5.0	1.00
	5mil	0.326	0.331	11.1	43.4	47.0	-1.3	-4.9	1.00
	10mil	0.329	0.331	11.5	43.3	47.2	-1.3	-4.9	1.00

Key Observations

- Gloss of all films is lower than gloss of tint base
- Slight increase of gloss as thickness increases
  - Surface binder enrichment
- All tinted films have perfect contrast ratio
- Films with similar L* values have similar gloss values as well

What about solar reflectance?

Comparison of Solar Reflectance at Similar L*

g per 100g of Tint Base	Wet Film Thickness (mil)	SR Over Black	SR Over White	L*
CB 1.25	3	0.306	0.309	65.9
	5	0.307	0.308	65.9
	10	0.308	0.307	65.9
CIO 2.5	3	0.426	0.478	63.9
	5	0.455	0.473	64.0
	10	0.468	0.474	64.2

Comparison of Solar Reflectance at Similar L*

g per 100g of Tint Base	Wet Film Thickness (mil)	SR Over Black	SR Over White	L*
CB 2.5	3	0.226	0.226	60.4
	5	0.226	0.225	57.6
	10	0.226	0.226	57.7
CTMO 2.5	3	0.420	0.484	58.0
	5	0.453	0.478	57.8
	10	0.465	0.470	57.8
CIO 5.0	3	0.363	0.396	55.2
	5	0.383	0.394	55.4
	10	0.393	0.395	55.6

Comparison of Solar Reflectance at Similar L*

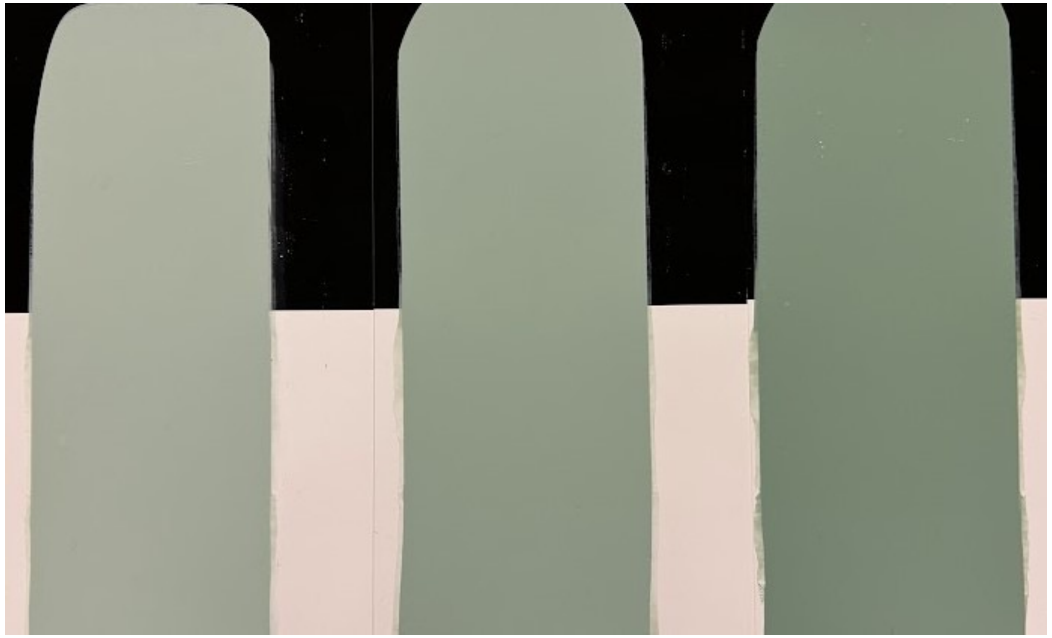
g per 100g of Tint Base	Wet Film Thickness (mil)	SR Over Black	SR Over White	L*
CB 5.0	3	0.151	0.151	47.1
	5	0.151	0.150	47.1
	10	0.151	0.151	47.2
CTMO 5.0	3	0.372	0.414	48.8
	5	0.396	0.409	48.7
	10	0.406	0.408	48.6
CIO 10.0	3	0.311	0.333	46.9
	5	0.326	0.331	47.0
	10	0.329	0.331	47.2

Conclusions

- Results of this study indicate, within the range of variables examined,
  - Particle size of nepheline syenite affects the solar reflectance; larger particles provide a small increase in solar reflectance
  - Particle size of calcium carbonate does not affect the solar reflectance
- Results of the calcium carbonate – titanium dioxide hybrid materials point to possibility of enhancing both solar reflectance and hiding
- Hybrid pigments can provide small increases of SR
- Hollow spherical materials provide greater increases in SR
- IR reflective black pigments provided the highest increase in SR

Future Work

- Additional colors
- Optimum film thickness
- Energy savings calculations
    - eQuest? Other?



Acknowledgements

- Coating raw material suppliers
- Golden Gate Society for Coatings Technology
- Cool Roof Rating Council
- Kenneth N Edwards Western Coatings Technology Center

Zacharie Danega

Olivia Everitt

Wally Kesler

Lia Roccucci

Soroush Arjomandi