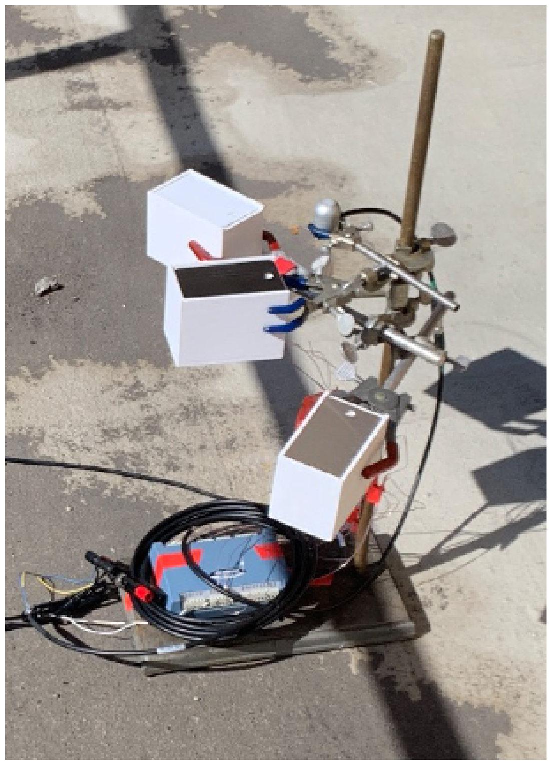
Thermal Test Stand

Colby Snyder 2023



During downtime between battery experiments in 2023, I started another materials research project based on my interest in the urban heat island effect. Without a graduate student to mentor me on this project, I had complete ownership of experimental design. My goal was to assess the real-world performance of roof coating materials that performed well in laboratory environments, but we didn't have an apparatus for these types of tests. To solve this problem quickly, I built my own thermal test stand that measures polymer coatings' response to solar irradiation.

Figure 1: Penn's Energy Week Lightning Talk Competition, where I delivered a winning presentation on my urban heat work.

Problem Definition

The core challenge was to create an apparatus that precisely measured roof surface temperatures while controlling for environmental variables.

Quantity of interest: Roof surface temperature
Independent variable: Roof coating material
Controls:

- Solar intensity (both natural and artificial sources)
- Ambient temperature (convective heat transfer to heat environment)
- Ambient humidity (affects heat transfer coefficient and radiative cooling)
- Solar angle of incidence
- Test stand surface temperature (conductive heat transfer to test environment)
- Substrate for coating

Assumptions:

- Linear heat transfer over thin polymer coatings (less than 30µm)
- No significant wind, small breezes and drafts approximated as $0.1 m/s$.
- Uniform solar intensity over test area
- No heat transfer between insulated clamps, model walls, and roof substrate

Design

I iterated through several designs to maximize precision and ease of use. Major decisions included:

1. **Experimental controls:**

- Integrated solar intensity measurement through a pyranometer to confirm constant radiation exposure from a heat lamp across all samples.
- The lab was maintained at a constant ambient temperature and roughly constant ambient humidity.
  - An earlier attempt to control humidity was placing supersaturated $MgNO_3$ salt solutions near the apparatus (fixed equilibrium relative humidity around 53%), but this didn't show significant improvements over no control.
- A heat lamp was positioned directly overhead (normal) to represent conditions at solar noon. The angle was adjusted until a maximum reading on the (leveled) pyranometer, which is affected by the angle of incidence, was obtained.
- The test enclosures were suspended by insulated ring stand clamps. With very small contact areas and a low thermal conductivity (silicone rubber, $k = 0.2\,W/m \cdot K$), conductive heat transfer through the test stand could be assumed to be zero.
- Smooth aluminum "Q-Panel" substrates commonly used in the paints and coatings industries were selected. This selection facilitates uniformly-thick application, and the high thermal conductivity of aluminum helps reach steady-state faster.

2. **Addressing outdoor challenges with controls:**

- Since solar intensity could not be controlled outdoors, the pyranometer was used to constantly log data. For outdoor tests (uncontrolled radiation), this data could be used to normalize temperature results by radiative heat flux.
- A similar observational approach was taken for ambient temperature. A type T thermocouple was placed under a radiation shield outside of the test enclosures to measure air temperature, and the building's rooftop weather station was used for humidity.
  - An earlier attempt to measure humidity was using an Arduino RH probe, but this was highly susceptible to local disturbances.
- Experiments were conducted around solar noon (+/- 1 hour) to ensure near-normal angles of incidence.

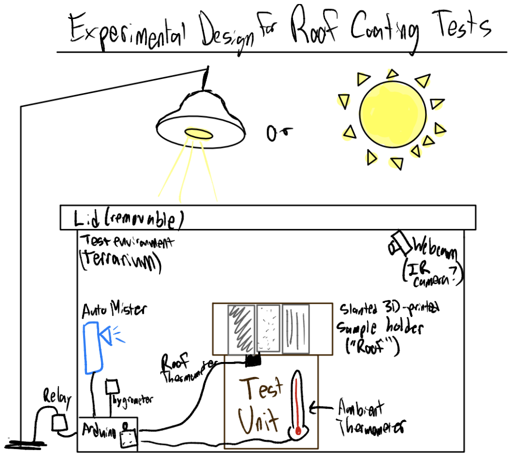
3. **Accurately recording roof temperatures**

- Several options for temperature measurement were considered, including large Arduino-powered air temperature sensors, RTD probes, IR cameras, and thermocouples.
- Small thermocouples were chosen for their ability to respond quickly to changes in temperature without significantly affecting the overall system temperature.
- RTD probes and Arduino sensors were discarded due to their relatively high thermal masses, which could impact the system and produce inaccurate data.
- Type T thermocouples were selected for their accuracy at low (natural) temperatures in the 20ºC–100ºC range and their resistance to oxidation in the presence of moisture.

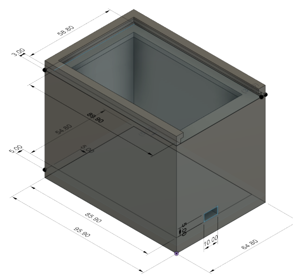
4. **Enclosure dimensions for high-throughput experimentation**

- Before the 3D-printed box, some laboratory experiments took multiple hours to reach steady state. This was unacceptable because it reduced our decision-making rate and exposed samples to more solar variability over the data collection period.

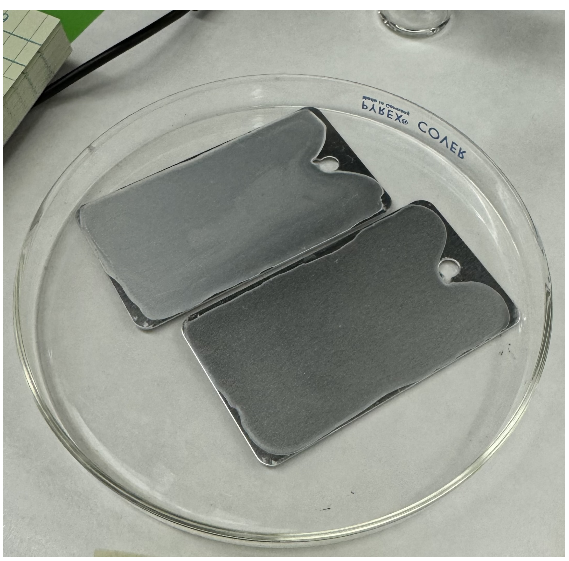
- Goal: Design a model house to reach thermal steady-state in approximately 90 minutes.
- The base of the rectangular prism was constrained to 95x65 mm to accommodate the Q-Panel substrate, so I tuned the thermal mass and surface area by varying the height of the enclosure.
- Using an iterative MATLAB script (calculations in appendix), I identified the optimal height as 60 mm.



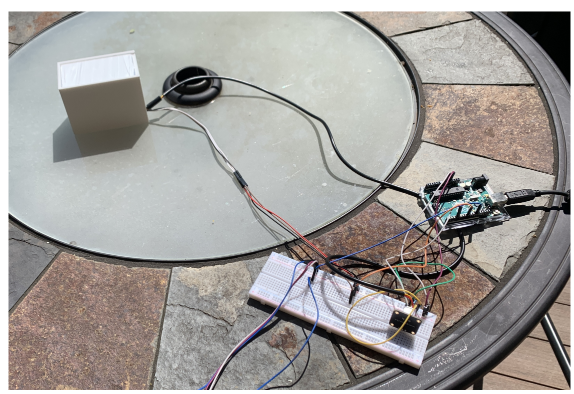
(a) First sketch of a climate-controlled roof testing system



(b) Fusion360 CAD design of simple model "house" enclosure with openings for wires and roof



(c) Preparing aluminum substrates



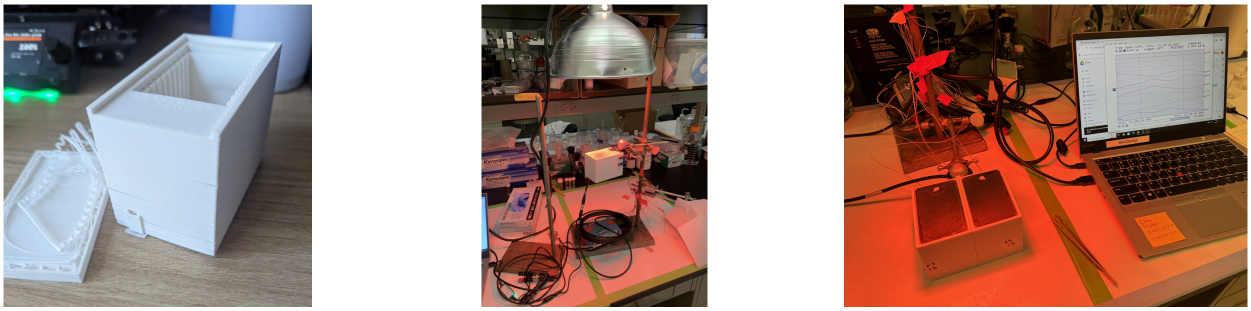
(d) Arduino proof-of-concept system

Figure 2: Early concepts for the thermal test stand

Build

I 3D-printed the model house enclosures from white ASA filament using a Prusa MK4 printer. The material was selected using a decision matrix that considered heat deflection and glass transition temperatures, outdoor durability, and printability. ASA was ultimately selected because of its relatively high heat deflection temperature of 86°C (high for a printable thermoplastic), its enhanced durability (chemical and warping resistance) versus alternatives like ABS, and its UV resistance (important for outdoor tests). The white color was important to ensure minimal heat was absorbed by the model house, since I wanted to isolate the effects of radiation on the roof coatings.

After printing the enclosures, I installed the thermocouples in each enclosure, one contacting the roof and one measuring the internal air temperature, and an additional ambient temperature thermocouple was installed outside as previously described. The model houses and pyranometer were suspended on a ring stand, leveled, and connected to a data acquisition device for testing.



(a) Unsuccessful 3D-printing attempt due to old ASA filament

(b) First full indoor apparatus with a successful 3D-printed enclosure

(c) Data acquisition with TracerDAQ

Figure 3: Building the test stand

Collect and Analyze Data

- I used an Omega data acquisition device to accept analog thermocouple inputs.
- Measured temperatures at 0.25 Hz and exported the time-series data using TracerDAQ software.
- After collecting the data, I calculated 30-second moving averages in Python to smooth over granular disturbances from wind and other sources and plotted my results.
- During tests with a polymer coating last spring, the time to reach steady-state ranged from 60 minutes to just over 90 minutes, corresponding to the target from my preliminary height calculations.

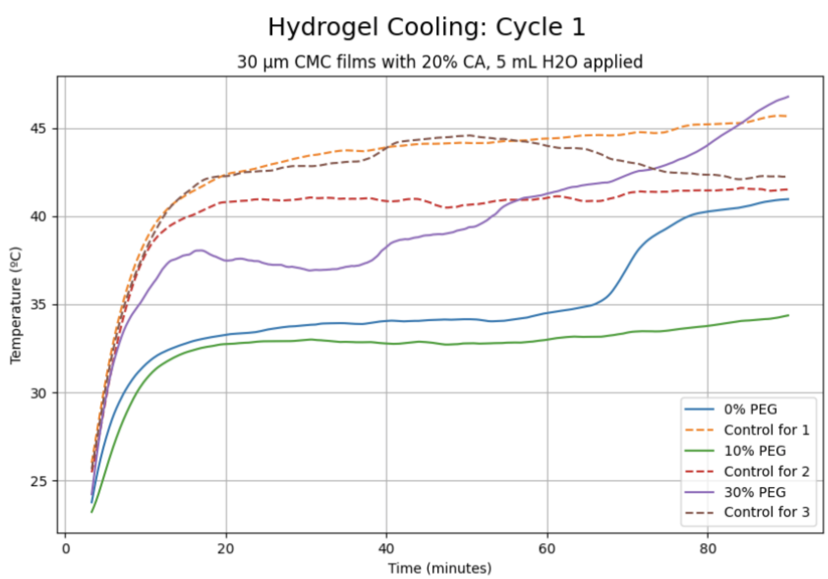


Figure 4: Example of results from the test stand. The solid lines represent cool coatings and the dashed lines are commercially-available controls.

Complete

Today, the test stand is used for ongoing cool roof coating research. It's been used to evaluate radiative cooling paints, evaporative cooling hydrogels, and more. By enabling multiple tests to proceed in parallel and outputting data in an easy-to-process manner, I've accelerated test throughput over 6x from my initial prototype.

Appendix: Thermal Test Stand Height Calculation

I wanted to estimate the necessary height h of a model house enclosure to reach steady state in approximately 90 minutes. The enclosure is made of ASA with an aluminum roof and will be placed outside at noon starting at 25°C. It has a base of 95 mm × 65 mm, ASA walls of 5 mm thickness (on five faces), and an aluminum roof (substrate for polymer coatings) of 1 mm thickness. The specific heat capacities and densities of ASA and aluminum are given.

Known Values

- Base dimensions: L = 95 mm, W = 65 mm
- Wall thickness (ASA): $t_{\mathrm{ASA}} = 5\,\mathrm{mm} = 0.005\,\mathrm{m}$
- Roof thickness (Aluminum): $t_{\mathrm{Al}} = 1\,\mathrm{mm} = 0.001\,\mathrm{m}$
- Starting temperature: $T_0 = 25\,^\circ\mathrm{C}$
- Ambient temperature: $T_\infty = 25\,^\circ\mathrm{C}$
- Specific heat capacities: $c_{\mathrm{ASA}} = 1300\,\mathrm{J/(kg \cdot K)}, c_{\mathrm{Al}} = 900\,\mathrm{J/(kg \cdot K)}$

Assumptions

1. Lumped-system analysis is applicable
2. Air properties: Prandtl number $\mathrm{Pr} = 0.707$, air velocity $v = 0.1\,\mathrm{m/s}$
3. Nusselt number: Nu = 22.13 based on laminar flow regime, natural convection, Reynold's number corresponding to 0.1 m/s air, and Prandtl number for air
4. Steady state approximated as 3τ, so $3\tau \approx 5400\,\mathrm{s}$
5. The characteristic length is approximately equal to the height h (to speed up MATLAB code).
6. The convective heat transfer coefficient h_{conv} can be estimated using the Nusselt number:
$$h_{\mathrm{conv}} = \frac{\mathrm{Nu} \cdot k_{\mathrm{air}}}{h}$$
7. The time constant τ is given by:
$$\tau = \frac{mc_p}{h_{\mathrm{conv}} A_s}$$
where m is the mass of the enclosure, c_p is the specific heat capacity (weighted average), and A_s is the surface area through which heat transfer occurs.

Iterative Solution using MATLAB

Step 1: Initial Guess of Height $h = 39\,\mathrm{mm} = 0.039\,\mathrm{m}$

1a. Calculate Surface Area, Volume, Mass, and Thermal Capacity

Surface Area A_s:

$$A_s = 2(Lh + Wh) + LW$$

$$A_s = 2(0.095 \times 0.039 + 0.065 \times 0.039) + 0.095 \times 0.065 = 0.018\,655\,\mathrm{m}^2$$

Volume and Mass of ASA Walls: Volume of side walls:

$$V_{\text{walls}} = 2(Lht_{\text{ASA}} + Wht_{\text{ASA}}) = 2(0.095 \times 0.039 \times 0.005 + 0.065 \times 0.039 \times 0.005) = 6.24 \times 10^{-5}\,\text{m}^3$$

Volume of base:

$$V_{\text{base}} = LWt_{\text{ASA}} = 0.095 \times 0.065 \times 0.005 = 3.0875 \times 10^{-5}\,\text{m}^3$$

Total volume of ASA:

$$V_{\text{ASA}} = V_{\text{walls}} + V_{\text{base}} = 9.3275 \times 10^{-5}\,\text{m}^3$$

Mass of ASA:

$$m_{\text{ASA}} = \rho_{\text{ASA}} V_{\text{ASA}} = 1100 \times 9.3275 \times 10^{-5}\,\text{m}^3 = 0.1026\,\text{kg}$$

Volume and Mass of Aluminum Roof: Volume of roof:

$$V_{\text{Al}} = LWt_{\text{Al}} = 0.095 \times 0.065 \times 0.001 = 6.175 \times 10^{-6}\,\text{m}^3$$

Mass of aluminum:

$$m_{\text{Al}} = \rho_{\text{Al}} V_{\text{Al}} = 2700 \times 6.175 \times 10^{-6}\,\text{m}^3 = 0.016\,67\,\text{kg}$$

Total Mass and Thermal Capacity: Total mass:

$$m = m_{\text{ASA}} + m_{\text{Al}} = 0.1026\,\text{kg} + 0.016\,67\,\text{kg} = 0.119\,27\,\text{kg}$$

Total thermal capacity:

$$C = m_{\text{ASA}} c_{\text{ASA}} + m_{\text{Al}} c_{\text{Al}} = (0.1026 \times 1300) + (0.01667 \times 900) = 148.39\,\text{J/K}$$

1b. Calculate Convective Heat Transfer Coefficient h_{conv}

Assuming $k_{\text{air}} \approx 0.0262\,\text{W/(m}\cdot\text{K)}$ at $25\,°\text{C}$:

$$h_{\text{conv}} = \frac{\text{Nu} \cdot k_{\text{air}}}{h} = \frac{22.13 \times 0.0262}{0.039} = 14.87\,\text{W/(m}^2\cdot\text{K)}$$

1c. Calculate Time Constant τ

$$\tau = \frac{C}{h_{\text{conv}} A_s} = \frac{148.39}{14.87 \times 0.018655} = 535\,\text{s}$$

1d. Iteration

Since $\tau = 535\,\text{s}$ is much less than the desired $\tau = 1800\,\text{s}$, we increase the height h and repeat the calculations. Using the MATLAB script below, I converged on h = 60 mm.

Conclusion

At $h = 60.0\,\text{mm}$, the time constant τ is approximately $1799.1\,\text{s}$, satisfying the condition $3\tau \approx 5400\,\text{s}$ (or 90 minutes). Therefore, the required height of the enclosure is:

$$\boxed{h = 60\,\text{mm}}$$

Appendix: MATLAB Code

MATLAB Code for Thermal Calculations

```matlab
% Given data and constants
Ta = 25 + 273.15; % ambient temperature in K (converted from C)
h_guess = 0.039;  % initial guess for height in m
h = h_guess;      % initialize height for iteration

% Air properties (from pseudocode)
air_properties = struct('nu', 15.89e-6, ...  % kinematic viscosity
    'alpha', 22.35e-6, ...  % thermal diffusivity
    'Pr', 0.707, ...        % Prandtl number for air
    'k', 0.026);            % air conductivity

% Other necessary material properties
c_aluminum = 900; % specific heat of aluminum
c_ASA = 1300;     % specific heat of ASA
rho_aluminum = 2700; % density of aluminum
rho_ASA = 1100;      % density of ASA

% Base dimensions of the box
l = 0.065; % 65 mm in m
w = 0.095;  % 95 mm in m

% Thickness of the materials
thickness_aluminum = 0.001; % top face is 1 mm thick
thickness_ASA = 0.005;      % other 5 faces are 5 mm thick

% Solar radiation incident on the top face
q_solar = 1000;

% Time constant target (1800 seconds = 30 minutes)
target_time_constant = 1800;
tau = 0;

% Start loop to adjust height until time constant is close to 1200 s
while (abs(tau - target_time_constant) > 1 && h < 1)  % Limit h to avoid
    excessive height
    h = h + 0.00001; % smaller increment for height (0.1 mm)

    % Calculate surface area and volume based on current height
    surface_area = 2*(l * w + l * h + w * h);
    v_ASA = l * w * h; % volume of the ASA box (without top)

    % Calculate mass and thermal capacitance for ASA material
    mass_ASA = v_ASA * rho_ASA;
    C_ASA = mass_ASA * c_ASA; % thermal capacity of ASA

    % Calculate mass and thermal capacitance of the aluminum top plate
    mass_aluminum = l * w * thickness_aluminum * rho_aluminum;
    C_aluminum = mass_aluminum * c_aluminum; % thermal capacity of aluminum

    C_total = C_ASA + C_aluminum;

    % Use height as the characteristic length (Lc = h)
    Lc = h;

```

```
    % Calculate convection coefficient h
    h_conv = ConvectionCoefficient(Ta + 20, Ta, Lc, air_properties); % Assume 20
        above ambient

    % Calculate time constant
    tau = time_constant(C_total, h_conv, surface_area);

    % Display time constant and height for debugging
    fprintf('Time constant: %.2f seconds\n', tau);
end

% Output results
fprintf('Final height: %.4f meters\n', h);
fprintf('Final time constant: %.2f seconds\n', tau);



% Time constant function
function tc = time_constant(C, U, A)
    % Calculate time constant (tc) based on total thermal capacity (C),
    % convection coefficient (U), and total area (A)
    tc = C / (U * A);
end

% Convection coefficient function
function h = ConvectionCoefficient(T_surface, T_ambient, L, air_properties)

    % Assume Nusselt number for slight breeze in air (0.1 m/s, Pr=0.707, laminar)
    Nu = 22.13;

    % Calculate convective heat transfer coefficient h
    h = Nu * air_properties.k / L;

    % Display result for debugging
    fprintf('Convective heat transfer coefficient h: %.4f W/m^2 K \n', h);
end
```