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A Report

On

Thermal Analysis & Design Strategy for

Batteries used in High-Performance Electric Vehicles

Case Study of the Tesla Model S Plaid

BY

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1 Technical Specifications: Tesla Model S Plaid

The vehicle selected for this project, which involves thermal analysis and design of cooling system of battery pack is the 2022-23 Tesla Model S Plaid. The Model S Plaid is a unique engineering case study as it uses an older cell type, ie. 18650 cells to achieve a peak power of a massive 1,020 hp, prioritizing thermal surface area over volumetric density.

1.1 Battery Pack Architecture

Parameter	**Specification**	**Inference**
Battery Capacity	100 kWh	A significant boost from the 85 kWh offered by the previous Model S [1].
Pack Voltage	407 V Nominal	Peak voltage of 400+ V is achieved primarily by the high voltage of the 110 cells arranged in series.
Cell Configuration	110S72P	The 110 cells in series achieves the 400V+ requirement. The 72 cells in parallel reduce the load per cell to manageable levels during peak power demand. Total number of cells = 110x72 = 7,920 Panasonic 18650 cells, each with a resistance of 25mΩ [1].
Cell Chemistry	NCA	Cathode: Nickel-Cobalt-Aluminum. Anode: Graphite. NCA is chosen for its superior specific power and energy density, which is critical for a high-performance sedan such as the Model S Plaid [3].
Operating Temperature	20°C to 55°C	20–35°C for longevity. When the car is in track mode, battery pack is preconditioned to 50°C to lower internal resistance for maximum power output [4].
Charging Power	250 kW Peak	Max C rate: 2-3C [2].
Vehicle Profile	High-Performance Sedan	The Model S Plaid is high-performance owing to its 1,000+ hp peak power. Can be used on city roads (regenerative braking recovers energy), on the track (requires sustained high-C discharge) and on highways (low drag for range efficiency) [4]

Table 1: Battery Pack Architecture of Tesla Model S Plaid

1.2 Interpretation of Design Choices

Unlike most other EVs like the Tesla Model 3 which use larger cells like 2170 or 4680, the Tesla Model S Plaid uses the comparatively smaller 18650 cell type. This is mainly to facilitate easier and more efficient thermal management choice. Smaller cells, such as the Panasonic 18650 have a higher Surface area-to-Volume ratio, allowing heat to be extracted from the core of the cell to the cooling coolant more rapidly than in larger cells. This minimizes the thermal gradient inside the cell during the Plaid's extreme 1,000+ horsepower acceleration runs [1].

The Model S Plaid utilizes NCA (Nickel-Cobalt-Aluminium) chemistry in its battery pack because the Aluminium dopant stabilizes the lattice structure during deep discharge cycles, allowing for a high gravimetric energy density of 253 Wh/kg [3]. Although LFP (Lithium-Iron-Phosphate) chemistry is safer and cheaper, its lower gravimetric energy density would make the 100kWh pack too heavy for a performance vehicle targeting a sub-2.0 second 0-60 mph time [3].

2 Thermal Analysis & Heat Generation Model

2.1 Methodology

The thermal behavior of the Tesla Model S Plaid battery pack was simulated using a lumped heat capacitance model. This approach assumes that the battery pack acts as a single thermal mass wherein temperature at all points is a constant at any instant. While being on the simpler side, this is a valid first-order approximation for the Model S Plaid because its highly conductive vertical cooling ribbons minimize internal thermal gradients, implying that all points are more or less at the same temperature [4].

Key Assumptions:

1. Uniform Temperature Distribution
2. Dominant Joule Heating
3. Constant Thermophysical Properties
4. Adiabatic Boundaries

Governing Equations:

1. **Heat Generation:** The heat generated is because of Joule's heating in which the primary source of heat is the internal resistance of the cells:

$$Q_{gen} = I^2 \cdot R_{internal}$$

2. **Heat Removal:** The heat removed is governed by Newton's law of cooling, in which the rate of heat rejection depends on the temperature difference between the battery pack and the liquid coolant, governed by the overall heat transfer coefficient (U):

$$Q_{cooling} = UA \cdot (T_{pack} - T_{coolant})$$

3. **Energy Balance:** In the lumped heat capacitance model, the fundamental energy balance equation states that the rate of change of internal energy is equal to the net heat generation minus heat removal:

$$m \cdot C_p \cdot \frac{dT}{dt} = Q_{gen} - Q_{cooling}$$

4. **Iterative Plotting of Temperature:** To plot the temperature over time, the finite difference method is used to simplify the above energy balance equation.

Approximating the derivative as $\frac{dT}{dt} \approx \frac{T_{new}-T_{old}}{dt}$ and rearranging terms yields the update rule for each time step (dt):

$$T_{new} = T_{old} + \frac{(Q_{gen} - Q_{cooling}) \cdot dt}{m \cdot C_p}$$

This logic allows us to visualize the cumulative effect of heat generation versus heat rejection over the 30-minute drive cycle.

2.2 Simulation Parameters

The following parameters were used in the MATLAB simulation to compute the heat generated in the battery pack and plot the temperature vs time plot during different drive modes. Based on teardown data [1] and cell chemistry properties [5]:

- **Pack Mass (m): 479 kg**. Verified from parts catalog (Cells + Modules) [1].
- **Specific Heat (C_p): 850 J/kg·K**. Weighted average for NCA cylindrical cells [5].
- **Pack Resistance (R): 0.038** Ω. Derived from cell configuration: $(0.025 \times 110)/72$.
- **Cooling Coefficient (UA): 1200 W/K**. Estimated heat transfer capability.

2.3 Results & Interpretation

Three distinct scenarios, namely highway cruise, charging and track were simulated to compute heat generated and evaluate thermal risk. The results highlight the non-linear nature of Joule heating (I^2R), wherein doubling the current quadruples the heat.

1. **Highway Cruise :**
   - Assume speed = 120 kph
   - **Load:** Around 22 kW continuous power (sum of power required to overcome drag, rolling friction and auxiliary loads)
   - **Current:** 55 A (Simulated constant load)
   - **Heat Generation:** $Q = (55)^2 \times 0.038 =$ **115W**
   - **Inference:** At cruising speeds, the heat generated is very small. From Figure 1, it can be seen that the temperature rise is negligible ($< 1°C$). Therefore, low thermal risk exists.

2. **Charging :**

   - **Load:** 250 kW peak from Table 1
   - **Current:** $I = 350A$
   - **Heat Generation:** $Q = (350)^2 \times 0.038 = \mathbf{4.66kW}$
   - **Inference:** 4.66 kW is a significant heat load. Without heat rejection, the battery pack would heat up significantly. A considerable amount of thermal risk which warrants the need of an appropriate thermal management system.

3. **Track :**

   - Aggressive mode of driving, ie. repeated 0-100 kph launches
   - **Load:** Peak power is 760 kW, but the Root Mean Square (RMS) current for thermal calculation is estimated at 1,000 A.
   - **Heat Generation:** $Q = (1000)^2 \times 0.038 = \mathbf{38.00kW}$.
   - **Inference:** Clearly, this is the critical design case as maximum heat is generated in this mode. Generating 38 kW of waste heat creates a rapid temperature rise. As shown in Figure 1, the temperature slope is steep, causing the pack to reach thermal throttling limits ($\approx 55°C$) very quickly if the cooling system cannot reject heat at an equivalent rate. Therefore, this thermal risk in this driving mode is maximum.

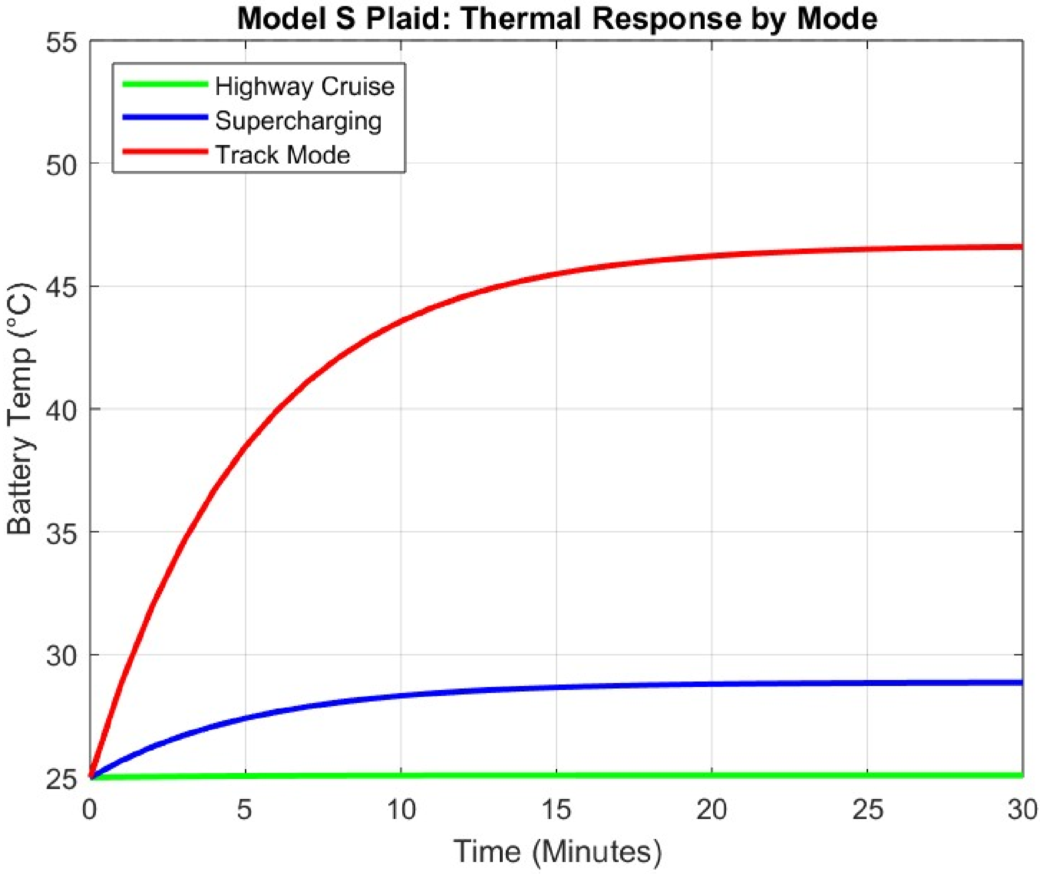

Figure 1: Temp. vs time plot for the battery pack in different drive modes

Scenario	Current (A)	Heat Gen (kW)	Max Temp (C)
Highway Cruise	55 A	0.11 kW	25.1 C
Supercharging	350 A	4.66 kW	28.9 C
Track Mode	1000 A	38.00 kW	46.6 C

Figure 2: Computed Heat Generation values from MATLAB simulation

3 Thermal Management Strategy

3.1 Glycol-based Liquid Cooling

As mentioned earlier, the prime design criterion for the thermal management system is to effectively counteract the 38 kW of heat generated in the track drive mode. Therefore, to manage this massive amount of heat, an Active Liquid Cooling approach using a 50/50 Ethylene Glycol and Water (EGW) mixture as the required coolant is selected. This aligns with the current industry standard for high-performance EVs [7].

Alternatives such as the following were rejected because:

- **Forced convection with air as working fluid:** The convective heat transfer coefficient (h) is too low to manage 38kW in a confined space.
- **Direct expansion of refrigerant:** Ensuring uniform refrigerant evaporation across all 7,920 individual cells is complex to design.

3.2 Heat Flow Path

The heat rejection path follows a thermal resistance network logic. The path is modeled as follows:

1. **Generation:** Heat is generated inside the battery pack.
2. **Internal Conduction:** Heat moves radially outward, from the cell center to the battery pack's outer casing.
3. **Interface:** Heat conducts through the potting compound (acts as a thermal interface) material to the cooling tube's outer wall carrying the EGW coolant.
4. **Convection:** Heat transfers from the tube's wall into the moving EGW coolant.
5. **Advection:** The pump circulates the now-hot EGW coolant out of the pack to the radiator.
6. **Rejection:** Heat is rejected from the radiator surface to the ambient air.

3.3 Geometry & Layout

1. Geometry: Vertical Cooling Ribbons

- Vertical Cooling Ribbons are serpentine channels that are in contact with each individual 18650 cell used in the battery pack.
- This particular geometry is chosen because cylindrical cells such as the 18650 used in the Tesla Model S Plaid have poor thermal conductivity along their height but better conductivity radially. Ribbons therefore provide a two-fold advantage for heat rejection. Firstly, they cool the sides of the cell, providing a large surface area for heat transfer. And secondly, a short thermal path for the heat to escape [1].

2. Flow Layout: Parallel Manifolds

- The cooling system uses a parallel flow of EGW coolant for the efficient heat rejection in individual cells.
- If EGW coolant is made to run in a single long line (series configuration), the fluid would be boiling hot by the time it reached the last cells which is naturally undesirable. Parallel flow of the coolant ensures every module gets fresh, cool EWG at the same temperature.

3.4 Relevant Calculations

Fluid Properties of EWG:

- Density: 1050 kg/m^3
- Specific Heat: 3440 J/kgK

Required Flow Rate: In order to keep the temperature difference across the pack low (assume $5°C$), required mass flow rate of the EWG coolant:

$$\dot{m} = \frac{Q_{max}}{C_p \cdot \Delta T} = \frac{38000}{3440 \cdot 5} = 2.21 \ kg/s$$

Using the density, the volume flow rate of the coolant is approximately 126 Liters/minute indicating that a high-performance automotive pump is required for proper circulation.

4 Future Battery Technology: Solid-state vs Li-ion

Solid-State Batteries or SSBs represent a significant shift in electrochemical storage architecture. Unlike conventional Lithium-ion or Li-ion batteries that use liquid organic electrolyte like lithium hexafluorophosphate (a salt) in carbonate solvents, SSBs a solid electrolyte material composed of ceramics, sulphides, or polymers. This change of electrolyte material is critical as it enables the replacement of the traditional porous graphite anode, as seen in Li-ion batteries with a pure Lithium-metal anode seen in modern-day SSBs thereby unlocking higher chemical potential and energy storage capacity [11].

There is high potential for SSBs to replace currently used Li-ion batteries in mobility applications. This is driven by three major advantages. Firstly, since SSBs use lithium-metal anodes, they can achieve gravimetric energy densities exceeding a whopping 500 Wh/kg, which is roughly double that of the best Li-ion batteries currently in production. Practically, this implies that the driving range of an EV with SSBs is nearly double than that with Li-ion batteries, despite both packs weighing equal [9]. Secondly, from a safety perspective, the absence of flammable liquid electrolytes in SSBs greatly reduces the chance of thermal runaway fires. This is important in making the battery safer under crash or puncture conditions. Furthermore, the thermal stability of solid electrolytes allows for higher operating temperatures, potentially enabling 0-80% charge times in under 10 minutes without the degradation risks typically associated with liquid electrolytes seen in Li-ion batteries [9].

However, several hurdles prevent SSB's replacement of the widely used Li-ion battery. The primary barrier to SSB dominance is manufacturing complexity. Processing brittle ceramic or sulphide electrolytes on a large scale is difficult and expensive compared to the standard roll-to-roll slurry processes used for manufacturing Li-ion batteries [10]. In addition, the solid electrolyte also poses an problem relating to interface contact, wherein, solid electrolyte must maintain perfect physical contact with the electrodes despite the expansion and contraction of materials during charging cycles. Failure to maintain constant contact leads to cracking and delamination, which severely limits cycle life which is of grave importance in mobility applications [11]. Finally, the cost of SSBs remains exorbitantly high; current prototype costs are around 4 to 8 times higher than mass-produced Li-ion cells, pushing them out of reach for economy vehicles [10].

In conclusion, SSBs can be envisioned to surpass Li-ion batteries in terms of usage only in premium and high-performance mobility sectors—such as a successor to the Tesla Model S Plaid—by the end of the ongoing decade. However, due to the immense existing infrastructure and cost efficiency of standard Li-ion battery technology, liquid-electrolyte batteries will likely remain the dominant standard for mass-market economy vehicles for at least another 5-6 years.

5 E20 Fuel Rollout in India

E20 fuel refers to a blend of 20% ethanol and 80% gasoline by volume. India's transition to E20 fuel will be accompanied by major differences in a vehicle's powertrain . While ethanol is a biofuel that improves combustion efficiency, its distinct physical and chemical properties need specific adaptations in regular internal combustion engine (ICE) platforms.

5.1 Alteration of Fuel & Combustion Properties

Using E20 as a vehicle's fuel will shift the following parameters that govern combustion characteristics:

1. **Stoichiometric AFR:**
   - Pure gasoline requires 14.7 kg of air to burn 1 kg of fuel (equivalence ratio, $\lambda = 1$). Pure ethanol, being an oxygenated biofuel (C_2H_5OH), carries its own oxygen and hence has a much lower stoichiometric ratio of approximately 9:1.
   - The E20 fuel shifts the stoichiometric AFR to approximately 13.5:1 [12]. So if a non-modified gasoline engine is run on E20, the engine will run dangerously *lean* ($\lambda > 1$), causing overheating and increased NO_x emissions.
2. **Lower Heating Value (LHV) & Energy Density:**
   - Gasoline has a high energy density of 43 MJ/kg whereas pure ethanol has a much lower energy density of around 26.8 MJ/kg.
   - The E20 blend on the other hand, results in a roughly 7-9% reduction in volumetric energy content compared to pure ethanol [13]. So as to achieve the same power output using the E20 blend, the volumetric fuel consumption must therefore increase proportionally, leading to a noticeable drop in fuel economy (km/L).
3. **Research Octane Number:**
   - Pure ethanol has a high Research Octane Number, RON of 108. E20 is seen to boost the base fuel's (gasoline) RON by 4 points or so. Since RON is a measure of increased anti-knock, engineers generally increase the compression ratio thereby theoretically improving thermal efficiency [14].

5.2 Vehicle Subsystem Adaptations

To accommodate these changes in fuel and combustion properties, specific subsystems in the engine require modifications:

1. **Fuel Injection System :**

    - Since the energy density of the E20 fuel is lower, the engine must inject more fuel volume per cycle to maintain the required energy release during combustion.

    - The fuel injectors inside the cylinders must hence be re-sized to accommodate a larger flow rate of E20 fuel. As mentioned previously, using E20 in a non-compliant car may max out the injectors at high RPM, leading to lean misfires.

2. **Engine Control Unit Calibration :**

    - The fuel maps used in the ECU must be rewritten for E20 fuel's 13.8:1 AFR target. ECU must also be calibrated to increase the injector duty cycle so as to inject more amount of E20 blend for combustion. Additionally, the spark timing maps should be modified benefit the higher RON so as to optimize efficiency.

3. **Material Compatibility :**

    - Traditional rubber components like cork gaskets, natural and rubber hoses will swell, dry out, or crack as ethanol is hygroscopic (absorbs water). Due to this phenomenon, fuel lines must be upgraded to ethanol-resistant elastomers like Teflon or Viton. Furthermore, fuel tanks and lines usually require coating like nickel-plating or HDPE plastic to prevent corrosion from the absorbed moisture [12].

References

[1] Munro & Associates, "Tesla Model S Plaid Battery Teardown: Engineering Mastery," Lean Design, 2022.

[2] Tesla Inc., "Model S Plaid Fast Charging Analysis," InsiderEV, 2021.

[3] Panasonic GmbH, "Panasonic 18650 NCA Cell Datasheet & Thermal Models," Battery Cell Explorer, 2020.

[4] Tesla, Inc., "Model S Owner's Manual – Model S High Voltage Battery Pack," 2024.

[5] Battery Design, "Specific Heat Capacity of Lithium Ion Cells (NCA)," 2022.

[6] F. P. Incropera and D. P. DeWitt, "Fundamentals of Heat and Mass Transfer," 7th ed., Wiley, New York, 2011.

[7] The Engineering Toolbox, "Ethylene Glycol Heat-Transfer Fluid Properties," [Online].

[8] F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 7th ed. New York: Wiley, 2011.

[9] QuantumScape Corporation, "Solid-State Lithium-Metal Battery Performance Data," *QuantumScape Shareholder Letter*, 2022.

[10] BloombergNEF, "Electric Vehicle Outlook 2023: The Path to Solid-State," *BNEF Research*,

[11] J. Janek and W. Zeier, "A Solid Future for Battery Development," *Nature Energy*, vol. 1, 2016.

[12] NITI Aayog, "Roadmap for Ethanol Blending in India 2020–25," Expert Committee Report, June 2021.

[13] J. B. Heywood, *Internal Combustion Engine Fundamentals*, 2nd ed. New York: McGraw-Hill Education, 2018.

[14] H. S. Farkade and A. P. Pathre, "Experimental Investigation of Effects of Ethanol-Gasoline Blends on Performance and Emission Characteristics of SI Engine," *International Journal of Engineering Research and General Science*, vol. 4, 2016.

Appendix: MATLAB Simulation Code

The following MATLAB script was used to calculate heat generation and simulate the temperature rise of the battery pack under three distinct operating scenarios: Highway Cruise, Charging, and Track Mode.

```
% MEF317: Tesla Model S Plaid - Simplified Thermal Analysis
% Calculates Heat Generation (Q) and Temperature Rise for 3 Scenarios

%% 1. Setup Parameters
Mass = 479;           % kg (Battery Mass)
Cp = 850;             % J/kg.K (Specific Heat Capacity)
R = 0.038;            % Ohms (Internal Resistance)
UA = 1200;            % Cooling Power (W/K)
T_amb = 25;           % Ambient Temp (deg C)

% Simulation Time (30 minutes)
time = 0:60:1800;     % Steps of 60 seconds

%% 2. Define Scenarios (Current & Cooling)
% Scenario 1: Highway Cruise (Steady 55 Amps)
I_cruise = 55;
T_cool_cruise = 25;  % Passive Cooling (Ambient)

% Scenario 2: Charging (Avg 350 Amps)
I_charge = 350;
T_cool_charge = 25;  % Active Cooling (Ambient)

% Scenario 3: Track Mode (RMS 1000 Amps)
I_track = 1000;
T_cool_track = 15;   % Active CHILLER (Sub-ambient 15C)

%% 3. Calculate Heat Generation (Q = I^2 * R)
Q_cruise = I_cruise^2 * R;
Q_charge = I_charge^2 * R;
Q_track  = I_track^2  * R;

%% 4. Simulate Temperature Rise
T_cruise_plot = zeros(size(time));
T_charge_plot = zeros(size(time));
T_track_plot  = zeros(size(time));

% Set starting temps
T_cruise_plot(1) = T_amb;
T_charge_plot(1) = T_amb;
T_track_plot(1)  = T_amb;

for t = 2:length(time)
    % --- Cruise ---
    Q_removed = UA * (T_cruise_plot(t-1) - T_cool_cruise);
    T_cruise_plot(t) = T_cruise_plot(t-1) + (Q_cruise - Q_removed)*60 / (Mass*Cp);

    % --- Charge ---
    Q_removed = UA * (T_charge_plot(t-1) - T_cool_charge);
    T_charge_plot(t) = T_charge_plot(t-1) + (Q_charge - Q_removed)*60 / (Mass*Cp);

    % --- Track ---
    Q_removed = UA * (T_track_plot(t-1) - T_cool_track);
    T_track_plot(t) = T_track_plot(t-1) + (Q_track - Q_removed)*60 / (Mass*Cp);
end

%% 5. Plots and Output
figure('Color','w');
plot(time/60, T_cruise_plot, 'g-', 'LineWidth', 2); hold on;
plot(time/60, T_charge_plot, 'b-', 'LineWidth', 2);
plot(time/60, T_track_plot, 'r-', 'LineWidth', 2);
yline(55, 'k--', 'Safety Limit');

xlabel('Time (Minutes)');
ylabel('Battery Temp (C)');
title('Model S Plaid: Thermal Response by Mode');
legend('Highway Cruise', 'Charging', 'Track Mode', 'Location', 'NorthWest');
grid on;

% PRINT RESULTS TABLE TO COMMAND WINDOW
fprintf('-------------------------------------------------------------\n');
fprintf('| Scenario       | Current (A) | Heat Gen (kW) | Max Temp (C) |\n');
```

```
fprintf('|----------------|-------------|---------------|--------------|\n');
fprintf('| Highway Cruise | %4d A      | %5.2f kW      | %5.1f C      |\n', I_cruise, Q_cruise/1000, max(T_cruise_plot));
fprintf('| Charging  | %4d A      | %5.2f kW      | %5.1f C      |\n', I_charge, Q_charge/1000, max(T_charge_plot));
fprintf('| Track Mode     | %4d A      | %5.2f kW      | %5.1f C      |\n', I_track,  Q_track/1000,  max(T_track_plot));
fprintf('------------------------------------------------------------\n');
```

Listing 1: Tesla Model S Plaid Thermal Analysis Script