Midterm Project

James Lee

Heat Transfer

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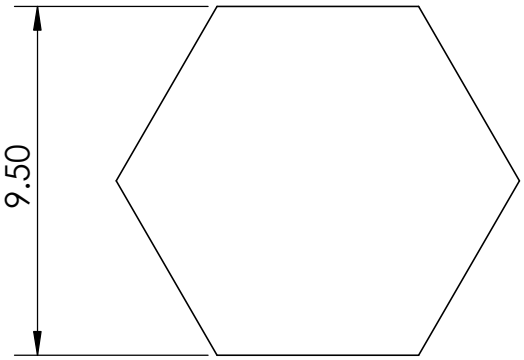
February 25, 2025

Overview

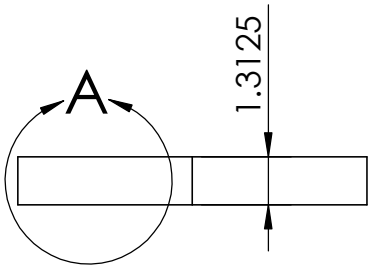
Heat shields play a critical role in spacecraft reentry, protecting vehicles from extreme thermal loads encountered when transitioning from space to the atmosphere. During reentry, a spacecraft can experience temperatures exceeding 1,500–3,000 K, primarily due to the compression of air ahead of the vehicle, leading to intense convective and radiative heating (Source 1). Without an effective thermal protection system, the spacecraft and its payload would be destroyed by these extreme conditions.

My interest in heat shield technology stems from my involvement in Rowan's Rocketry Clinic, where I serve as the lead payload engineer. While our rocketry projects do not involve atmospheric reentry, I have developed a strong interest in aerospace engineering and high-temperature material science. Additionally, I came across heat shield mechanics while playing the video game Kerbal Space Program, which simulates spacecraft physics, including reentry heating. This piqued my curiosity about the real-world thermal properties of heat shields and how they function under extreme conditions (Source 2).

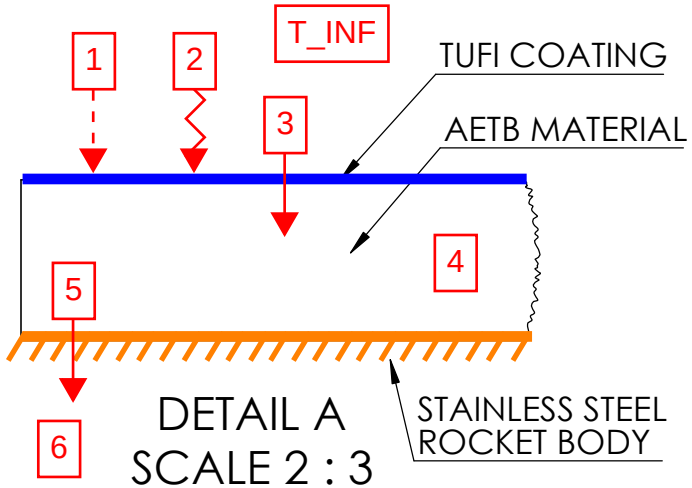
This project aims to analyze the transient heat transfer characteristics of the non-ablative heat shield panels used on SpaceX's Starship, which differ from traditional ablative designs. Starship's heat shield consists of hexagonal ceramic tiles, which are designed to withstand multiple reentries without material loss by radiating heat away and insulating the underlying structure. Unlike ablative shields (e.g., PICA, Avcoat), which erode over time to dissipate heat, these tiles rely on high-emissivity coatings and low thermal conductivity to prevent excessive heat transfer to the vehicle. This study will include an energy balance approach, a thermal resistance network, and a numerical model in Simscape to evaluate the temperature evolution over time. Understanding these principles is crucial for designing effective thermal protection systems in reusable spacecraft (Source 3).



FRONT VIEW



SIDE VIEW



DETAIL A
SCALE 2 : 3

ANNOTATED HEAT TRANSFER PROCESS:
1. AIR CONVECTS INTO TUFI COATING
2. AIR RADIATES INTO TUFI COATING
3. TUFI COATING CONDUCTS INTO AETB
4. AETB MATERIAL BEHAVES AS A THERMAL MASS
5. AETB MATERIAL CONDUCTS INTO STAINLESS STEEL UNDERNEATH
5. TEMP OF STAINLESS STEEL SURFACE OF ROCKET TO BE MEASURED OVER TIME. WILL BEHAVE AS A THERMAL MASS

DIMENSIONS OBTAINED FROM SOURCE 4

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	JL	2/26/25
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

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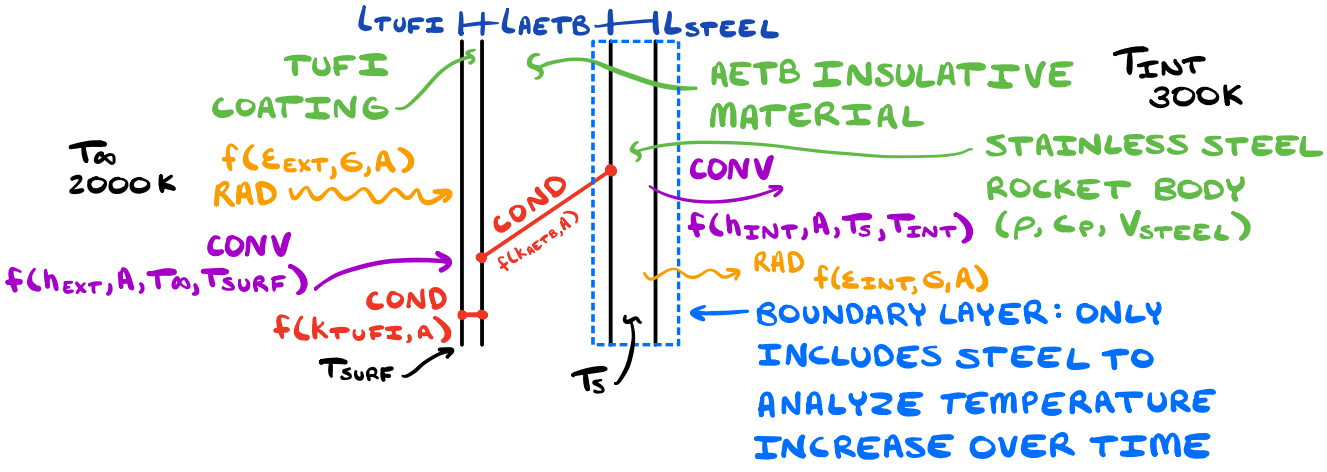
TITLE:
SpaceX Heat Shield

SIZE	DWG. NO.	REV
A	R1	
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Table 1: Numerical values for Heat Transfer Project

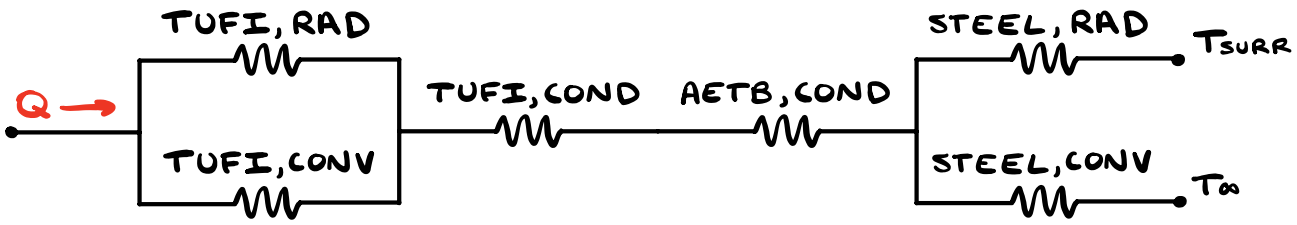
Variable	Value	Units	Source
h_ext	5000	W/m²·K	Source 1
h_int	10	W/m²·K	Source 1
ε_ext	0.9	–	Source 2
ε_int	0.8	-	Source 2
σ	5.67×10^{-8}	W/m²·K⁴	Source 3
T∞	2000	K	Source 4
T_surf	500	K	Assumed
T_int	300	K	Assumed
A	0.026	m²	Geometric Calculation
L_TUFI	0.002	m	Source 2
k_TUFI	1.5	W/m·K	Source 2
L_AETB	0.025	m	Source 5
k_AETB	0.24	W/m·K	Source 6
R_cond	4.057	K/W	Derived
ρ	8000	kg/m³	Source 7
c_p	500	J/kg·K	Source 8
L_steel	0.003	m	Assumed
V_steel	0.000078	m³	Derived

ENGINEERING DRAWING (PART II)



- THE INSIDE AIR OF THE ROCKET IS TREATED AS ADIABATIC, FOR PROBLEM SIMPLIFICATION
- SEE TABLE 1 FOR ALL RELEVANT VARIABLES & VALUES

THERMAL NETWORK



ENERGY BALANCE

$$\Sigma \dot{Q}_{IN} - \Sigma \dot{Q}_{OUT} = d/dt\, E_{ST\,IN\,CV}$$

$$\Sigma \dot{Q}_{IN} = mC_p\, dT/dt$$

$\dot{Q}_{IN}$, THE RATE OF HEAT TRANSFER INTO THE STEEL:
HEAT CONDUCTING THROUGH THE TUFI COATING & AETB INSULATIVE MATERIAL, R_{COND} ($R_{AETB} + R_{TUFI}$)

$\dot{Q}_{OUT}$, THE RATE OF HEAT TRANSFER OUT OF THE STEEL:
HEAT CONVECTING & RADIATING OFF THE STEEL INTO THE ROCKET

$$\dot{Q}_{COND} - (\dot{Q}_{CONV} + \dot{Q}_{RAD}) = mC\, dT/dt$$

$$R_{COND} = R_{TUFI} + R_{AETB} = \frac{L_{TUFI}}{k_{TUFI} \cdot A} + \frac{L_{AETB}}{k_{AETB} \cdot A}$$

$$\frac{T_{SURF} - T_{STEEL}}{R_{COND}} - (hA(T_S - T_{INT}) + \varepsilon \sigma A(T_S^4 - T_{INT}^4)) = \rho V_{STEEL} C_p\, dT_S/dt$$

Problem Setup - Assign Variables

$A = 0.026\ m^2$ $\sigma = 0.0000000567\ \frac{W}{m^2 * K^4}$ $h_{int} = 10\ \frac{W}{m^2 * K}$ $\varepsilon_{int} = 0.8$

$T_{int} = 300\ K$ $T_{surf} = 500\ K$ $L_{TUFI} = 0.002\ m$ $k_{TUFI} = 1.5\ \frac{W}{m * K}$ $L_{AETB} = 0.025\ m$

$k_{AETB} = 0.24\ \frac{W}{m * K}$ $R_{TUFI} = \frac{L_{TUFI}}{k_{TUFI} * A} = 0.0513\ \frac{K}{W}$ $R_{AETB} = \frac{L_{AETB}}{k_{AETB} * A} = 4.006\ \frac{K}{W}$

$R_{cond} = R_{TUFI} + R_{AETB} = 4.058\ \frac{K}{W}$ $h_{ext} = 5000\ \frac{W}{m^2 * K}$ $T_{inf} = 2000\ K$ $\varepsilon_{ext} = 0.9$

$c = 500\ \frac{J}{kg * K}$ $m = 0.624\ kg$

Part 1 - Steady-State Temperature

$$\frac{T_{surf} - T_s}{R_{cond}} = h_{int} * A * \left(T_s - T_{int}\right) + \varepsilon_{int} * \sigma * A * \left(T_s^4 - T_{int}^4\right)$$

$T_s = 371.724\ K$

To determine the steady-state temperature of the steel chassis, the energy balance was set to zero under the assumption that the heat entering from the insulation equals the heat leaving through the interior surface. The conduction into the steel was modeled through the TUFI and AETB layers using their combined thermal resistance, while the steel lost heat to the rocket interior through convection and radiation. Solving the nonlinear energy balance equation yielded a steady-state chassis temperature of approximately 371.7 K. This result reflects the point at which incoming and outgoing energy are balanced, and the steel no longer experiences a change in temperature.

Part 2 - Initial Rate of Temperature Change

$$T_{s0} = 300\ K \qquad Q_{in} = \frac{T_{surf} - T_{s0}}{R_{cond}} = 49.289\ W$$

$$dT_{s,dt} = \frac{Q_{in}}{m * c} = 0.158\ \frac{K}{s}$$

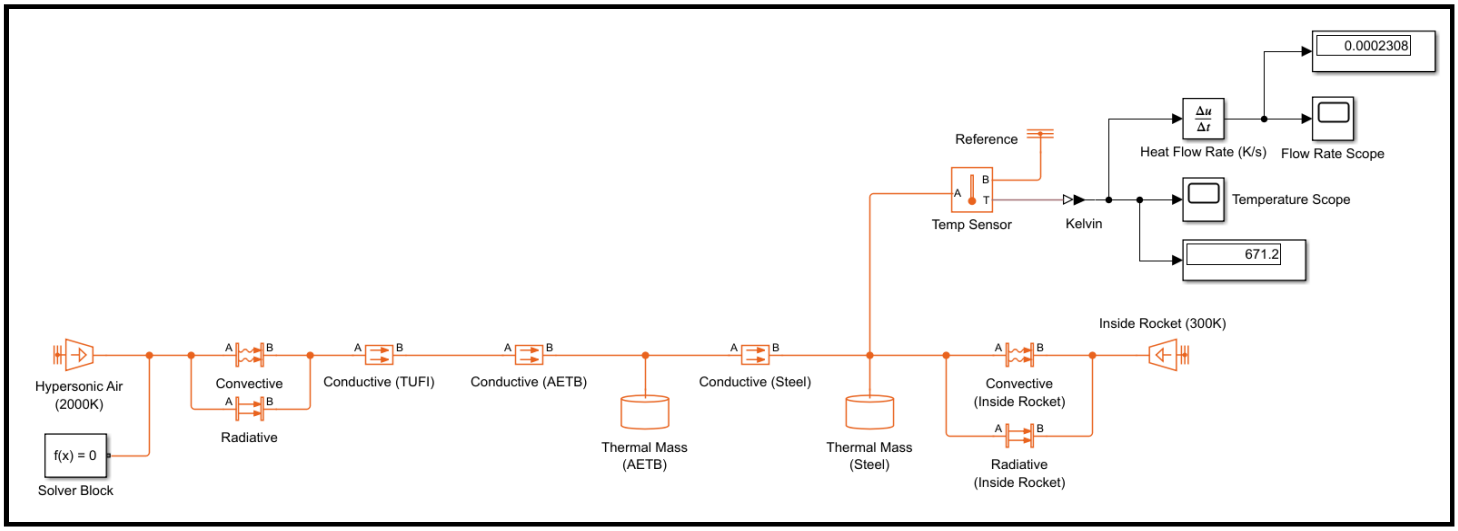
The initial rate of temperature change of the steel chassis was found by evaluating the transient energy balance at time t=0, assuming the steel starts at 300 K and the interface with the insulation is at 500 K. At this early moment, no heat is lost to the interior because the steel and cabin air are at the same temperature. The rate of change was calculated using the expression (T_surf - T_s)/(R_cond * m * c), which yielded a result of 0.158 K/s. This value indicates how quickly the steel begins to heat up when reentry heating first starts, before any significant heat loss occurs.

Part 3 - Biot Number

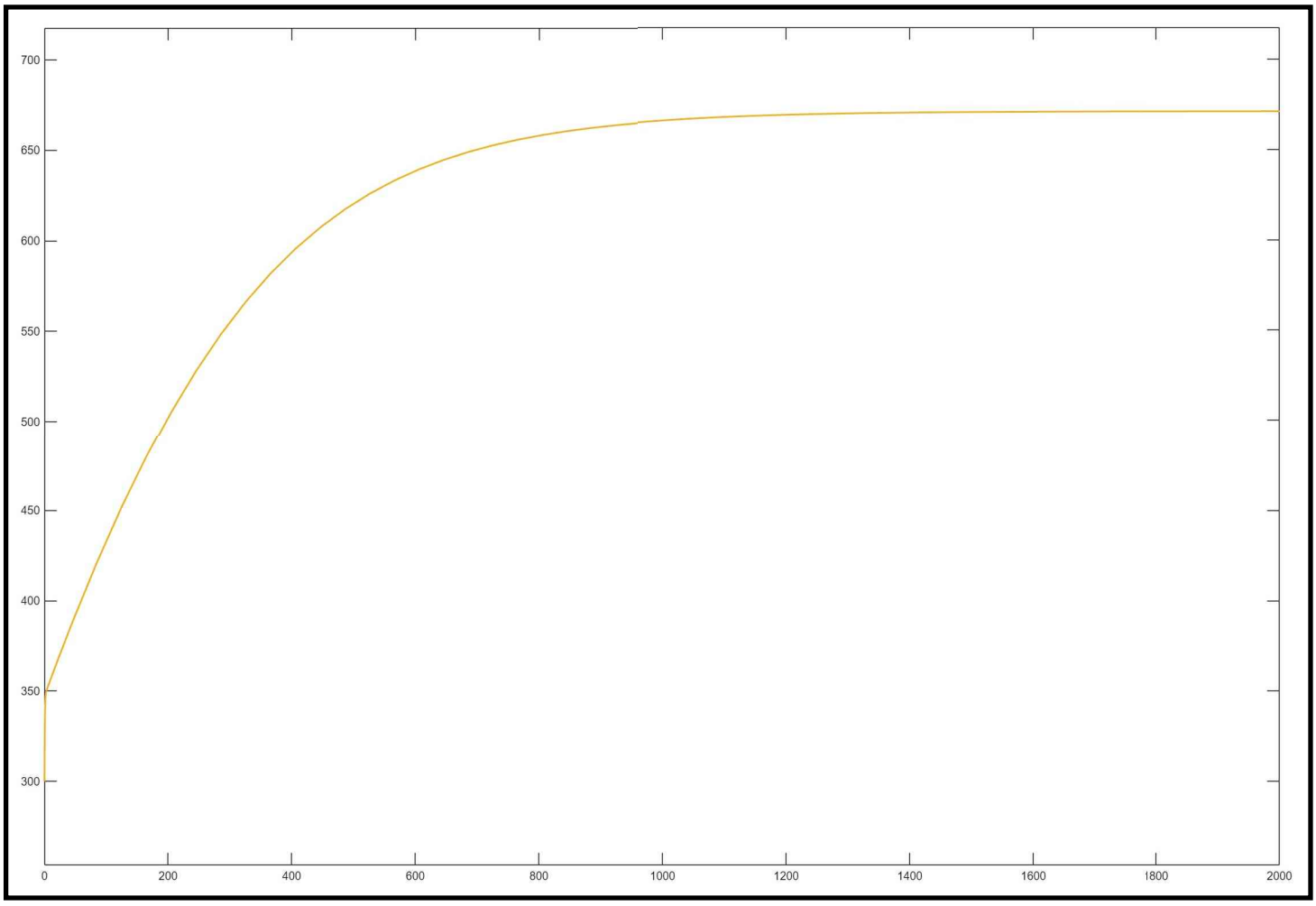
$$k_{steel} = 15\ \frac{W}{m * K} \qquad L_c = 0.003\ m \qquad Bi = \frac{h_{int} * L_c}{k_{steel}} = 0.002$$

The Biot number was calculated to assess whether the lumped capacitance model could be applied to the steel chassis. Using the convective heat transfer coefficient on the interior side of the steel (h=10 W/m^2*K), the steel thickness as the characteristic length, and a thermal conductivity of 15 W/m·K for stainless steel, the Biot number was found to be 0.002. Since this value is much less than 0.1, it indicates that temperature gradients within the steel are negligible. Therefore, the lumped capacitance model is valid in this scenario, and the assumption of a uniform internal temperature is justified.

SIMULINK MODEL:



TEMPERATURE SCOPE:



Results and Discussion

The comparison table shows a significant difference between the Blockpad and Simulink results. The steady-state temperature predicted by Blockpad is **371.7 K**, while Simulink reports **671.2 K**, resulting in a percent error of approximately **44.6%**. This discrepancy is largely due to the fact that Blockpad assumed a fixed interface temperature (500 K) between the insulation and the steel, whereas the Simulink model simulated a full heat path starting from a 2000 K reentry environment. As a result, the Simulink model allows more heat to enter the system, driving the steel temperature significantly higher.

The difference in the initial rate of temperature change is even more pronounced. Blockpad predicted an initial rate of **0.158 K/s**, while Simulink showed only **0.0002308 K/s**, a percent error exceeding **68,000%**. This large difference reflects the different assumptions about where and how heat enters the system. In Simulink, the heat must conduct through TUFI and AETB before reaching the steel, and the temperature at the interface builds up gradually. Blockpad, on the other hand, assumes the interface is already at 500 K at time zero, leading to a much faster heating rate.

Despite these differences, the models both reflect the core physics of the system. Simulink provides a more realistic transient solution because it models the full heat path from reentry air through insulation. Blockpad is a useful simplification that gives a quick analytical result but depends heavily on assumed boundary conditions. The biggest limitation of the Blockpad model is its reliance on a guessed interface temperature, while the Simulink model's primary weakness is the accuracy of user-defined material properties and convective coefficients. In practice, the true system behavior likely lies somewhere between the two models, depending on how quickly the insulation heats up during flight.

Sources

1. **Sutton, G. P., & Graves, R. (1971).** *Rocket Propulsion Elements* (3rd ed.). Wiley-Interscience.
2. **Squad. (2015).** *Kerbal Space Program* [Video game]. Squad.
3. **Anderson, J. D. (2006).** *Hypersonic and High-Temperature Gas Dynamics* (2nd ed.). AIAA Education Series.
4. phil1008. (1969, January 1). How many heat shield tiles are installed on starship and what is their total volume roughly?. Space Exploration Stack Exchange. https://space.stackexchange.com/questions/65703/how-many-heat-shield-tiles-are-installed-on-starship-and-what-is-their-total-vol
5. Posch, M. (2024, February 14). *How different are spacex thermal tiles from the Space Shuttle's?* Hackaday. https://hackaday.com/2024/02/14/how-different-are-spacex-thermal-tiles-from-the-space-shuttles/#:~:text=The%20fibrous%20material%20making%20up,as%20a%20shock%20to%20anyone.
6. **NASA SP-8055 —** *Thermal Protection Materials*
   NASA Technical Reports Server (SP-8055)
7. **NASA TM-1999-209727 —** *TUFI Coatings for Reusable Launch Vehicle Thermal Protection Systems*
   NASA Technical Memorandum TM-1999-209727
8. **Stefan–Boltzmann Constant —** Physical constant
   NIST Reference on Constants, Units, and Uncertainty
9. **Typical LEO Reentry Temperature —** Values referenced from *Hypersonic and High-Temperature Gas Dynamics* by John D. Anderson
10. **NASA TPS Handbook —** *Thermal Protection System Materials and Design Manual*
    NASA TPS Handbook (Archived)
11. **J. B. Rouse et al. —** *Characterization of AETB-8 tile insulation material*
    AETB Characterization (Example) *(You may need journal access)*
12. **Standard 304 Stainless Steel Properties —** Material Data
    MatWeb Data Sheet — 304 Stainless Steel
13. **Engineering Tables for Steel Specific Heat —** Standard references like Shigley or engineeringtoolbox.com
    Engineering Toolbox — Steel Specific Heat