PHYSICS 3300 Case Study - Thermal Contraction of the SLS Rocket During Propellant Loading

1 Overview

The Space Launch System (SLS, see figure) is America's next "heavy lift" rocket. It is designed to support human missions to deep space - the moon, Mars, and beyond. On a recent tour of the launch facilities at Kennedy Space Center, the Carthage Microgravity Team learned about some of the design issues around launching this 240 ft. three-stage rocket that is capable of lifting 70 tons of payload into orbit. Here is one of them.

"Umbilicals" refer to the attachments between launch tower and rocket prior to lift-off. These are typically electrical and fluid connections that deliver propellant during tank loading and provide interfaces for power, data, environmental controls, and propellant venting for the vehicle as it awaits liftoff. At Liftoff, these umbilicals break away from the rocket as the rocket climbs past the service tower. We will specifically consider the effect of thermal expansion and contraction on these connection points during and after the cryogenic propellant is loaded into the massive propellant tanks that comprise the SLS. You will make an estimate of how much "give" the umbilical systems must have in order to support the expansion and contraction of the rocket under thermal loads.

2 Technical Data

The SLS rocket stands 321 feet from bottom to top. We will consider the "core stage" of the rocket, which is essentially a cylinder of height $L_0 = 212$ ft. and radius $R = 13.8$ ft. This is the stage which, for the purposes of this problem, can be considered entirely filled with liquid hydrogen (LH_2) at a temperature of $T_{LH_2} = -253°C$.

The propellant tanks and core stage are made of aluminum. Aluminum has a volume coefficient of expansion of $\beta_{Al} = 6.9 \times 10^{-5} K^{-1}$.

The unloaded (dry) rocket sits on the launch pad at $T_{dry} = 20°C$. When the rocket is fully loaded with propellant, the core stage is brought to the temperature of the LH_2.

3 Analysis

The SLS with the Orion crew capsule sits on the launch pad with at least six umbilical assemblies attached to it at various points along its height (see figure). These umbilicals must provide power, cooling, data, and venting to the rocket until liftoff at $t = 0$. The problem arises when the SLS is loaded with propellant and the structure shrinks under the cooling influence of all that cryogenic hydrogen. Your question is how much vertical height change will the umbilicals have to accommodate as the rocket is loaded with propellant?

1. In your discussion groups, define the following terms and concepts with appropriate mathematical expressions involving measurable or known quantities: (1) Volume Coefficient of Expansion; (2) Linear Coefficient of Expansion. What is the relationship between these two quantities for a cylinder?

2. Discuss the assumptions you can make in this problem to simplify the calculation. List the assumption(s) and justify them with numerical estimates.

3. Under the assumptions you've made above, calculate the vertical height loss between the dry and the fully loaded and cooled SLS stack. This is the height change that engineers must accommodate in the design of the umbilical attachments.

4. While not as dramatic, commercial airplanes experience similar dynamics each time they fly. On the ground at, let's say $20°C$, the aluminum tube representing the passenger cabin of a Boeing 757 is 155 ft. long. At cruising altitude, the temperature of the aluminum skin may drop to -35$°C$. What is the effective change in length of the aircraft under these conditions?

5. In fact, because the inside of the aircraft above is kept at room temperature, there is a shear force exerted on the aluminum skin of the aircraft at cruising altitude. The shear force arises from the cold temperature of the external metal reacting against the warm metal on the inside of the aircraft. Can you estimate this force? What might be some of the consequences of this force?

4 Submission

Submit full narrative responses to each question above with all governing equations symbolically derived and all constants and variables explicitly defined. While you can work together to understand the problem, your writeup should be entirely your work. Where you have received guidance or useful ideas from classmates, cite them by name and identify the contribution or insight they provided.

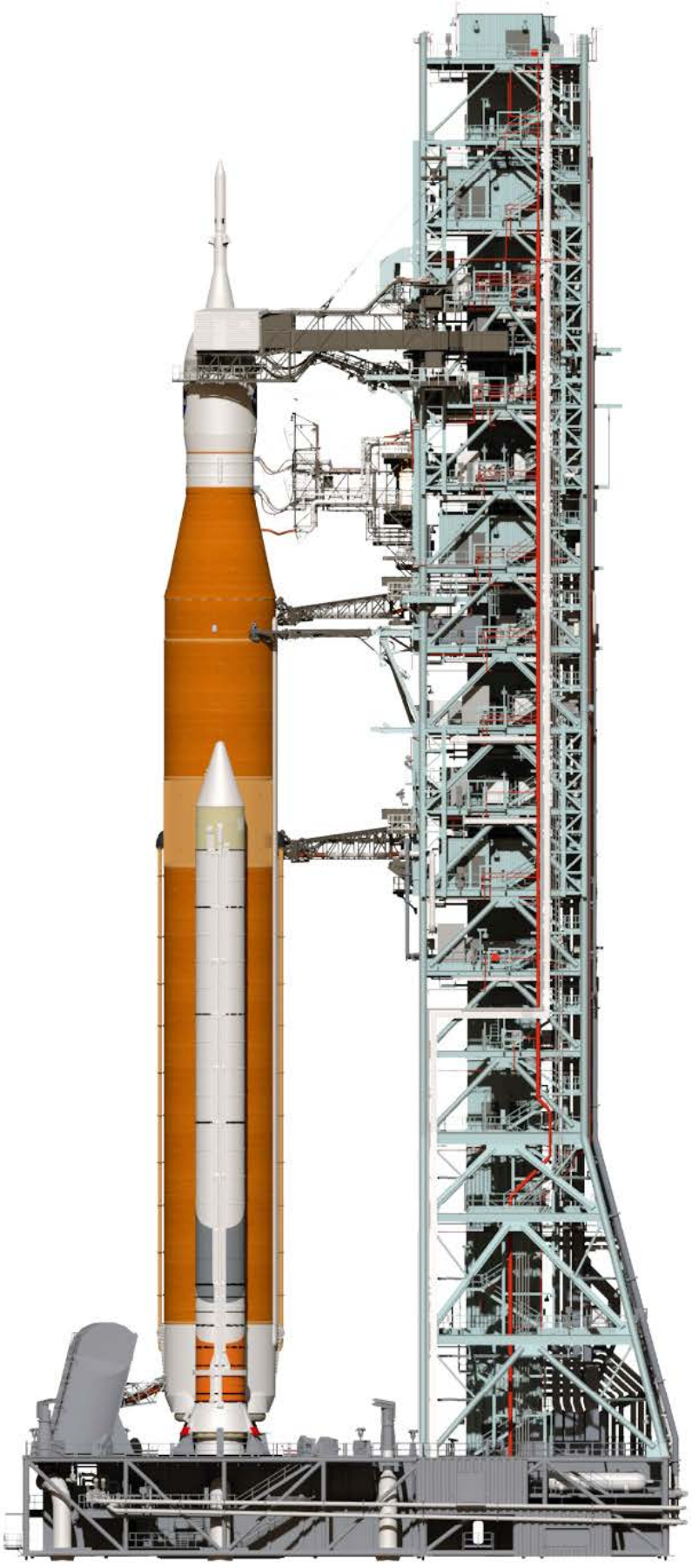

Figure 1: SLS and Orion Crew Capsule on launch platform. The Umbilicals are the connections between the SLS stack and the Launch Service Tower.