Hot Car in Space: Analysis of Soyuz MS-22 Spacecraft's Coolant System Failure and Effects on Internal Environment Through Re-entry

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April 2023

Abstract

This project analyzes the Soyuz MS-22 incident where a micro-meteor impact disabled the spacecraft's cooling systems, causing internal temperatures to rise well above normal levels. Therefore, it was deemed unsafe to return the crew to Earth on MS-22, prompting a rescue mission. This project conducts an in-depth thermal analysis and dynamics analysis of the Soyuz re-entry to simulate the internal cabin temperature over time. It was found the final cabin temperature of Soyuz reaches between 53-55 degrees Celsius, which is of extreme danger to humans. As a result, this project concludes the crew would have likely suffered severe health complications or potentially death during re-entry had they returned on the damaged MS-22 spacecraft. Therefore, the MS-23 mission to rescue the crew was likely the correct choice.

Team Member Contributions:
- **Robert Cummisky:** Human survival research, Electronics safety research, Writing section 4
- **Brayden Havenstein:** Thermal Properties Research, Citations
- **Drew Lundin:** Spacecraft volume-weighted properties calculation, Writing of respective section 2.1.
- **Surya Manikhandan:** Spacecraft Re-entry trajectory simulation, Spacecraft thermal simulation, Writing of respective sections 2.2 & 2.3. Documentation of limitations in section 3.
- **Shreya Sharma:** Spacecraft TPS research, Writing of section 1.

1 Introduction

The Soyuz Spacecraft, designed initially during the 1960s by the Soviet Union, has proven to be a very reliable vehicle for crew transport to and from space. The spacecraft has completed close to 150 crewed flights to date across multiple programs such as the Apollo-Soyuz test project, the Salyut & Mir space stations, and extensively to the International Space Station (ISS). The Soyuz has been instrumental in keeping the International Space Station continually supplied and habited by a human crew for 22 years with extreme reliability.

On September 21, 2022, a Soyuz capsule (serial number MS-22) successfully launched to and docked to the International Space Station, delivering three crew members to the orbiting laboratory. The capsule was to be docked to the ISS until the end of the crew's mission, when it would then be utilized to return the crew back to Earth. However, the spacecraft suffered an anomalous incident on December 15th, 2022, when the spacecraft's service module was impacted by a micro-meteorite. The service module of the spacecraft houses several critical systems such as the propulsion system for orbital maneuvering, the life support systems for crew (including the cabin heating and cooling systems), electrical power systems, among others.

The micro-meteor impact had severely damaged the spacecraft's environmental control system (ECS - responsible for heating / cooling the spacecraft's interior to maintain a human-safe environment). The impact had caused the spacecraft to leak the onboard coolant fluid from the ECS radiator loop, rendering it difficult to control the temperature of the spacecraft's environment.

Figure 1: Coolant Leak from ECS System Visible on Soyuz MS-22

The Russian Space Agency (Roscosmos) and NASA conducted a series of tests on the spacecraft, and eventually concluded it was unsafe to return the crew on the vehicle due to a possibility of a thermal runaway during the heat-intensive earth re-entry process. In fact, the temperature in the crew capsule had reportedly increased to about 30 degrees Celsius (86 degrees Fahrenheit) when docked to the ISS. The temperature inside the Soyuz spacecraft is typically maintained between 18-24 degrees Celsius (64-75 degrees Fahrenheit) through the full reentry process (Christy, 2023).

The Soyuz MS-22 crew were forced to re-enter Earth on a separate rescue vehicle (Soyuz MS-23), leaving the damaged spacecraft to re-enter autonomously. Both spacecraft re-entered successfully, and the crew returned safely in the new capsule. While no official report has been released yet, Roscosmos leadership stated the temperatures within the damaged MS-22 vehicle had reached significantly higher values when compared to a nominal re-entry with functioning cooling systems. Should the spacecraft have entered with a crew onboard, it is likely their lives would have been in danger.

This project seeks to characterize the spacecraft and simulate the internal temperature curve over time without an operational cooling system (as observed during the MS-22 incident). To achieve this goal, this project seeks to create an approximate thermal model of the spacecraft. Then, the internal temperature of the spacecraft can be modeled through the whole re-entry process. Finally, this project seeks to estimate the probability of survival for the crew if they were to have re-entered on the damaged MS-22 capsule. This will be accomplished by studying the limits of human survivability in high-temperature environments.

2 Soyuz Spacecraft Analysis

As mentioned previously, this project requires multiple analyses to model the internal temperature of the spacecraft over time. The distinct steps are as follows:

1. Generating an approximate thermal model of the Soyuz spacecraft by conducting research on the material composition of the spacecraft's walls. Additionally, it is necessary to obtain the initial internal temperature of the spacecraft prior to the re-entry phase.

2. Calculating the trajectory of the Soyuz vehicle through the atmospheric re-entry process (which takes the spacecraft from the upper atmosphere to the ground). During this period, the spacecraft experiences severe, sustained aerodynamic heating as it decelerates from orbital velocity (~ Mach 25) to subsonic speeds for an earth landing.

3. Leveraging the spacecraft thermal model obtained from part (1) and the trajectory data obtained from part (2) to estimate heat flux to the spacecraft and model the internal temperature over time.

The following sections will explain in detail the analysis done to complete each listed objective.

2.1 Characterization of Soyuz Vehicle and Spaceflight Radiation Environment to Determine Initial Conditions for Reentry

The Soyuz is a spacecraft designed to transport humans and cargo into Earth orbit (European Space Agency, 2018). Soyuz is made of 3 components, the orbital module, descent module, and instrumentation and service module (European Space Agency, 2018). During the reentry process, the crew are situated in the descent module. Prior to the re-entry process, the crew in the descent module are separated from the orbital module and the instrumentation & service module (Zak, April 2023). Therefore, for the reentry heating analysis, the system of interest is the descent module alone.

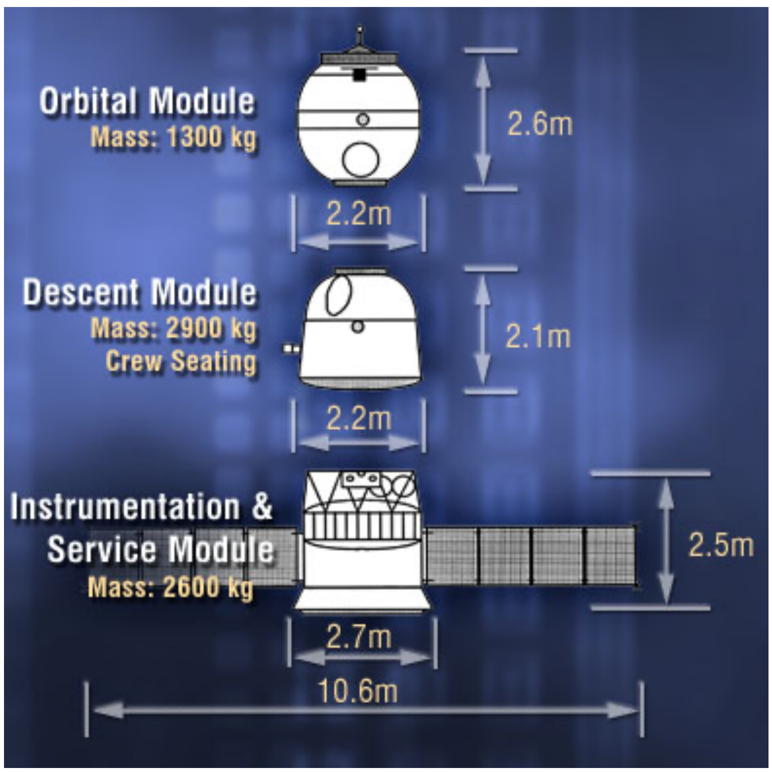

Figure 2: Soyuz Spacecraft Modules

The Descent module is an axisymmetric capsule 2.1 m in length, and 2.2m in diameter (European Space Agency, 2018). The shape of the vehicle is approximately cylindrical, however the heat shield and back shell are rounded, so the geometry of the descent module is best approximated as a sphere with radius of 2.2 meters (Figure 3).

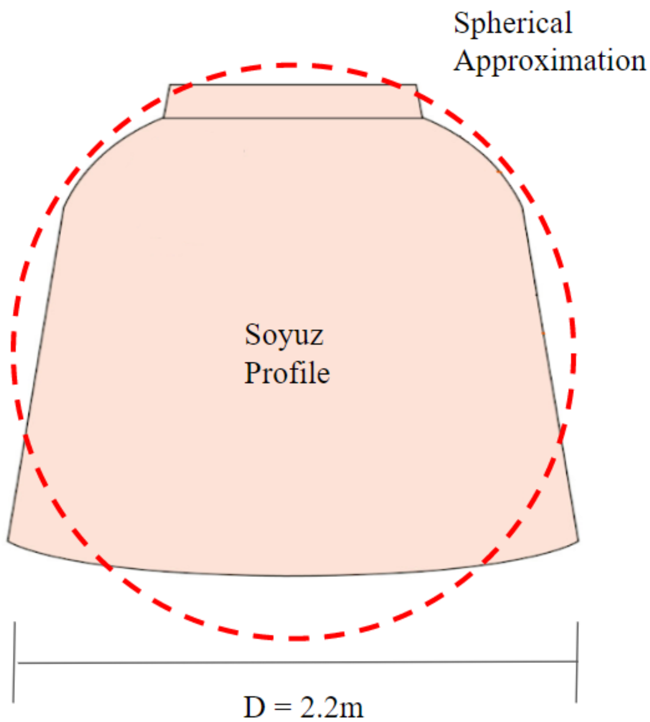

Figure 3: Spherical Approximation of Soyuz Capsule

Observing Figure 3, the spherical assumption of the Soyuz overestimates the volume, and surface area of the vehicle. The overestimation of the surface area of the vehicle will lead to an overestimation of the heat transfer rate given a flux. However, this assumption is necessary to determine the surface area of Soyuz.

The descent module is made of various materials including the aluminum airframe, heat shield and insulating layers, and the air inside of the cabin (Davis, 2013). The backshell of the Soyuz (the structure excluding the heat shield) was most documented in available sources, so we assume the Soyuz airframe is uniformly the backshell configuration.

The backshell of the Soyuz descent module includes layers of insulation, metallic airframe, vacuum sealed layers, and the air inside of the cabin. The descent module can be simplified to 6 radial layers show in Figure 4.

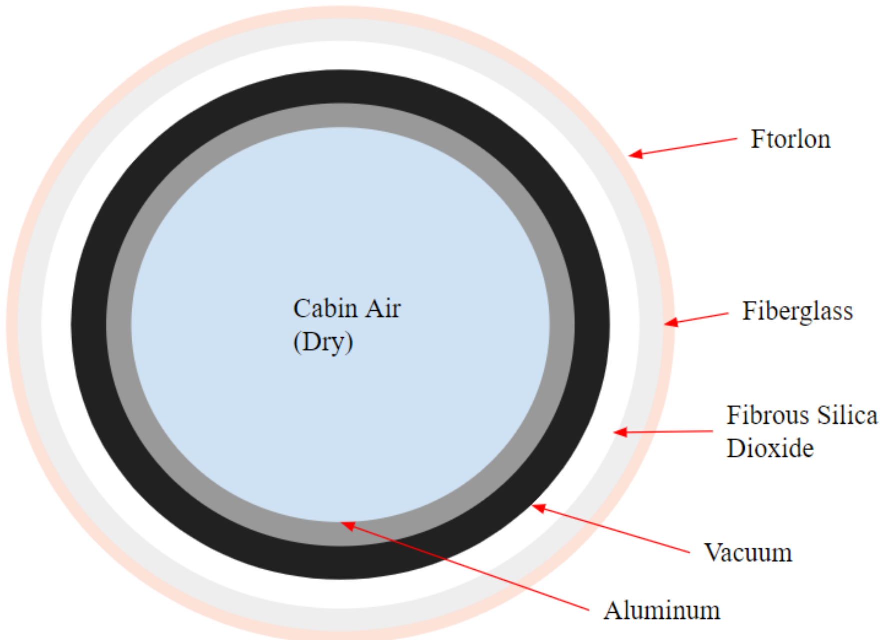

Figure 4: Thermal Protection System Layers as Approximate Spherical Descent Module

The outermost layer is made from a polyamide-imide thermos-plastic: Ftorlon. The next layer is made from a fiberglass composite. Then inside of the fiberglass is a layer of fibrous silicon insulation. There is a vacuum layer separating the silicon layer and an aluminum layer. The innermost layer is the air inside of the crew cabin (Davis, 2013). The thickness of each layer is averaged for the windward and leeward side of the vehicle backshell to find an average thermal protection system that can be assumed to be uniform.

Table 1: Thickness & Specific Heat Capacity of Soyuz Module Materials

Material	**Thickness [m]**	**Specific Heat Capacity [J/kg*K]**	**Source**
Ftorlon	0.00130	998.5	(Davis, 2013)
Fiberglass	0.001625	700	(Davis, 2013) (Wilson,2019)
Fibrous Silicon-dioxide	0.00290	840	(Davis, 2013) (Adams, 2013)
Vacuum Layer	0.00505	N/A	(Davis, 2013)
Aluminum	0.00200	890	(Davis, 2013) (Engineering Toolbox 2013)
Air	1.0928	700	(Davis, 2013) (Urieli, 1994)

The descent module must be modeled as a uniform material to be utilized in the thermal analysis conducted in Section 2.3. The volume of each spherical layer was computed then used as a weight to find a volume weighted average for specific heat capacity ($\overline{C_p}$).

$$\overline{C_p} = \frac{1}{\sum V_i} \sum C_{p_i} V_i = 685 \frac{\mathrm{J}}{kg * K}$$

Where:

$$\overline{C_p} = \text{average specific heat capacity of spacecraft}$$
$$C_{p_i} = \text{specific heat capacity of a layer}$$
$$V_i = \text{volume of a layer}$$

The mass of the Soyuz descent module is also a necessary parameter that will dictate the temperature variation of the capsule. From the Soyuz descent module and crew upon reentering the atmosphere have a total mass of $2900\ kg$ (Wright, 2015). There is some lost mass as descent module's heat shield ablates away, but it is assumed that this loss of mass is negligible.

The initial temperature of the cabin air will impact the temperature distribution of the vehicle. Once the environmental control system failed, the primary mode of heat transfer between the spacecraft and its environment was radiation. In orbital spaceflight, the radiation heat flux to the Soyuz is approximately constant.

For a surface normal to the sun, outside of the atmosphere the solar radiation heat flux is a known values called the "solar constant" (Libretexts, 2021). The solar constant varies throughout the calendar year due to differences in the distance between the earth and sun; however, the average solar radiation flux is $\dot{q_{avg}} = 1353\ W/m^2$ (Libretexts, 2021). We assume that the solar radiation can be approximated as the heat transfer to a surface normal to the sun of an equivalent area of the Soyuz descent module. This assumption overestimates the radiation heat transfer to the vehicle, since it does not account for the portion of descent module facing away from the sun.

Since the vehicle experiences a constant heat flux in the radiation environment, and the Soyuz MS-22 capsule was without coolant from December 15, 2022, only returning to earth March 28, 2023 (104 days) it can be assumed that the air in the cabin reached a steady state that can serve as an initial condition for the transient heating of the reentry (Malik, 2023).

Shortly after the loss of the coolant, the temperature in the Soyuz MS-22 began to rise. On December 18, 2022, The Russian space agency, Roscosmos claimed that the temperature in the vehicle reached $30°C$ **(**Guardian News and Media, 2022). On December 19th, 2022, Roscomos claimed that the temperature in parts of the Soyuz had reached $40°C$ **(**Zak, March 2023). However, in later communications it was stated that the vehicle had stabilized between $28°C$ and $30°C$**,** further justifying the steady-state assumption prior to re-entry (TASS, 2022). Therefore, we will consider an initial temperature between $28°C$ and $30°C$ in the re-entry heating analysis of Section 2.3.

2.2 Calculation of Soyuz Vehicle's Re-entry Trajectory.

The atmospheric re-entry of a spacecraft is a process by which a spacecraft decelerates from orbital velocity (approx. Mach 25) at the upper atmosphere to subsonic speeds for an earth surface landing. Most of the spacecraft's energy is dissipated in the form of heat, some of which will ger absorbed into the spacecraft's structure. Therefore, spacecraft often experience sustained severe aerodynamic heating until velocities have dropped sufficiently.

The simplest form of re-entry is known as a "ballistic re-entry". A ballistic re-entry is one where the spacecraft produces no lift. Often, ballistic re-entries cause incredibly high decelerations and therefore high g-loadings on the crew and spacecraft (often causing peak loading of 8g or greater). A ballistic re-entry also causes the instantaneous thermal loads on the spacecraft to be incredibly high. In order to mitigate the high g-loading and heating, the Soyuz spacecraft performs a special "lifting re-entry". The Soyuz descent module is designed to provide a positive lift during re-entry, allowing the spacecraft to spend more time in the thinner upper atmosphere. This significantly reduces g-loading to 2.5-3g and lowering instantaneous heating (Babu et.al, 2018).

Unfortunately, there seems to be a lack of literature which provides concrete data on Soyuz's reentry profile. Therefore, the group elected to stimulate the lifting reentry leveraging the two-body problem model. The equations of motion for a spacecraft in atmospheric re-entry over a spherical, non-rotating planet are as follows (French and Griffin, 2004).

$$\frac{dV}{dt} = -\frac{D}{m} - g\sin(\gamma) \tag{1}$$

$$\frac{Vd\gamma}{dt} = \frac{L}{m} - \left(g - \frac{V^2}{r}\right)\cos(\gamma) \tag{2}$$

$$\frac{ds}{dt} = \left(\frac{R}{r}\right)V\cos(\gamma) \tag{3}$$

$$\frac{dh}{dt} = \frac{dr}{dt} = V\sin(\gamma) \tag{4}$$

$$L = \left(\frac{L}{D}\right)_{Trim} \cdot D \tag{5}$$

$$D = \frac{1}{2}\rho V^2 S C_D \tag{6}$$

$$M = \frac{V}{\sqrt{\gamma_{air} \cdot R \cdot T_\infty}} \tag{7}$$

Where:

V = Spacecraft inertial velocity (m/s)
R = Radius of planet (m)
h = Geopotential height above planet (m)
r = Radius from planetary center (m)
s = Downrange travel distance (m)
γ = Spacecraft flight path angle (rad / deg)
m = Vehicle mass (kg)
L, D = Lift and drag forces, respectively (N)
$\frac{L}{D_{trim}}$ = Spacecraft lift to drag ratio at trim condition (unitless)
ρ = Density of atmosphere (kg/m^3)
S = Cross-sectional area of spacecraft (m^2)
C_D = Drag coefficient of spacecraft (unitless)
M = Mach number of spacecraft (unitless)
γ_{air} = Ratio of specific heats of air (unitless)
R = Gas constant of air (unitless)
T_∞ = Atmospheric temperature (K)

The above equations of motions (EOMs) can be integrated over time using a numerical ODE solver. This project uses a series of MATLAB scripts (Appendices B-F) which performs the numerical integration of these equations of motion using the ODE45 solver to determine the spacecraft trajectory given specific initial conditions. The initial conditions of the Soyuz capsule at the start of atmospheric reentry are as follows (Zak, April 2023).

- $h_i = 122\ km$ – initial entry altitude
- $\gamma_i = -1.35°$ – initial flight path angle
- $V_i = 7870\ m/s$ – initial entry velocity

The aerodynamic and mass properties of the Soyuz descent module are as follows (Weiland, 2014).

- $C_D = 1.3\ km$ – vehicle drag coefficient
- $\frac{L}{D} = 0.25$ – vehicle lift to drag ratio at trim condition
- $D_c = 2.2\ m$ – cross-sectional diameter of vehicle
- $m\ = 2900\ kg$ – vehicle mass (descent module only)

Given the above EOMs and initial conditions, the aforementioned MATLAB script was used to simulate the Soyuz lifting re-entry. The simulation was run from time $t_i = 0\ sec$ until the spacecraft reached the ground (such that $h = 0\ m$). The International Standard Atmosphere (ISA) tables were leveraged to calculate certain atmospheric conditions such as temperature and sonic speed at altitude (Tewels, 1976). The COSPAR International Reference Atmosphere was used to compute atmospheric density at any given height along the reentry profile (Jursa, 1985).

The computed trajectory result is depicted graphically on the following page.

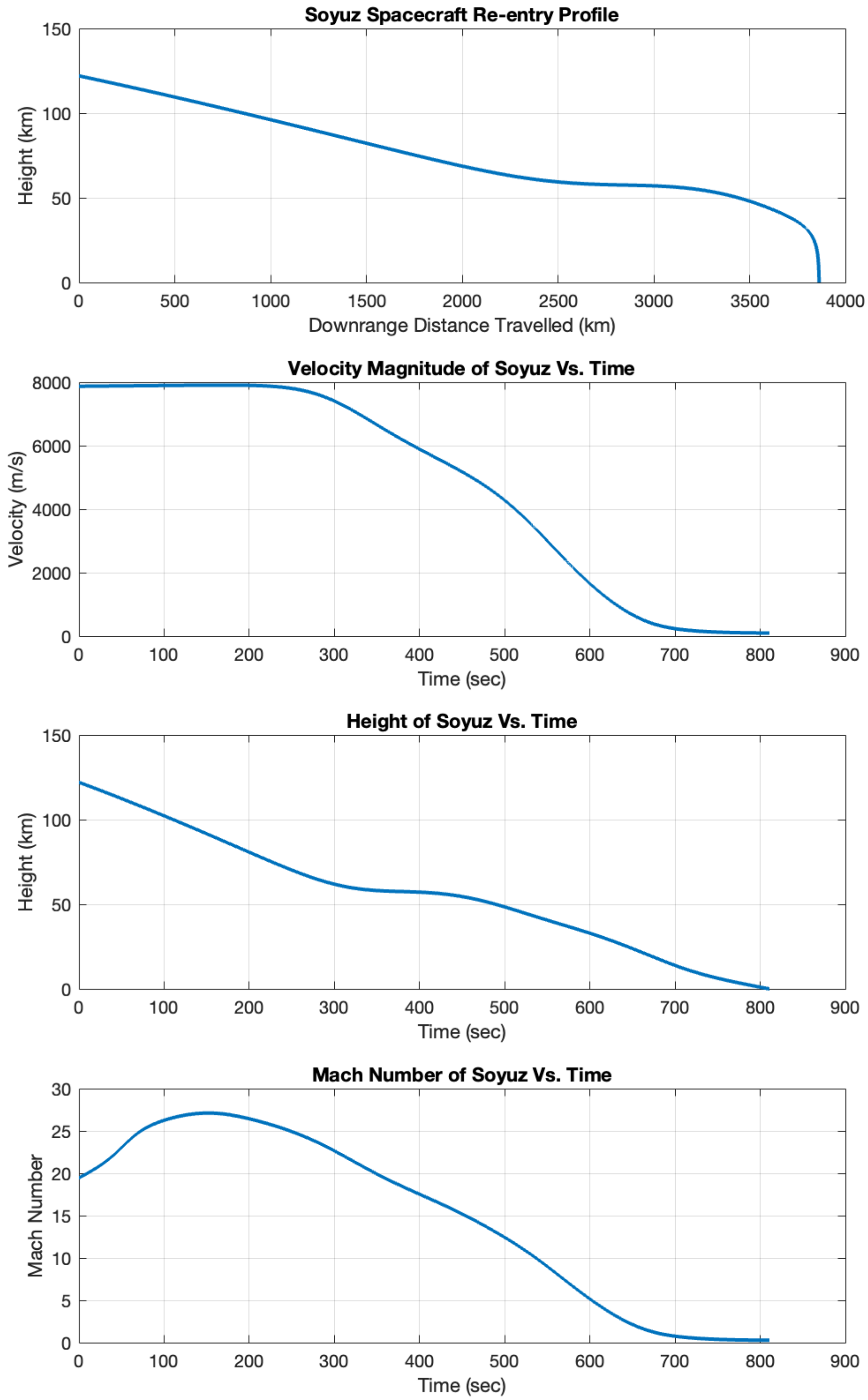

Figure 5: Simulated Soyuz Re-entry Trajectory

The total time for re-entry was approximately 811 seconds (approx. 13 min & 31 seconds), with a peak deceleration g-loading of approximately 2.5g. This is highly consistent with the real-world Soyuz re-entry (Zak, April 2023). Therefore, the results of the simulation are likely accurate and can be used for further calculation.

2.3 Calculation of Re-entry Heat Flux and Temperature vs. Time Profile.

As mentioned in the start of Section 2, Re-entry is a phase where the spacecraft experiences severe aerodynamic heating when decelerating from orbital velocity (~Mach 25 to subsonic velocities). This is since, during atmospheric flight, the Soyuz descent module develops a thin boundary layer close to the spacecraft's skin where viscous effects (such as skin friction) are prevalent. The convection heating from this boundary layer over the vehicle is dominant and causes significant energy input to the spacecraft body and cabin, causing temperatures to rise.

While reentry heating is an incredibly complex and hard-to-model phenomenon, there are many existing, well accepted textbooks which provide approximate solutions to modeling the heat flux imparted to a spacecraft due to convection heating. One such book is the second edition of *Space Vehicle Design* which provides the following equation to approximate heat flux due to re-entry effects (French and Griffin, 2004).

$$\dot{q}_w = \kappa\left(\frac{\partial T}{\partial y}\right) = \left(\frac{Nu}{Pr}\right)\left(\frac{\mu}{L}\right)(H_{oe} - H_w) \tag{8}$$

Where:

Nu = Nusselt number
Pr = Prandtl number
μ = Viscosity of fluid
L = Spacecraft nose radius (m)
H_{oe}, H_w = Enthalpy at outer edge (oe) and wall (w), respectively

The authors of the book then make a series of simplifications to the above formula, thereby yielding the formula below. The derivation of this equation is non-trivial and is outside the scope of this project and therefore will not be covered. Readers interested in confirming the derivation are encouraged to consult sections 6.3.3 and 6.3.4 of the aforementioned book.

$$\dot{q}_{avg} \approx \frac{C_F}{4}\rho V^3 \tag{9}$$

Where:

C_F = Skin friction coefficient of wetted spacecraft area (unitless)
ρ = Air density (kg/m^3)
V = Spacecraft Velocity (m/s)
$\dot{q}_{avg}$ = Body averaged heat flux (W/m^2)

The equation above will be used to calculate the average heat flux to the spacecraft due to reentry heating & convection effects. While the value of Soyuz spacecraft's C_F is not available in the public domain, this project assumes the wetted area skin friction coefficient of Soyuz is approximately equal to that of the Apollo spacecraft, where there is an abundance of publicly available aerodynamic data. The C_F is therefore assumed to be approximately .08 (Moseley, 1986). Additionally, French and Griffin discuss how approximately only 2% - 5% of the total heat flux of re-entry goes toward heating the & spacecraft's backshell structure (2004). The rest of the energy is dissipated by atmospheric losses in the dethatched bow shock or dissipated by the spacecraft's ablative heat shield. For this analysis, our group assumes approximately 2% of the re-entry heat flux goes toward heating the backshell and, ultimately, the cabin.

Leveraging a MATLAB script (Appendices B-F), the heat flux to the spacecraft can be calculated using equation 8 and the trajectory information obtained in the previous section. The resulting curve of heat flux to the spacecraft vs. time is as follows.

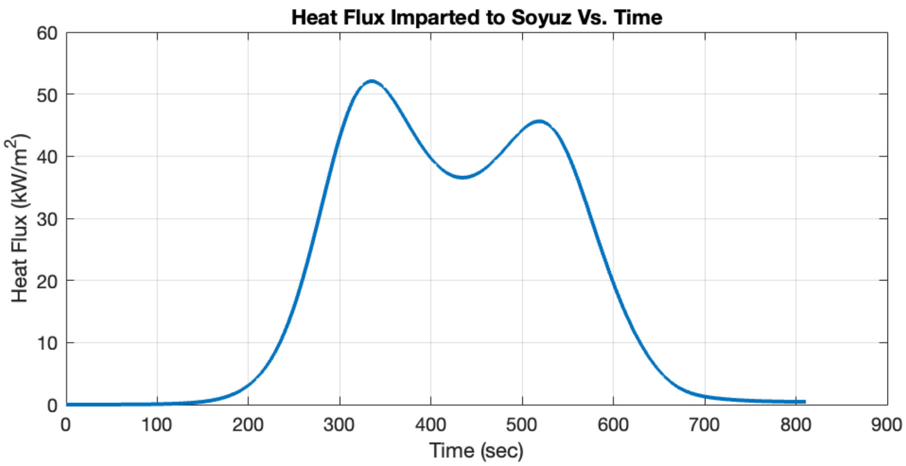

Figure 6: Heat Flux Imparted on Soyuz as a Function of Time

Comparing our values to historical data, the Space Shuttle engineering team recorded a sustained re-entry heat flux of approximately 50 kW/m^2 at the belly portion of the orbiter at Frame Station 877 (FS877) during the first flight of the spacecraft (Ko et.al, 1982). FS877 is located at approximately the middle of the orbiter where the wing box begins. Therefore, it seems the heat flux calculations done are reasonable when compared to real-world expectations.

Though the definition of heat flux, it is possible to integrate the heat flux over time to obtain the cumulative heat transfer to the vehicle in joules at any given time.

$$Q(t) = \int_0^t \dot{q}_{avg} \cdot A_w \ dt \tag{10}$$

Where A_w represents the wetted area of the Soyuz spacecraft, which is approximately 3.4 sq. m (Weiland, 2014). Therefore, the total heat transfer (energy addition) to the Soyuz spacecraft over time is as follows:

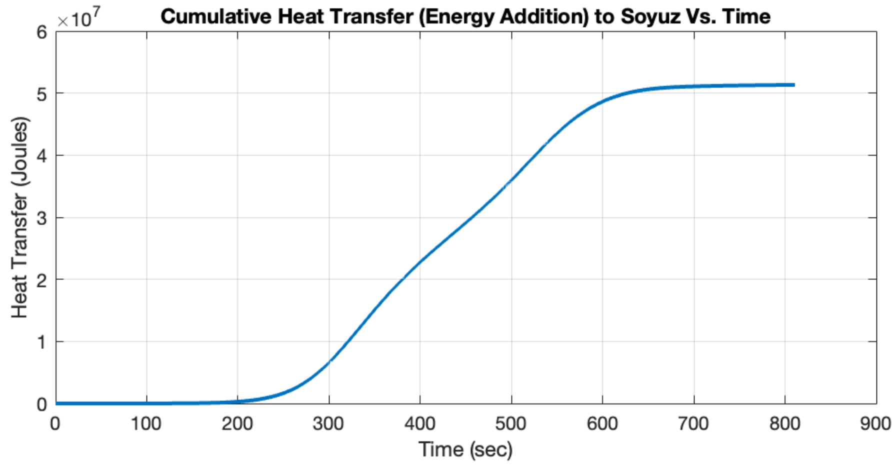

Figure 7: Cumulative Heat Transfer (i.e., energy addition) to Soyuz over Time

Finally, we can calculate the temperature profile of the spacecraft over time using the following formula. The specific heat capacity c_p is the volume-averaged heat capacity of the whole spacecraft backshell & cabin (neglecting the heatshield) as defined in Section 2.1.

$$Q = mc_p dT \tag{9}$$

Applying the above equation with an initial spacecraft cabin temperature of 28-30 Celsius (the approximate range quoted for MS-22's internal temperature prior to re-entry as discussed in previous sections) to obtain the following temperature curve. The lower bound represents the lower quoted initial internal temperature of 28 Celsius and the upper bound represents the higher quoted initial temperature of 30 Celsius. A mid temperature curve has been included for readability.

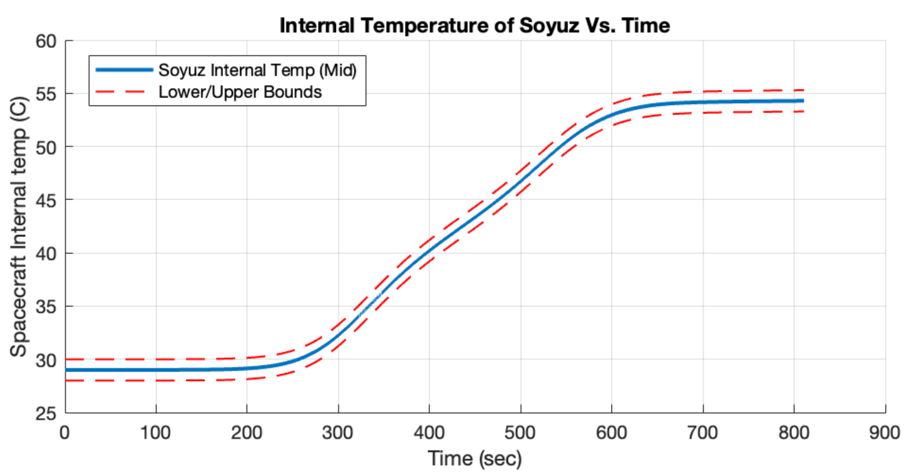

Figure 8: Internal Temperature of Soyuz over Time

The following sections will discuss in detail the limitations of the analysis and implications of these results.

3 Limitations and Possible Future Work

The results obtained in the previous sections of this report hold great significance. However, the analysis conducted has several limitations which are worth addressing.

To begin, the thermal model of the spacecraft is vastly simplified. As discussed in Section 3.1, the geometry of the spacecraft had to be simplified down to a sphere to obtain the volume-averaged specific heat capacity of the spacecraft. While this assumption maintains the diameter of the real spacecraft, this leads to an overestimation of the spacecraft's true surface area and volume, which would have ultimately led to inaccuracy in the heat flux to calculation. Using a Computer Aided Design (CAD) software to compute area and volume of the spacecraft and its thermal protection system (TPS) layers would be more accurate in comparison to the method leveraged in this report.

Additionally, it was assumed the spacecraft's thermal protection system is uniform across the whole backshell. While this assumption is acceptable for the purposes of this project and necessary for the calculations in Section 2.1, the Soyuz spacecraft has many zones where the composition of the TPS layering is different. This is to account for the non-uniform re-entry heating across different parts of the spacecraft body. To increase the fidelity of the thermal model, future work may include accounting for the variations in the TPS when deriving thermal resistance or the spacecraft's heat capacity.

The dynamics and thermal analyses completed in Section 2.2 & 2.3 also have several limitations. Specifically looking at the thermal simulation, a main assumption was that re-entry heating was distributed uniformly across the wetted surface area of the spacecraft. In reality, this is not the case as the majority of the heating takes place on the windward side of the spacecraft where the TPS has increased thermal resistance. Additionally, the thermal analysis assumes the heat energy added to the system instantaneously and uniformly increases the backshell & cabin temperature. While this first-order model is acceptable for this project, a higher fidelity model would certainly increase the accuracy of the analysis.

The group also had to estimate the Soyuz spacecraft's friction coefficient for heat flux calculations based on available data from the Apollo program. While the calculated heat flux value seems to be consistent with other spacecraft such as the U.S. Space Shuttle, the true value for Soyuz's heat flux is likely to be higher, especially considering the Space Shuttle has a much higher lift-to-drag ratio causing a prolonged reentry at a lower sustained heat flux. The final major assumption was that only approximately 2% of the re-entry heat flux goes towards heating the backshell and, by extension, the cabin. As mentioned in Section 2.2, heat absorption ranges between 2-5% have been observed historically, however there is not a true value known for the Soyuz spacecraft.

Despite these limitations, the group firmly believes the results of this study are worthwhile and a practical application of AAE338 class materials to a real-world problem. With further study and resources, the limitations above may be addressed to make the analysis and results more accurate.

4 Discussion and Conclusion

The Soyuz MS-22 mission's primary goal was to transport one astronaut: Francisco Rubio, and two cosmonauts: Sergey Prokopyev and Dmitry Petelin, to and from the International Space Station. With the failure of the coolant system due to a micro-meteor strike, temperatures within the capsule would be free to fluctuate due to the radiation environment in space as well as the hypersonic re-entry of the spacecraft.

In a nominal Soyuz mission, the spacecraft's internal cabin temperature during re-entry & descent is maintained at a temperature of 21 degrees Celsius to 24 degrees Celsius (70 to 75 degrees Fahrenheit) (Christy, 2023).These values are well within the safe range of what humans can withstand and operate safely in.

The maintenance of optimal temperatures for human safety is a thoroughly researched and comprehensively understood subject. Such data serves as a fundamental constraint for the design of manned spacecraft by both NASA and Roscosmos.

During the onset of the space race, NASA conducted a wide variety of studies to determine safe ranges for human survival within spacecraft & space habitation modules. One such study titled Criteria of Thermal Regulation for Manned Spacecraft Cabins, characterized the temperature limits at which humans can survive for indefinite periods of time. The study concluded these limits to be between of 4 degrees Celsius and 35 degrees Celsius (40 95 degrees Fahrenheit). (Johnson, 1966)

In addition, this study examined the highest temperature that a human would be able to withstand for a short period of time. The study determined this value to be approximately 53 degrees Celsius. At this temperature, humans would start to experience severe hyperthermia (the opposite of hypothermia). Onset of hyperthermia is a severe medical emergency that requires immediate treatment. If left untreated, it can lead to serious complications such as organ failure, seizures, and eventually death.

NASA recognizes that spacecraft temperatures above this limit can cause several health problems for a crew such as dehydration, heat exhaustion, and heat stroke. If the internal spacecraft temperature approaches or exceeds the safety limit, NASA will be forced to abort the mission to preserve the crew.

As depicted below in Figure 9, The predicted final internal spacecraft temperature is between 53-55 degrees Celsius (127 to 131 degrees Fahrenheit). Although no final report has yet been released for the MS-22 incident, Roscosmos engineers have stated on multiple occasions that the descent module reached & potentially exceeded internal temperatures of 50 degrees Celsius (Smith, 2023). Therefore, our spacecraft thermal model seems to align with real-world.

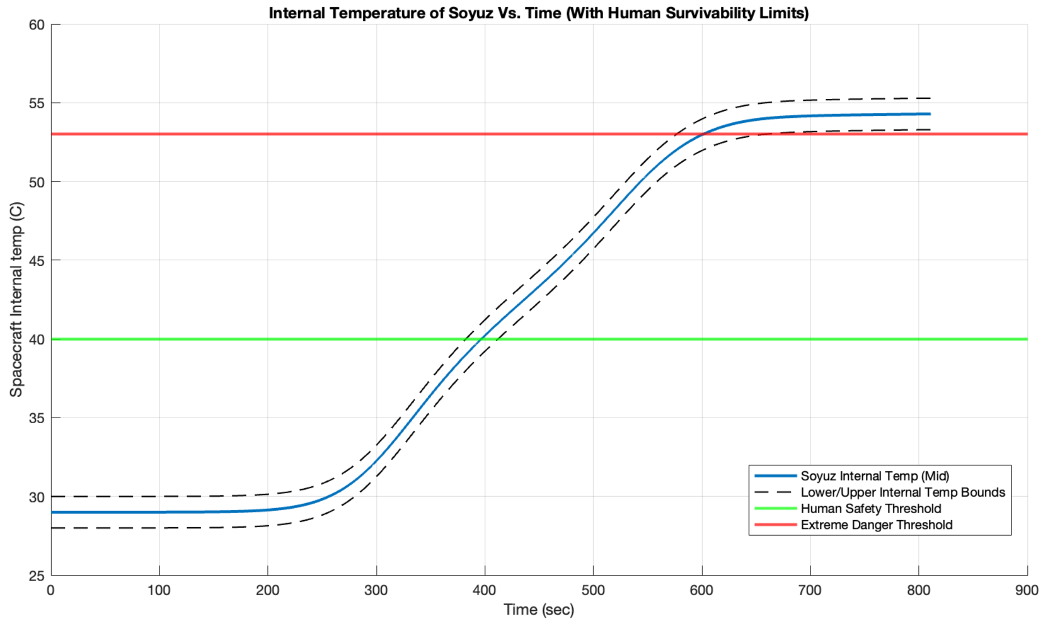

Figure 9: Internal Temperature of Soyuz over Time With Temperature Limits

The predicted internal temperature curve clearly shows crew cabin conditions would exceed the safety threshold of 40 degrees Celsius established by NASA. Additionally, the final temperature observed exceeds the danger threshold for any human. In such a scenario, the crew would be at an elevated risk of suffering from hyperthermia, a potentially life-threatening condition as discussed previously.

In addition to the health effects posed by high temperatures, the delicate electronics housed inside of the Soyuz decent module could be damaged. These electronics control the landing sequence of the decent module. Although most of the electronics are safeguarded by the thermal protection system, the crew-operated instruments are still susceptible to high internal temperatures. Such exposure could potentially cause these critical systems to malfunction, posing an additional risk to the safety of the crew.

Based on this prediction and analysis, our group concludes the crew would have likely suffered severe health complications or even death on their descent back to Earth if they had returned on the damaged MS-22 spacecraft. Therefore, the MS-23 mission to rescue the crew was likely the correct decision, a decision that saved the lives of the three crew members and ensured their safe return to Earth.

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6 APPENDIX A – Code for Calculation of Spacecraft Thermal Properties

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%     AAE 338 Final Project        %
% Group 17 - Soyuz Material Characterization%
%  Drew Lundin - alundin@purdue.edu    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Material Propertis
rho_Torlon = 1.30 * 10^3; % Density of Ftorlon material [kg/m^3]
cp_Torlon = 998.5 ; % Specific heat of Ftorlon material [J/kg/K]

rho_FG = 1.625 * 10^3; % Density of fiberglass material [kg/m^3]
cp_FG = 700; % Specific heat of fiberglass material [J/kg/K]

rho_VIM = 145; % Density of the silica glass material material [kg/m^3]
cp_VIM = 741 % Specific heat of the silica glass material [J/kg/K]
rho_VAC = 0;
cp_VAC = 0;

rho_Al = 2.7 * 10^3; % Density of the aluminum materials [kg/m^3]
cp_Al = 890; % Specific heat of the aluminum material [J/kg/K]

rho_air = 1.164; % Density of the cabin air [kg/m^3]
cp_air = 700; % Specific heat of the air [J/kg*K]

% Average Thickness of Each Material
t_Torlon = 3.5 * 10^-3; % Average thickness of the ftorlon material [m]
t_FG = 2.35 * 10^-3; % Average thickness of the fiberglass material [m]
t_Al = 2.0 * 10^-3; % Average thickness of the aluminum AMG-6 material [m]
t_VIM = 2.9 * 10^-3; % Average thickness of the fiberous filica material [m]
t_air = r_soyuz - sum([t_FG,t_Al,t_VIM]); % thickness of air [m]
t_VAC = 50.5 * 10^-3;

% Computing Volume of each spherical layer
v_Torlon = 4/3*pi*(r_soyuz)^3 - 4/3*pi*(r_soyuz - t_Torlon)^3;

v_FG = 4/3*pi*(r_soyuz - t_Torlon)^3 - 4/3*pi*(r_soyuz - t_Torlon - t_FG)^3;

v_VIM = 4/3*pi*(r_soyuz - t_Torlon -  t_FG)^3 -...
    4/3*pi*(r_soyuz - t_Torlon -  t_FG - t_VIM)^3;

v_VAC = 4/3*pi*(r_soyuz - t_Torlon -  t_FG - t_VIM)^3 -...
    4/3*pi*(r_soyuz - t_Torlon -  t_FG - t_VIM - t_VAC)^3;

v_Al = 4/3*pi*(r_soyuz - t_Torlon -  t_FG - t_VIM - t_VAC)^3 -...
    4/3*pi*(r_soyuz - t_Torlon -  t_FG - t_VIM - t_VAC - t_VAC - t_Al)^3;

v_air = 4/3*pi*(r_soyuz - t_Torlon -  t_FG - t_VIM - t_VAC - t_VAC - t_Al)^3;

cp_list = [cp_Torlon,cp_FG,cp_VIM,cp_VAC, cp_Al, cp_air]
v_list = [v_Torlon,v_FG,v_VIM,v_VAC, v_Al, v_air]

% Volume weighted average specific heat capacity
cp_soyuz = (sum(v_list))^-1 * sum(cp_list.*v_list)
```

7 APPENDIX B – Code for Spacecraft Reentry/Thermal Simulation

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%     AAE 338 Final Project         %
% Group 17 - Soyuz Reentry Analysis %
%  Surya M - smanikha@purdue.edu    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear;clc;close all force hidden;

% This main script runs the reentry simulation by leveraging EOMs found in
% OrbitEoms.m and the initial conditions laid out in this file.
%   Dependencies:
%       - OrbitEoms.m : Reentry planar flight EOMS implementation
%       - temperature.m : ISA implementation for atmospheric temperature
%       - density.m : CIRA Ref. Atm. Model implementation for atm density
%       - sonicspeed.m : Calcualte sonic speed at a certain altitude

% Soyuz Entry ICs:
    entryAlt =  122*1000; % Height of initial thermal interface (m)
    fpa =  (-1.35)*(pi/180); % Initial flight path angle of Soyuz (rad)
    vi =  7870; % Initial velocity at thermal interface (m/s)

% Soyuz Properties
    cd = 1.3; % Drag coeff at trim condition
    ld = .25; % Lift to Drag Ratio of Spacecraft
    Ac = (pi/4) * (2.2^2); % Capsule cross sectional area (m^2)
    m = 2900; % descent module mass (kg)

% Simulation Parameters
    Re = 6376; % Radius of Earth (km)
    mu = 3.986e5; % Gravitational Parameter of Earth
    tf = 20*60; % Final time (sec)
    t = linspace(0,tf, 10000); % Time array (sec)
    stop_alt = 10; % stop at this altitude (km)
    options = odeset('RelTol',1e-12, 'AbsTol',1e-12);

% Run Simulation
    [t,y] = ode45(@(t,y) OrbitEOMS(t,y,cd,mu,ld,Re,m,Ac), ...
        [0,tf], [vi, fpa, 0, entryAlt+(Re*1000)],options);

% Extract values:
    R = y(:,4); % Radius result array
    boolArr = (R-(Re*1000)) > 0; % boolean array to get values where h > 0
    V = y(:,1); % Velocity result array
    Gamma = y(:,2)*(180/pi); % FPA result array
    S = y(:,3); % Downrange travel result array
    h = R-(Re*1000); % Height result array
    a = sonicspeed(h); % sonnic speed at each point in trajectory
    M = V ./ a; % Mach number at each point in trajectory

% Calculate Reentry Heating
    v_excl = V(boolArr);
    q = .02.*(.08/4).*(density( ... % Calculate instantaneous heat flux
        h(boolArr)./1000)).*(power(v_excl,3));
```

```matlab
    Tim = 35; % Initial spacecraft temp condition bounds (C)
    Tiu = 40;
    Til = 30;
    cp = 685; % Spacecraft specific heat capacity

    x = t(boolArr);
    y = q;
    Q = [];
    for idx = 2:length(y) % integrate q to fid heat addition Q
        Q = [Q; trapz(x(1:idx), y(1:idx))*(6.8/2)];
    end

    dT = Q ./(m*cp); % find temperature curve Q = mcpdt

 % Plot Reentry Heat Information
    figure();
    subplot(3,1,1);
    plot(t(boolArr), q/1000, 'LineWidth',2);
    grid on;
    xlabel('Time (sec)');
    ylabel('Heat Flux (kW/m^2)')
    title('Heat Flux Imparted to Soyuz Vs. Time')

    subplot(3,1,2);
    plot(x(2:end), Q, 'LineWidth',2);
    grid on;
    xlabel('Time (sec)');
    ylabel('Heat Transfer (Joules)')
    title('Cumulative Heat Transfer (Energy Addition) to Soyuz Vs. Time')

    subplot(3,1,3); hold on;
    plot(x(2:end), Tim+dT, 'LineWidth',2, 'LineStyle', '-');
    plot(x(2:end), Til+dT, 'LineWidth',1, 'LineStyle', '--', Color='Red');
    plot(x(2:end), Tiu+dT, 'LineWidth',1, 'LineStyle', '--', Color='Red');
    grid on; legend(["Soyuz Internal Temp (Mid)","Lower/Upper Bounds"]);
    xlabel('Time (sec)');
    ylabel('Spacecraft Internal temp (C)')
    title('Internal Temperature of Soyuz Vs. Time')

% Plot Reentry Trajectory:
    figure();
    subplot(4,1,1);
    plot(S(boolArr)./1000, h(boolArr)./1000, 'LineWidth',2);
    grid on;
    xlabel('Downrange Distance Travelled (km)');
    ylabel('Height (km)');
    title("Soyuz Spacecraft Re-entry Profile")

    subplot(4,1,2);
    plot(t(boolArr), V(boolArr), 'LineWidth',2);
    grid on;
    xlabel('Time (sec)');
    ylabel('Velocity (m/s)')
    title('Velocity Magnitude of Soyuz Vs. Time')
```

```
    subplot(4,1,3);
    plot(t(boolArr), h(boolArr)./1000, 'LineWidth',2);
    grid on;
    xlabel('Time (sec)');
    ylabel('Height (km)');
    title("Height of Soyuz Vs. Time")

    subplot(4,1,4);
    plot(t(boolArr), M(boolArr), 'LineWidth',2);
    grid on;
    xlabel('Time (sec)');
    ylabel('Mach Number')
    title('Mach Number of Soyuz Vs. Time')

% Plot internal temp with safety regions:
    figure(); hold on;
    plot(x(2:end), Tim+dT, 'LineWidth',2, 'LineStyle', '-');
    plot(x(2:end), Til+dT, 'LineWidth',1, 'LineStyle', '--', Color='black');
    plot(x(2:end), Tiu+dT, 'LineWidth',1, 'LineStyle', '--', Color='black');
    yline(40, 'g-', 'LineWidth',2);
    yline(53, 'r-', 'LineWidth',2);
    grid on;
    legend(["Soyuz Internal Temp (Mid)","Lower/Upper Internal Temp 
Bounds",...
            "", "Human Safety Threshold", "Extreme Danger Threshold"]);
    xlabel('Time (sec)');
    ylabel('Spacecraft Internal temp (C)')
    title('Internal Temperature of Soyuz Vs. Time (With Human Survivability 
Limits)')

% Old Plots, No longer needed:
    %figure();
    %plot(t(boolArr), Gamma(boolArr));
    %grid on;
    %xlabel('Time (sec)');
    %ylabel('FPA (deg)');
    %title('FPA of Spacecraft Vs. Time');

    %figure();
    %plot(t(boolArr), S(boolArr));
    %grid on;
    %xlabel('Time (sec)');
    %ylabel('Downrange (m)');
    %title("Downrange Motion of Spacecraft Vs. Time")


    %tmod = t(boolArr);
    %figure();
    %plot(tmod(2:end), (diff(V(boolArr))./diff(t(boolArr)))/9.8);
    %grid on;
    %xlabel('Time (sec)');
    %ylabel('G Loading (g)');
    %title("Axial Loading of Spacecraft Vs. Time");
```

8 APPENDIX C – Code Implementation of Planar Flight EOMs

```
function ydot = OrbitEOMS(t, y, Cd, mu, LD, Re, m, S)
    % This file depicts the EOMs for Planar Flight over a spherical
    % nonrotating planet to be used for reentry. See parameters list.
    % AAE 338 Final Project - Surya M. (smanikha@purdue.edu)
        % Cd: Spacecraft drag coeff
        % mu: Gravitational parameter of orbiting body
        % LD: Spacecraft Lift to Drag Ratio
        % Re: Radius of orbiting body
        % m: Mass of spacecraft
        % S: cross sectional area of object

    % State Variables
    v = y(1);
    gamma = y(2);
    s = y(3);
    r = y(4);
    rho = density((r/1000)-Re);

    % Spacecraft Aerodynamic Model
    D = 0.5 * rho * (v^2) * S * Cd;
    L = LD * D;

    % Gravitational Model
    g = 9.8;

    % Diff EQs
    dvdt = (-D/m) - (g*sin(gamma));
    dgammadt = ((L/m) - ((g - ((v^2)/r))*cos(gamma)))/v;
    dsdt = (Re/r)*v*cos(gamma);
    drdt = v*sin(gamma);

    % State Matrix
    ydot = [dvdt;dgammadt;dsdt;drdt];
end
```

9 APPENDIX D – Code Implementation of ISA for Atmospheric Temperature

```
function temp = temperature(h)
    %:temperature: Returns temperature at altitude h through
    % AAE 338 Final Project - Surya M. (smanikha@purdue.edu)
        %          International Standard Atmosphere
        %:param h float: Height above MSL (m)
        %:return temp float: Temperature at altitude h (kelvin)

    % Atmosphere sample points: Altitude (m) and corresponding temp (C)
    alt = [-1000, 0, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000,...
        10000, 15000, 20000, 25000, 30000, 40000, 50000, 60000, 70000,...
        80000,90000,100000,105000,110000,115000,120000,125000,130000];

    TRef = [21.5, 15, 8.5, 2, -4.49, -10.98, -17.47, -23.96, -30.45, ...
        -36.94, -43.42, -49.9, -56.5, -56.5, -51.6, -46.64, -22.8, -2.5,...
        -26.13, -53.57, -74.51,-86.28,-78.07,-64.31,-33.15,26.85,85.85,...
        144.08,196.12];

    T = interp1(alt, TRef, h, "spline","extrap"); % Perform Interpolation
    temp = T+298;
end
```

10 APPENDIX E – Code Implementation of CIRA Model for Atmospheric Density

```
function rho = density(h)
    %:density: Returns density at altitude h through
    %          CIRA Reference Atmosphere Model.
    %          Valid up to 180 km
    % AAE 338 Final Project - Surya M. (smanikha@purdue.edu)
    %:param h float: Height above MSL (km)
    %:return rho float: Density at altitude h (kg/m^3)
    % See : https://www.spaceacademy.net.au/watch/debris/atmosmod.htm

    a0 = 7.001985e-2; % Define polynomial fit coefficients
    a1 = -4.336216e-3;
    a2 = -5.009831e-3;
    a3 = 1.621827e-4;
    a4 = -2.471283e-6;
    a5 = 1.904383e-8;
    a6 = -7.189421e-11;
    a7 = 1.060067e-13;

    polyfn = ((((((a7.*h + a6).*h + a5).*h + a4).*h + a3).*h + a2)...
             .*h + a1).*h + a0;
    rho = 10.^polyfn; % Calculate density at h using 7th order polynomial.
end
```

11 APPENDIX F – Code of Helper Function to Calculate Sonic Speed at Altitude

```
function a = sonicspeed(h)
    %:sonicspeed: Returns sonic speed at altitude h through
        %         International Standard Atmosphere
    % AAE 338 Final Project - Surya M. (smanikha@purdue.edu)
        %:param h float: Height above MSL (m)
        %:return a float: Sonic speed at altitude (m/s)

        gamma = 1.4;
        R = 287;
        T = temperature(h);
        a = sqrt(gamma*R*T); % simple formula to calculate sonic speed
end
```