
SEMESTER 1 ASSESSMENT PAPER 2020/21

TITLE: **Advanced Astronautics**

DURATION – 24 hours

This paper contains **FOUR** questions.

Attempt all **FOUR** questions. Your answer to each question attempted should commence on a new page and be appropriately numbered.

All Questions are worth 25 marks (total 100 marks). An outline marking scheme is shown in brackets to the right of each question. Note that marks will only be awarded when appropriate working is given.

Your answers should be handwritten, unless you have a statement of additional examination requirements (AERs) approved by Enabling Services which specifies that you may type your answer.

You will need to be in a quiet space for the duration of your assessment with no interruptions and to check all your equipment to ensure that they are set up correctly.

This final assessment is recommended to take **approximately 4 hours of working time**. You are advised to allocate your time accordingly.

You are not permitted to obtain assistance by improper means or ask for help from or give help to any other person.

All calculations should be done accurately, using a spreadsheet or similar tool such as Python or Matlab. It should be clearly stated when such a tool has been used.

You should provide explanations for every answer and indicate the unit(s) used in **ALL** calculations. All numeric answers should be provided with **FOUR** significant figures.

Results from the lecture material (anything on the Blackboard module site) can be used wherever needed. Any resources accessed from the internet must be properly cited.

Q1. A geostationary satellite requires 2 kW of power for a nominal 10-year lifetime. The bus voltage is to be 42 V(±1.0V) in sunlight at EOL (End-Of-Life). Its solar array will be maintained pointing directly to the Sun during the mission. The same satellite also requires 260W of power to charge a secondary power system. The properties of the power module used in the satellite including a solar array and battery pack are listed as:

Solar Cell	
Maximum operating temperature	401 K
Minimum operating temperature	301K
EOL degradation (10 year) for both voltage and current at maximum power	70.0% of beginning- of-life (BOL) capacity for both voltage and current at maximum power
Solar intensity	1350 W/m^2 at 1 A.U.
Voltage at maximum power at 301K	2.3 V
Current at maximum power at 301K	400 mA
Temperature coefficient at EOL for voltage	-2.2 mV/K
Temperature coefficient at EOL for current	250 μA/K
Packing factor	10% loss for spacing

As a secondary power system, a Li-ion battery is used. The design data of the Li-ion battery are given as:

Average cell charge voltage	4.20 V
Average cell discharge voltage	3.55 V
Maximum eclipse time	70 min.
Maximum DOD	40 %
Specific energy based on discharge capacity	170 Wh/kg

Assume there are no transmission losses and voltage drop. Answer the following questions. Provide explanations for every answer and indicate the unit(s) used in your calculations.

Q1. Cont…

Q1. Cont…

(i) Calculate the number of cells in a string, which are connected in series, to support the bus voltage at the maximum operating temperature during the entire mission period.

[5 marks]

(ii) Calculate the number of strings in a solar array, which are connected in parallel, to support the satellite power requirement at the maximum operating temperature during the entire mission period.

[5 marks]

(iii) Estimate the maximum power generated by the solar array during the mission.

[5 marks]

(iv) The charge rate drives battery size. If the charge rate is too high, it can cause overheating of the battery. A good rule for the allowable charge rate is

$$R_{charge} = \frac{C_{charge}}{15}$$

where C_{charge} is charge capacity in Ah. Find the desired charge current of the secondary power system, and estimate the required weight of a Li-ion battery to support the required power load.

[10 marks]

[Total 25 marks]

TURN OVER

Q2. Use the given information to answer the following questions. Indicate the unit(s) used in **ALL** your calculations.

(i) The Orion spacecraft will use high-temperature reusable surface insulation tiles to protect the bottom of the spacecraft during the reentry. The tiles use a black borosilicate glass coating that has an emittance value of 0.8 and covers areas of the vehicle in which temperatures reach up to 1,200 °C. The insulation tile should prevent heat transfer to the underlying orbiter aluminium skin and structure, which should be below 3,600 W/m^2 with a maximum temperature of 300 °C. Conduction will be the most significant means of heat transfer within the insulation tile. The average thickness of the insulation tile on the Orion spacecraft is 10.0 cm. Calculate the allowed maximum thermal conductivity of the tile.

[5 marks]

(ii) The visible albedo of asteroid 2062 Aten is approximately 0.25, and its thermal emissivity is 0.7. The average intensity of solar radiation is 1,400 W/m^2 at 2062 Aten's orbit. 2062 Aten has no atmosphere. Assume the surface temperature of 2062 Aten is mainly dictated by incident solar radiation. Estimate the temperature of the Sun-facing surface of 2062 Aten.

[5 marks]

Q2. Cont…

Q2. Cont…

A spacecraft requiring an average power loading of 600 W during Sun-time has a solar array which consists of two deployed single-panel wings. The solar array is maintained pointing directly to the sun during the mission. Each solar panel is 1.5m wide and 2.0m long and has 2,500 Advanced Triple Junction (ATJ) solar cells. Each ATJ cell is 0.14mm thick with sides 3 cm by 4 cm. The emissivity and absorptance of the used ATJ solar cell are 0.85 and 0.92, respectively.

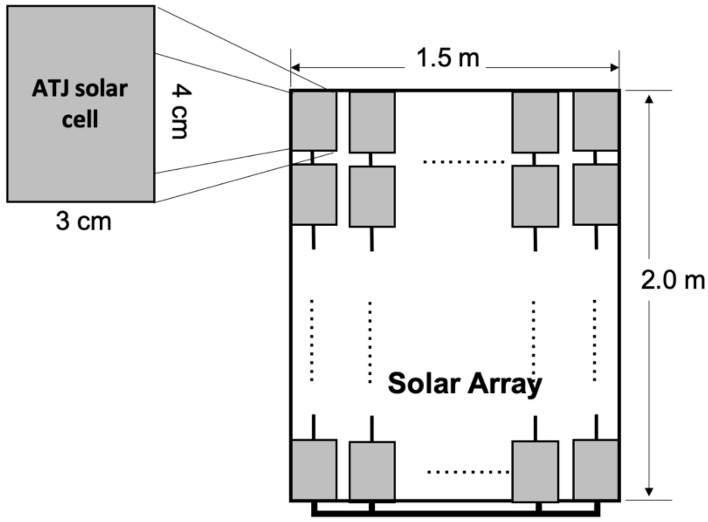

Figure Q2. A schematic of a solar array using ATJ solar cells.

The degradation of the ATJ solar cell voltage and current at maximum power at the mission orbit is expected to be 5% at the end-of-mission. The ATJ solar cell at the mission orbit has maximum power operating characteristics of $V_{mp} = 2.30\ \mathrm{V}$ and $I_{mp} = 200.0\ \mathrm{mA}$ at 300 K. The temperature coefficients for ATJ solar cell are $10.0\ \mu\mathrm{A/K}$ and $-7.0\ \mathrm{mV/K}$ for current and voltage, respectively. The packing factor of the solar array is 90%, and the temperature coefficients are constant during the mission. ATJ solar cell efficiency used in the solar array is 28.5%. Assume ATJ solar cell efficiency will be constant during the mission. During the mission, the spacecraft encounters large solar distance variations from 1 AU near Earth to 0.3 AU. Use the given information to answer questions (iii) and (iv).

Q2. Cont…

TURN OVER

Q2. Cont…

(iii) Assume that only direct solar radiation affects the temperature of the solar array. Ignore the heat loss by radiation from the back of the solar array. Calculate the maximum and minimum temperatures of the solar array during its operation.

[8 marks]

(iv) The solar array consists of 50 strings, and 50 ATJ solar cells are connected on each string in series. The surface temperature of a solar array needs to be maintained below 500 K. Include the heat loss by radiation from the back of the solar array. The back side of the solar array has an emissivity of 0.9. Assume both sides of the solar array will be at the same temperature. Calculate the amount of heat that should be added or removed by a thermal control system on each solar panel.

[7 marks]

[Total 25 marks]

Q3 The Mars Science Laboratory (MSL) spacecraft is being designed to carry a large rover (> 800 kg) to the surface of Mars using a blunt-body entry capsule as the primary decelerator. MSL is designed for a direct entry (ballistic entry) with an angle of attack of -15.2 degree. It has an entry mass of about 3,000 kg and is a 70 degree half-angle spherically blunted cone with 4.5 metres in diameter. The ballistic coefficient of MSL is about 140 kg/m^2, and it will enter the Martian atmosphere at speeds of about 5.9 km/s. For the prediction of the Martian atmosphere, the Mars GRAM model can be used, which has been successfully used for the Mars Pathfinder mission. As shown in Figure Q4, the GRAM model has two altitude sections, 0 ~ 25.65 km and 25.65 ~ 125 km, with an exponential atmosphere model in each. The parameters of the exponential atmosphere models are shown in Table Q3.

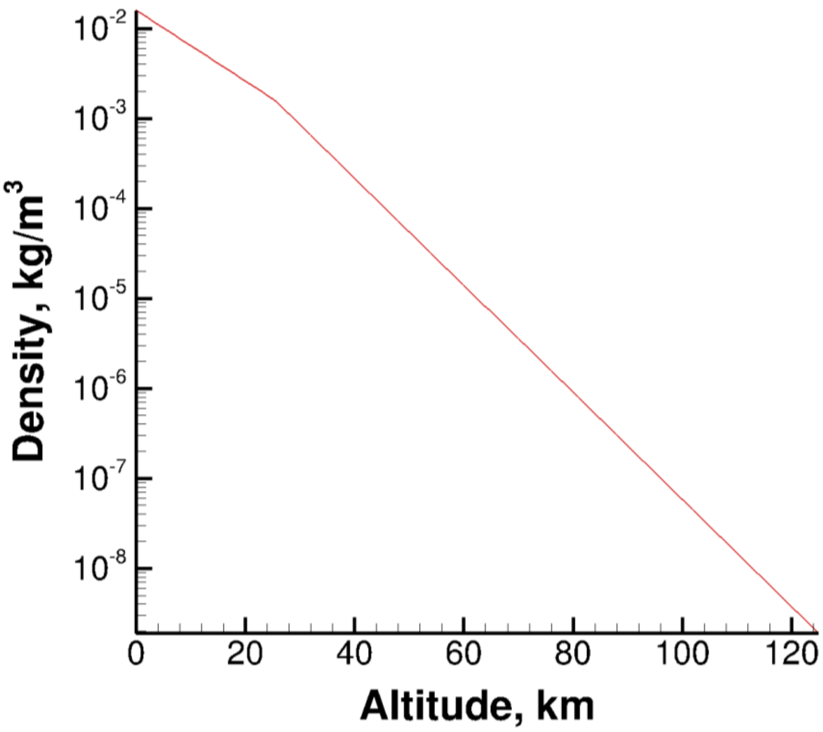

Figure Q3. Exponential Mars Atmosphere Model

Table Q3. The parameters of exponential atmosphere model for Mars

Altitude Range	Surface density, kg/m^3	Scaled height, km
0 ~ 25.65 km	0.0159	11.049
25.65 ~ 125 km	0.0525	7.295

Q3. Cont…

TURN OVER

Q3. Cont…

Use the given information to answer the following questions. Indicate the unit(s) used in ALL your calculations.

(i) The MSL EDL system confirms the successful start of EDL sequence when its velocity reaches 5.5 km/s. Find the corresponding altitude in km.

[4 marks]

(ii) Assume the density of Martian atmosphere is 0.0 kg/m^3 when MSL will enter the Martian atmosphere at speeds of about 5.9 km/s. Calculate the speed of MSL at the altitude of 15 km, which is one of the critical moments during the EDL.

[8 marks]

(iii) Calculate the altitude and speed of MSL at which maximum deceleration occurs during Mars entry.

[10 marks]

(iv) MSL is equipped with a PICA Thermal Protection System (TPS) consisting of 113 different Tiles. During peak heating of the EDL sequence, the PICA Heatshield of the vehicle has to withstand a thermal load of more than 5,700 J/cm^2 with a turbulent air flow around the entry vehicle. At this point, Long-range IR sensors showed that the peak heat rate on PICA TPS is greater than 200 W/cm^2. The emissivity of a PICA TPS is 0.85. Calculate the minimum surface temperature of the PICA TPS at peak heating.

[3 marks]

[Total 25 marks]

Q4. A spacecraft of mass m is equipped with a novel type of solar sail that can be switched between fully transparent and fully reflective.

When fully tranparent, the solar sail has no effect on the spacecraft. In its fully reflective state, the force on the spacecraft from the solar sail is always pointing radially away from the Sun and its magnitude is given by

$$F_{SRP} = \frac{m \cdot \mu_{SRP}}{r^2}$$

where $\mu_{SRP} = 1.020 \cdot 10^9\ km^3/s^2$ and r is the distance from the sun. Apart from the solar sail and the solar gravity ($\mu_{Sun} = 1.3 \cdot 10^{11}\ km^3/s^2$) there are no other perturbations to the motion of the spacecraft.

Use the given information to answer the following questions. Provide explanations for every answer and indicate the unit(s) used in **ALL** your calculations.

(i) State all assumptions made in the restricted 2-body problem, and verify that they apply to the Sun-spacecraft system.

[2 marks]

(ii) Starting from Newton's second law, derive the equations of motion of the spacecraft position $\ddot{\vec{r}}$ taking into account solar gravitational acceleration and solar radiation pressure (from the solar sail), assuming the restricted 2-body problem.

[4 marks]

(iii) Show that switching on the solar sail mathematically has the same effect as slightly reducing the mass of the central body, and solve the equations of motion for the scalar radial distance as a function of the angle around the Sun. Hint: combine the similar mathematical expressions of the two forces into an "effective" total force.

[4 marks]

Q4. Cont…

TURN OVER

Q4. Cont…

(iv) If the spacecraft instantaneously switches the solar sail from fully transparent to fully reflective **at apogee** and assuming the spacecraft remains at apogee after the switch, which of the following quantities change **instantaneously** as well?

- Position
- Semi-major axis
- Eccentricity
- Velocity
- Apogee radius
- Perigee radius
- Angular momentum

[4 marks]

(v) Initially, the solar sail is **fully transparent** and the spacecraft is in a $1.5 \times 10^8\ km\ (= 1\ A.U.)$ circular orbit around the Sun. The spacecraft then switches the solar sail to **fully reflective** and maintains this configuration until its distance from the Sun reaches a **maximum**. At that point, what are the spacecraft's new scalar values of position r and velocity v?

[6 marks]

(vi) Right at apogee, the spacecraft switches the solar sail back to **fully transparent** and maintains this configuration until it returns to its **minimum** distance from the Sun. At that point, what are the spacecraft orbit's new semi-major axis and eccentricity?

[5 marks]

[Total 25 marks]

END OF PAPER