A Journey to Europa 🚀

IJSO Theory Mock Test

This is an IJSO mock test, a paper made to mimic the style and difficulty of IJSO questions. Its aim is to help students in preparing for the IJSO and IJSO like competitions.

The questions in this paper were made by the following members of our team (in alphabetical order):

- Alex Jicu (Romania)
- Filip Kilibarda (Serbia)
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- Kotryna Mieldažytė (Lithuania)
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No.	Problem	Author	Marks
1	Gaseous Planets	Alex Jicu	5.25
2	Before the Journey in Europa	Thenura Wickramaratna	3.85
3	Discovery during the Journey	Thenura Wickramaratna & Jailson Godeiro	4.25
4	Life in Europa	Kasiban Parthipan & Kotryna Mieldažytė	9.40
5	Life-sustaining Chemicals	Alex Jicu	2.25
6	Jicu and His Rover	Thenura Wickramaratna	5.00

In solving the questions, you might need to use the following constants:

Constant	Notation	Value
Acceleration due to gravity	g	$9.8\ \mathrm{ms^{-2}}$
Gravitational constant	G	$6.67 \cdot 10^{-11}\ \mathrm{m^3/\ kg \cdot s^2}$
Planck's constant	h	$6.62 \cdot 10^{-34}\ \mathrm{J \cdot s}$
Elementary charge	e	$1.6 \cdot 10^{-19}\ \mathrm{C}$
Speed of light in vacuum	c	$3 \cdot 10^{8}\ \mathrm{ms^{-1}}$
Density of water	ρ	$1000\ \mathrm{kg\ m^{-3}}$
Stefan-Boltzmann constant	σ	$5.67 \cdot 10^{-8}\ \frac{\mathrm{W}}{\mathrm{m^2 K^4}}$
Universal gas constant	R	$8.314\ \mathrm{J\ mol^{-1}\ K^{-1}}$ $0.08206\ \mathrm{atm\ L\ mol^{-1}\ K^{-1}}$
Avogadro's number	N_A	$6.022 \cdot 10^{23}\ \mathrm{mol^{-1}}$
Faraday's constant	F	$96\,500\ \mathrm{C/mol}$
Pi	π	3.14
Electrical permittivity of free space	ε_0	$8.85 \cdot 10^{-12}\ \mathrm{F \cdot m^{-1}}$
Magnetic permeability of free space	μ_0	$4\pi \cdot 10^{-7}\ \mathrm{H/m}$
Mass of Earth		$5.97 \cdot 10^{24}\ \mathrm{kg}$
Mass of Moon		$7.35 \cdot 10^{22}\ \mathrm{kg}$
Mass of Sun		$1.99 \cdot 10^{30}\ \mathrm{kg}$
Radius of Earth		$6.4 \cdot 10^{6}\ \mathrm{km}$
Radius of Moon		$1.7 \cdot 10^{6}\ \mathrm{km}$
Radius of Sun		$6.96 \cdot 10^{8}\ \mathrm{km}$
Specific heat capacity of water	c_w	$4200\ \mathrm{J/kg \cdot {}^\circ C}$
Average molar mass of air	M	$28.9\ \mathrm{g/mol}$

If any other value is provided in the problem, use the value provided, not the one in the table. You can also use the following conversion formulas:

$\mathrm{T\ (K) = t\ (^\circ C) + 273}$	$\mathrm{t\ (^\circ F)} = \frac{9}{5}\mathrm{t\ (^\circ C)} + 32$
$1\mathrm{bar} = 1\mathrm{atm} = 101\,000\mathrm{Pa} = 760\mathrm{mmHg}$	$1\mathrm{u} = 1\mathrm{Da} = 1.66 \cdot 10^{-27}\mathrm{kg}$
$1\mathrm{L} = 10^{-3}\ \mathrm{m^3}$	$1\ \mathrm{day} = 24\mathrm{h}$

If needed, you can use the periodic table given below:

(Use atomic masses rounded to two decimal places.)

IUPAC Periodic Table of the Elements

Key: atomic number / **Symbol** / name / abridged standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.0080 ± 0.0002																	2 **He** helium 4.0026 ± 0.0001
3 **Li** lithium 6.94 ± 0.06	4 **Be** beryllium 9.0122 ± 0.0001											5 **B** boron 10.81 ± 0.02	6 **C** carbon 12.011 ± 0.002	7 **N** nitrogen 14.007 ± 0.001	8 **O** oxygen 15.999 ± 0.001	9 **F** fluorine 18.998 ± 0.001	10 **Ne** neon 20.180 ± 0.001
11 **Na** sodium 22.990 ± 0.001	12 **Mg** magnesium 24.305 ± 0.002											13 **Al** aluminium 26.982 ± 0.001	14 **Si** silicon 28.085 ± 0.001	15 **P** phosphorus 30.974 ± 0.001	16 **S** sulfur 32.06 ± 0.02	17 **Cl** chlorine 35.45 ± 0.01	18 **Ar** argon 39.95 ± 0.16
19 **K** potassium 39.098 ± 0.001	20 **Ca** calcium 40.078 ± 0.004	21 **Sc** scandium 44.956 ± 0.001	22 **Ti** titanium 47.867 ± 0.001	23 **V** vanadium 50.942 ± 0.001	24 **Cr** chromium 51.996 ± 0.001	25 **Mn** manganese 54.938 ± 0.001	26 **Fe** iron 55.845 ± 0.002	27 **Co** cobalt 58.933 ± 0.001	28 **Ni** nickel 58.693 ± 0.001	29 **Cu** copper 63.546 ± 0.003	30 **Zn** zinc 65.38 ± 0.02	31 **Ga** gallium 69.723 ± 0.001	32 **Ge** germanium 72.630 ± 0.008	33 **As** arsenic 74.922 ± 0.001	34 **Se** selenium 78.971 ± 0.008	35 **Br** bromine 79.904 ± 0.003	36 **Kr** krypton 83.798 ± 0.002
37 **Rb** rubidium 85.468 ± 0.001	38 **Sr** strontium 87.62 ± 0.01	39 **Y** yttrium 88.906 ± 0.001	40 **Zr** zirconium 91.224 ± 0.002	41 **Nb** niobium 92.906 ± 0.001	42 **Mo** molybdenum 95.95 ± 0.01	43 **Tc** technetium [97]	44 **Ru** ruthenium 101.07 ± 0.02	45 **Rh** rhodium 102.91 ± 0.01	46 **Pd** palladium 106.42 ± 0.01	47 **Ag** silver 107.87 ± 0.01	48 **Cd** cadmium 112.41 ± 0.01	49 **In** indium 114.82 ± 0.01	50 **Sn** tin 118.71 ± 0.01	51 **Sb** antimony 121.76 ± 0.01	52 **Te** tellurium 127.60 ± 0.03	53 **I** iodine 126.90 ± 0.01	54 **Xe** xenon 131.29 ± 0.01
55 **Cs** caesium 132.91 ± 0.01	56 **Ba** barium 137.33 ± 0.01	57-71 lanthanoids	72 **Hf** hafnium 178.49 ± 0.01	73 **Ta** tantalum 180.95 ± 0.01	74 **W** tungsten 183.84 ± 0.01	75 **Re** rhenium 186.21 ± 0.01	76 **Os** osmium 190.23 ± 0.03	77 **Ir** iridium 192.22 ± 0.01	78 **Pt** platinum 195.08 ± 0.02	79 **Au** gold 196.97 ± 0.01	80 **Hg** mercury 200.59 ± 0.01	81 **Tl** thallium 204.38 ± 0.01	82 **Pb** lead 207.2 ± 1.1	83 **Bi** bismuth 208.98 ± 0.01	84 **Po** polonium [209]	85 **At** astatine [210]	86 **Rn** radon [222]
87 **Fr** francium [223]	88 **Ra** radium [226]	89-103 actinoids	104 **Rf** rutherfordium [267]	105 **Db** dubnium [268]	106 **Sg** seaborgium [269]	107 **Bh** bohrium [270]	108 **Hs** hassium [269]	109 **Mt** meitnerium [277]	110 **Ds** darmstadtium [281]	111 **Rg** roentgenium [282]	112 **Cn** copernicium [285]	113 **Nh** nihonium [286]	114 **Fl** flerovium [290]	115 **Mc** moscovium [290]	116 **Lv** livermorium [293]	117 **Ts** tennessine [294]	118 **Og** oganesson [294]

57 **La** lanthanum 138.91 ± 0.01	58 **Ce** cerium 140.12 ± 0.01	59 **Pr** praseodymium 140.91 ± 0.01	60 **Nd** neodymium 144.24 ± 0.01	61 **Pm** promethium [145]	62 **Sm** samarium 150.36 ± 0.02	63 **Eu** europium 151.96 ± 0.01	64 **Gd** gadolinium 157.25 ± 0.03	65 **Tb** terbium 158.93 ± 0.01	66 **Dy** dysprosium 162.50 ± 0.01	67 **Ho** holmium 164.93 ± 0.01	68 **Er** erbium 167.26 ± 0.01	69 **Tm** thulium 168.93 ± 0.01	70 **Yb** ytterbium 173.05 ± 0.02	71 **Lu** lutetium 174.97 ± 0.01
89 **Ac** actinium [227]	90 **Th** thorium 232.04 ± 0.01	91 **Pa** protactinium 231.04 ± 0.01	92 **U** uranium 238.03 ± 0.01	93 **Np** neptunium [237]	94 **Pu** plutonium [244]	95 **Am** americium [243]	96 **Cm** curium [247]	97 **Bk** berkelium [247]	98 **Cf** californium [251]	99 **Es** einsteinium [252]	100 **Fm** fermium [257]	101 **Md** mendelevium [258]	102 **No** nobelium [259]	103 **Lr** lawrencium [262]

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

For notes and updates to this table, see www.iupac.org. This version is dated 4 May 2022.

Problem 1—Gaseous Planets (5.25 points)

As experienced astronomers, the crew discusses various planets in the solar system during their voyage to Europa. One crew member recalls that on distant planets like Uranus and Neptune, diamonds can form naturally from methane under extreme pressure.

Part A: Diamond Formation

The crew begins to discuss the chemistry behind such transformations. To understand how graphite can turn into diamond, they start crunching the numbers. The reaction is given below:

$C\ (graphite) \rightarrow C\ (diamond)$ (1)

The enthalpies of formation are

$H_f\ (graphite) = 0\ kJ/mol$,

$H_f\ (diamond) = 1.9\ kJ/mol$

A1. Find the enthalpy change of reaction (1).

(0.25 points)

A2. The ratio between the rate constants of reaction (1) at temperatures $T_1 = 3000K$ and $T_2 = 2500K$ is r = 75.

Using the Arrhenius equation:

$$k = Ae^{-\frac{E_a}{RT}}$$

Find the activation energy E_{a_1} of reaction (1)

(1.00 points)

A3. Find the activation energy E_{a_2} of the inverse reaction.

(0.25 points)

Part B: Decomposition of methane

Still fascinated by planetary chemistry, the crew begins discussing how methane—abundant in the atmospheres of gas giants—could form under extreme heat or pressure. They decide to analyze the thermodynamics of this transformation, starting from graphite and hydrogen. The reaction is given below:

$C\ (graphite) + 2H_2 \rightarrow CH_4$ (2)

The enthalpy of formation of methane, $H_f\ (CH_4) = -74.2\ kJ/mol$.

B1. Calculate the enthalpy change of reaction (2)

(0.25 points)

B2. Which of the following will increase the rate of the forward reaction? *Tick the appropriate boxes.*

- ☐ Increase the temperature.
- ☐ Decrease the temperature.
- ☐ Increasing the pressure.
- ☐ Decreasing the pressure.
- ☐ Adding more methane.
- ☐ Adding a catalyst.

(0.50 points)

B3. If the equilibrium constant K for the reaction is 0.25 at 1000 K. At equilibrium, the concentration of methane is measured to be 0.10 mol/L. Find the equilibrium concentration of hydrogen gas $[H_2]$ in mol/L.

(0.75 points)

Part C: Reaction in the Planets

To understand the reaction better, the scientists created a simplified model and carried out the reaction inside it. The diamonds are formed from methane according to the reaction given below.
$CH_4 \rightarrow C\ (diamond) + 2H_2$ (3)
Calculate the enthalpy change of reaction (3)

(0.25 points)

Part D: Methane combustion

In proper conditions, methane can react with oxygen to produce water and formaldehyde (CH_2O). The reaction is exothermic.

D1. Write the balanced equation for this reaction.

(0.30 points)

D2. The unit of the equilibrium constant for this reaction is $mol^a \cdot L^b$. Find the values of constants a and b.

(0.30 points)

D3. An equimolar mixture of methane and oxygen is introduced in a reactor of volume $V = 1.00 \cdot 10^{-3} m^3$. To start the reaction, the mixture is heated to $T = 1.00 \cdot 10^3 K$. At this temperature, the pressure inside the reactor is $P = 1.00 \cdot 10^5$ Pa. What is the total mass of the gases inside the reactor?

(0.50 points)

D4. After a very long time, the partial pressure of methane becomes $p = 1.00 \cdot 10^{-9}$Pa. What is the value K_0 of the equilibrium constant?

(0.60 points)

D5. A. The pressure inside the container is raised by lowering the volume to $\frac{V}{2}$. The new equilibrium constant is K_A

B. The temperature inside the container is raised to 2T. The new equilibrium constant is K_B.

C. The conversion of methane to formaldehyde is frequently catalyzed by nitrogen oxides. A small catalytic amount ($n = 1.00 \cdot 10^{-4}$mol) of nitrogen monoxide is introduced in the reactor. The new equilibrium constant is K_C.

Compare each of the values of constants K_A, K_B and K_C with the initial K_0 value.

(0.30 points)

Problem 2—Before the Journey in Europa (3.85 points)

Before embarking on a multi-day expedition across Europa's harsh icy terrain, Jicu and his international science team (consisting of a total of 10 members) are preparing the HydroRover—their hydrogen-oxygen fuel-cell-powered vehicle. They're also calibrating analytical equipment, checking thermal shielding, and finalizing energy budgets. At the mission base, Europa's surface temperature hovers around –160°C, and the atmosphere is nearly nonexistent, making pressure regulation, gas compression, and thermal management critical.

Part A: Preparing the Fuel Supply

The fuel cell operates using compressed hydrogen and oxygen stored in gas tanks. The fuel cell reaction is

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l) \qquad \Delta H = -286 \frac{\text{kJ}}{\text{mol } H_2}$$

A1. If the rover is expected to consume $1 \cdot 10^6$ kJ of energy over the entire journey, how many grams of hydrogen gas do we need?

(0.60 points)

A2. If the hydrogen is stored at 300K and 200 atm, what is the minimum tank volume (in liters) needed to store all the hydrogen?

(0.65 points)

A3. Each crew member uses approximately 12000 kJ/day, and their bodies generate energy primarily through aerobic respiration of glucose. Assuming 100% of energy comes from glucose oxidation, calculate the extra tank volume (in liters) needed to store the oxygen needed for the entire trip if the trip lasts for 2 weeks.

(0.60 points)

Part B: Thermal Shielding & Material Selection

The thermal flux (heat per unit time) through a piece of a material with thermal conductivity K, thickness Δx and surface area A is:

$$\Phi = KA\frac{\Delta T}{\Delta x}$$

where ΔT is the temperature difference between the faces of the material.

Europa's surface is extremely cold, and the rover electronics are insulated using a thin aluminum layer. The inner walls must maintain a temperature of 25°C.

B1. If the thermal conductivity of aluminum is 205 W/m·K, and the wall is 1.0 cm thick, what is the heat flux (W/m²) through the aluminum if one side is at 25°C and the other at –160°C?

(0.50 points)

B2. To reduce heat loss, Jicu's team wants to add a 2 cm thick polyurethane foam layer (thermal conductivity = 0.030 W/m·K) inside the aluminum panel.

Assuming the same temperature difference, calculate the new total heat flux through the combined system (aluminum + foam), treating the layers as resistors in series.

(1.00 points)

B3. Although Europa receives little sunlight, the rover's solar panel casing absorbs some thermal radiation during surface daylight. Assume daylight lasts for 5 days throughout the trip.

Europa is located $7.80 \cdot 10^8$km from the sun. The sun emits $3.8 \cdot 10^{26}\ W$. The solar panel has an area of 0.5 m², and an absorptivity of 0.85.

Calculate the total energy absorbed (in joules) by the solar panel due to sunlight throughout the whole trip.

(0.50 points)

Problem 3—Discovery during the Journey (4.25 points)

Halfway through the rover expedition, Jicu's team stops near a cracked ridge on Europa's surface.

Part A: Chemical Analysis of the Reddish Sample

Their instruments detect strange reddish streaks across the ice—possibly organic salts or oxidized metal compounds from Europa's subsurface ocean erupting and freezing instantly.

The sample is suspected to contain a mixture of Fe^{2+} (from $FeSO_4$) and Mg^{2+} (from $MgCl_2$). To analyze Fe^{2+} content, the sample is dissolved in water and treated with excess $NaOH$, forming a green precipitate of $Fe(OH)_2$.

A1. If 1.80 g of $Fe(OH)_2$ precipitate is formed, calculate the mass of $FeSO_4$ originally present.

(0.50 points)

A2. If 0.875 g of $Mg(OH)_2$ is obtained, calculate the mass of $MgCl_2$ in the original sample.

(0.50 points)

A3. Based on your answers to A1 and A2, calculate the mass percent composition of $FeSO_4$ and $MgCl_2$ in the original 10.0 g sample.

(0.25 points)

Part B: The depth of the crater

During the exploration, they also discover a crater. Their main goal is to discover its depth; their method will consist of dropping an object and measuring the time it takes for the sound produced to be detected. The most important parameters for the experiment will be the gravity of Europa and the speed of sound.

B1. An experiment was done to determine the gravitational acceleration; it consisted of dropping an object from a known height (20 m) and measuring the time it took to hit the ground (5.50 s). What is the gravitational acceleration on Europa?

(0.50 points)

B2. The speed of sound through the air is given by the equation $v = \sqrt{\frac{\gamma RT}{M}}$. Assume that $\gamma = 1.4$. Where M is the molar mass of the air, note that it is not the same speed of sound for the earth because Europa's atmosphere is different from Earth's. Considering that the air is fully oxygen and it has a temperature of 120K, what is the speed of sound?

(0.75 points)

B3. An instrument was placed near the crater to detect the sound wave produced by the collision of the object with the bottom. It also has a chronometer. Timing starts from the moment the object is dropped and ends when it detects a sound wave. It measured a time of 15.21 seconds. What is the depth of the crater?

(1.50 points)

B4. The instrument detected a frequency of 5.84 kHz. What is the wavelength of that sound wave?

(0.25 points)

Problem 4—Life in Europa (9.40 points)

While analyzing reddish streaks on Europa's surface, Jicu's rover detects a thermally active crevice releasing volatile compounds. Filament-like structures—thin and spiraling—emerge from the plume, responding to light and heat. Spectroscopy reveals organic molecules, iron, and sulfur, hinting at possible chemosynthetic life. A sampling probe is deployed for closer analysis.

Part A: Interpreting Signs of Life

The initial atmospheric data and the subsequent discovery of potential microbial structures raise fundamental questions about how scientists identify and characterize life, especially in extraterrestrial environments. The presence of certain gases and the very definition of life become critical.

A1. The atmospheric analysis of Europa revealed oxygen, water vapor, methane, and carbon dioxide. Identify two of these gases whose simultaneous presence in significant quantities in Europa's atmosphere (which lacks widespread surface photosynthesis) provides the strongest indication of potential ongoing biological or complex disequilibrium processes.

(0.50 points)

A2. Which of the following classes of macromolecules is LEAST exclusively formed by biological processes and can sometimes have abiotic origins in simpler forms, making it a slightly weaker primary indicator of current life on its own compared to others? *Tick the appropriate box.*

- ☐ Proteins with specific chirality (e.g., L-amino acids)
- ☐ Nucleic acids (like DNA or RNA)
- ☐ Polysaccharides (e.g., storage or structural polymers)
- ☐ Hydrocarbons or amino acids

(0.30 points)

A3. The simultaneous persistence of significant amounts of the two gases (found in part A1) on a moon like Europa is particularly interesting because these gases tend to react with each other, leading to their mutual destruction over geological timescales.

For both gases to remain present in noticeable quantities, their combined net production rate must be at least what in relation to their combined net destruction rate? *Tick the appropriate box.*

- ☐ Greater than
- ☐ Equal to
- ☐ Less than
- ☐ Has no effect

(0.30 points)

Part B: Life in the Europan Ocean Depths

The mission confirmed a subsurface ocean with hydrothermal vents—environments known to support life on Earth. In a 0.010 mL fluid sample, microscopic analysis showed an average of 250 rod-shaped structures per field of view, with 40 total fields. Each structure averaged 2.0 µm in length and 0.5 µm in diameter, approximated as cylinders for volume calculations.

B1. Based on the information provided:
a) Calculate the concentration of these structures in terms of structures per mL.

(0.40 points)

b) Calculate the approximate volume of a single average rod-shaped structure in cubic micrometers (μm^3).

(0.50 points)

c) What is the volume of a single structure in liters?

(0.30 points)

B2. Life thriving near Europan hydrothermal vents would be extremophilic. Select all likely adaptations these microbes might possess, given their environment. *Tick the appropriate boxes (continuation on next page):*

- ☐ Cell membranes with specialized lipids to maintain fluidity under high pressure and low ambient temperatures (away from direct vent heat).
- ☐ Enzymes that function optimally at near-freezing temperatures (psychrophilic) for life further from vent openings.
- ☐ Efficient mechanisms to repair DNA damage, considering Jupiter's radiation environment and potential residual radiation.
- ☐ Strict dependence on sunlight for energy production.

 Ability to utilize inorganic chemical compounds as an energy source.

 Thick cell walls primarily composed of cellulose for structural support.

(0.60 points)

B3 (Fill-in-the-blank)

To maintain cell membrane fluidity in the generally cold deep ocean of Europa (away from the immediate vent plume), the fatty acid chains in their phospholipid bilayer membrane would likely need a ___________ (higher / lower) proportion of chemical bonds that introduce kinks into the fatty acid chains, such as ________ (double / triple / single) bonds.

(0.40 points)

Part C: Metabolism and the Chemistry of Alien Life

Understanding the energy pathways and fundamental chemical makeup of any potential Europan life is a primary goal. The presence of sulfur compounds near vents and the atmospheric gases provide clues.
The primary energy source for these Europan organisms is believed to be chemosynthesis. A key reaction hypothesized involves hydrogen sulfide (H_2S) from the vents and dissolved oxygen (O_2) from the Europan ocean water (or another suitable oxidant). One simplified proposed reaction is

$$2\,H_2S\,(aq) + O_2\,(aq) \rightarrow 2S\,(s) + 2H_2O\,(l)$$

This reaction releases approximately 210 kJ of energy per mole of O_2 consumed.

C1. When considering the above case,

a) What is the general metabolic term for organisms that obtain energy by oxidizing inorganic substances, like the Europan microbes utilizing H_2S?

(0.30 points)

b) In the given reaction, is H_2S acting as an oxidizing agent or a reducing agent?

(0.20 points)

C2. if the S production rate was identified to be 0.64 g for every 12 hours. How much energy (in kJ) does this colony generate per hour from this reaction?

(0.40 points)

C3. Scientists sometimes speculate about life forms based on silicon (Si) rather than carbon (C).

a) For each of the following statements, evaluate its accuracy and relevance to the potential of group 14 elements to form macromolecules:

- ✓ **(Tick):** If the statement is scientifically correct AND directly relevant to the context.
- **0 (Zero):** If the statement is scientifically correct BUT its direct relevance to the context is minor or indirect, or it pertains to a different aspect not central to the discussion.
- ✗ **(Cross):** If the statement is scientifically incorrect.

Statements	Evaluation
A. The tendency of Group 14 elements to form extended chains by bonding with themselves (catenation) is a key factor in their ability to create the framework of macromolecules.	
B. Due to possessing four valence electrons, elements in Group 14 typically engage in forming up to four covalent bonds with other atoms.	
C. Certain microorganisms, like diatoms, incorporate silicon into their cell walls in the form of silica, creating intricate protective structures.	
D. When forming the structural basis of large molecules, Group 14 elements achieve stability primarily through the formation of ionic bonds.	
E. The energy and stability of the bonds formed between identical atoms of a Group 14 element (e.g., C-C vs. Si-Si) are virtually the same, making them equally suitable for chain formation under all conditions.	

(0.50 points)

b) If a silicon-based organism existed on Europa and metabolized silicon-containing compounds, and assuming it required a liquid solvent, which of the following hypothetical solvents might be considered, given that silicon compounds often have different solubilities and reactivities than carbon compounds in water? *Tick the appropriate box.*

- ☐ Liquid methane (a non-polar solvent abundant in the outer solar system)
- ☐ Highly purified water (as it is a universal solvent)
- ☐ Molten sulfur (found in volcanic regions) could dissolve some silicon compounds.
- ☐ Gaseous hydrogen (as a lightweight atmospheric component)

(0.40 points)

c) Fill in the blanks.

Biological catalysts and many cellular structures on Earth are primarily made of macromolecules called proteins. These are polymers of ____________ ____________. For any molecule to effectively serve as the primary hereditary material (e.g., DNA on Earth), it must primarily be capable of accurate self-____________ and the stable ____________ of genetic information. A major challenge for hypothetical silicon-based life (compared to carbon-based life that produces gaseous CO_2 as a waste product) is that the primary oxide of silicon (silicon dioxide, SiO_2) is typically a ____________ (physical state) at common planetary surface temperatures, making its metabolic cycling and disposal difficult.

(0.60 points)

Part D: Dynamics of Europan Microbial Life

Following the initial discoveries, the Thalassian Odyssey team focused on a specific, well-monitored hydrothermal vent, designated 'Vent Prime,' to study the population dynamics and genetic makeup of the dominant rod-shaped chemoautotrophs. Continuous monitoring and sample analysis provided insights into their growth patterns and genetic variation.

D1. A patch of microbes near Vent Prime was found to contain an initial population (N_0) of approximately 2.0×10^4 viable cells. These organisms reproduce by binary fission. Under the prevailing stable conditions with ample nutrients and energy from the vent, the population's mean generation time (the time it takes for the population to double) was determined to be 10 Earth hours.

a) Assuming continuous exponential growth, calculate the number of microbial cells expected after 40 Earth hours.

(0.70 points)

b) How many generations would have occurred during these 40 Earth hours?

(0.30 points)

D2. Further genetic analysis of 200 microbial individuals sampled from the Vent Prime population focused on a gene designated 'ThermoStab,' which influences cell membrane stability during temperature fluctuations, which are common near the vent. Two alleles were identified: T_S (associated with superior membrane stability at higher temperatures) and T_F (associated with greater membrane flexibility at typical vent temperatures but less stability during heat bursts). The observed genotype counts from the sample were

- $T_S T_S$: 60 individuals
- $T_S T_F$: 80 individuals
- $T_F T_F$: 60 individuals

a) Calculate the frequency of the T_S allele in this sampled population.

(0.60 points)

b) Calculate the frequency of the T_F allele in this sampled population.

(0.60 points)

c) If the Vent Prime microbial population were in Hardy-Weinberg equilibrium for the ThermoStab gene, what would be the expected frequency of the $T_F T_S$ (heterozygous) genotype? Show your calculation.

(0.60 points)

d) The observed frequency of the $T_S T_F$ genotype is different from the calculated frequency. Select all the plausible evolutionary factors, potentially related to the specific environmental conditions at Vent Prime (e.g., occasional bursts of very hot water or the general nature of the vent environment) or the population's structure, that could explain the mismatch of heterozygote frequency when compared to Hardy-Weinberg expectations. *Tick the appropriate boxes.*

- ☐ Heterozygous genotypes are more suited since they have both characters.

- ☐ Lacking distinct specializations reduces an organism's fitness in environments that specifically favor any one of those specializations.

- ☐ The TS and TF alleles are codominant, and codominance inherently causes a disruption in the expected Hardy-Weinberg equilibrium for heterozygotes.

- ☐ The population at Vent Prime is small and relatively isolated, leading to a higher incidence of inbreeding.

- ☐ Vent Prime may consist of distinct micro-habitats with differing selective pressures.

(0.60 points)

e) If intense and frequent heat bursts led to the T_S allele becoming the *only* allele for this gene present in the population at Vent Prime, what term describes the status of this allele in the population?

(0.30 points)

Problem 5—Life-Sustaining Chemicals (2.25 points)

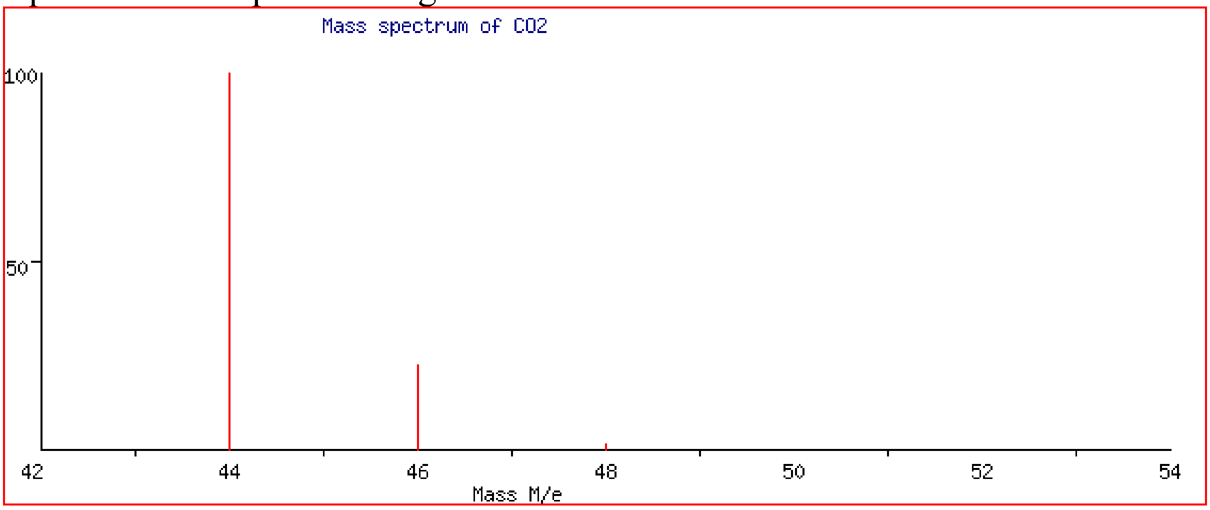
As the search for life continues on Europa, astrochemists, along with astrobiologists, look for life-sustaining chemicals. As you know (hopefully), organic compounds are the base of life, and carbon is the base of organic compounds. So, it's not a surprise that the discovery of carbon dioxide on Europa was a huge discovery. As the NASA website says:

"Astronomers using data from NASA’s James Webb Space Telescope have identified carbon dioxide in a specific region on the icy surface of Europa. Analysis indicates that this carbon likely originated in the subsurface ocean and was not delivered by meteorites or other external sources."

Two almost identical compounds in which the only difference is the isotope in which one (or more) atom(s) is (are) found are called isotopologues. For example, H_2O and D_2O are isotopologues.

A mass spectrometer is a machine that can separate particles with different masses (for example, isotopologues of a molecule). It records the number of particles with each mass and calculates their respective frequencies (abundances). The result is a mass spectrum that shows a number of peaks corresponding to each molecular mass, each peak having a relative intensity assigned. The peak with the highest abundance is assigned a relative intensity of 100%, and the others are assigned their relative intensities proportionally.

As soon as the crew gets on Europa, the crew's astrochemist collects a CO_2 sample from the site indicated by NASA and puts it in a mass spectrometer. The spectrum has three peaks, corresponding to molecular masses of 44u, 46u, and 48u. Below, a picture of the spectrum is given:



A. If in the sample carbon is only found as one isotope and oxygen as two isotopes, find the mass numbers of the isotopes.

(0.50 points)

B. Find the number of neutrons in each isotope.

(0.25 points)

C. If the 44u peak has a 100% relative intensity, the 46u peak has a 22.22% relative intensity, and the 48u peak has a 1.23% relative intensity.
Find the relative abundances of the three isotopologues.

(0.25 points)

D. Consider the abundance of the lower mass O isotope is a_1 and that of the higher mass O isotope is a_2, it can be shown that the abundances of the three isotopologues are equal to a_1^2, a_2^2, $2 \cdot a_1 \cdot a_2$

1. Attribute each abundance to its isotopologue.

(0.50 points)

2. Calculate the abundances of the two oxygen isotopes in the sample from Europa.

(0.75 points)

Problem 6—Jicu and His Rover (5.00 points)

Part A: Uncontrolled Descent

Two days after the end of the trip, Jicu takes a small trip in his four-wheeled rover, and he finds a heat signature. Eager to investigate, he overrides the rover's cautious autopilot and initiates a manual descent down a 15° icy slope. Filip, back on the orbiter, watches nervously as the rover begins to accelerate faster than expected.

Jicu casually radios, "Relax, bro. I've got this. The rover has top-tier braking systems."

Filip responds, "Top-tier brakes mean nothing on ice, Jicu. This isn't a Go-Kart. There is negligible friction on this surface."

As the rover slides, the crew needs to do the math—can the braking motors save the descent, or is Europa claiming another hero?
(For this problem, use the value you found in part B1 in problem 3 for gravity.)

A1. Assume that Jicu weighs 70 kg and that the rover weighs 500 kg. Find how much force is pulling the rover downhill with Jicu onboard.

(0.25 points)

A2. Assuming no brakes and no slipping, calculate the acceleration of the rover.

(0.25 points)

A3. Filip tells the AI to apply torque to hold speed steady. How much braking torque per wheel is needed to maintain constant speed (i.e., zero acceleration)? Assume the radius of a wheel to be 0.30 m.

(0.50 points)

A4. If the rover slips and reaches a rough patch with μ_k of 0.15. Calculate the thermal energy generated by friction over 4 m (along the slope) of uncontrolled slide in the rough patch.

(0.50 points)

Despite Filip's warnings, Jicu refuses to engage the brakes in time. The rover's wheels begin to slide, losing grip on the icy slope.

The system logs a surge in frictional heating — but it's too late. With a dramatic spin, the rover skids sideways and flips into a Europan snowbank, landing at an awkward tilt.

Filip sighs and mutters into the comms: "Well… at least now you've got a better view of the ice crystals."

After the dramatic tumble, sensors indicate the rover impacted the icy surface at a horizontal velocity of 3.2 m/s before flipping. The collision time with the snowbank is estimated to be 0.8 seconds. Assume the impact was perfectly inelastic and the rover came to a stop.

A5. Estimate the energy dissipated during the impact (in kJ).

(0.50 points)

A6. If the center of mass of the rover was 1.2 m above the ground at the moment of the flip, calculate the rotational kinetic energy lost, assuming it pivoted onto its side during the crash. (Assume all mass is concentrated at the center.)

(0.50 points)

Part B: Aftermath of the Crash

After the rover finally comes to a stop, Jicu and Filip begin assessing the situation. The rover's systems are offline, but there's still hope to salvage the mission. They need to determine whether the rover's structural integrity has been compromised enough to require a full evacuation or if they can repair the damage and continue their exploration of Europa's surface.

B1. The rover has a metal frame that's designed to withstand impacts, but the crash was severe. The frame has a compressive yield strength of $2.5 \times 10^8 N/m^2$, and it's made of a lightweight alloy. If the impact force from the crash is distributed evenly across the contact area of the rover's bottom (0.5 m²), calculate whether the frame would have deformed plastically or remained intact.

(1.00 points)

B2. Post-impact, the rover starts emitting low-frequency vibrations due to its sudden stop. Filip uses the rover's onboard sensors to monitor these vibrations. Assume the oscillation frequency is found to be 4 Hz and that the effective mass of the rover's top section is 200 kg. Calculate the spring constant of the rover's suspension system based on the observed vibrations.

(0.50 points)

B3. Now that the rover is stabilized, Jicu decides to perform a check on the navigation system. The slope at the crash site is roughly 12°. Assume the rover is now at the bottom of the slope and is at rest and that the frictional force between the tires and the icy surface is 0.15 times the normal force. How much force is required if Jicu attempts to move the rover uphill at a constant speed?

(0.75 points)

B4. With the rover's power reserves running low, Jicu and Filip must decide whether to use the last bit of energy to communicate the situation back to the base or use it for a self-repair operation. The rover's battery stores a total of 780,000 J of energy, and its power consumption is rated at 50 W for communication and 80 W for self-repair. If they need to send a distress signal, how much time (in minutes) will they have before the battery runs out?

(0.25 points)

— End of the Paper —