S5 AOI ON ATOMIC AND ELECTRONIC STRUCTURE

Scenario:

NASA is planning a deep-space mission powered by a ***Radioisotope Thermoelectric Generator (RTG)*** containing 16 kg of Plutonium-238 (^{238}Pu). This isotope undergoes a series alpha decay and subsequently beta decay toward greater nuclear stability. The RTG currently produces 600 watts of thermal energy, expected to drop to 300 watts over 87.7 years.

Although the RTG is built to be secure under normal conditions, there are safety concerns in the event of a failed launch or crash. If Plutonium-238 is released into the environment, it could contaminate soil and water, potentially entering the food chain and exposing humans and wildlife to long-term alpha radiation hazards.

Task:

Analyze the nuclear decay sequence above and its role in increasing nuclear stability, determine the half-life of the suggested radioisotope and evaluate the ethical and environmental risks associated with failed launch or crush of the ***RTG***.

SAMPLE RESPONSE

Decay Processes and Nuclear Stability

Alpha Decay of Plutonium-238

Reaction:

$$^{238}_{94}Pu \longrightarrow {}^{4}_{2}He + {}^{234}_{92}U$$

Explanation:

- In alpha decay, the nucleus emits an **alpha particle**, which contains 2 protons and 2 neutrons.
- Alpha emission reduces both the number of protons and the number of neutrons.
- There must be a series of alpha emissions until a very stable nuclide is formed because stability cannot be gained by one alpha emission.
- The atomic number drops by 2 and the mass number by 4.
- This process reduces **repulsive forces between protons** and helps the nucleus move toward a more stable neutron-to-proton ratio.

Beta Decay of the Daughter Nucleus

$$^{234}_{92}U \longrightarrow {}^{0}_{-1}e + {}^{234}_{93}Np$$

Explanation:

- In **beta decay**, atomic number increases by 1 but keeping the mass number the same.
- This and forms a **more stable nucleus**.

Stability Insight:

- The sequence of **alpha followed by beta decay** moves the nucleus step-by-step toward a region of nuclear stability, reducing the tendency to undergo further decay.

(ii) Calculating the Half-Life of Plutonium-238

$$ln\left(\frac{N_0}{N_t}\right) = \lambda t$$

$$ln\left(\frac{600}{300}\right) = \lambda \times 87.7$$

$$\lambda = 0.0079\ per\ year$$

$$t_{1/2} = \frac{0.693}{\lambda} = \frac{0.693}{0.0079} = 87.7\ years\ hence\ confirmed$$

(iii) Ethical Responsibilities in Using Radioactive Materials

Potential Benefits:

1. **Reliable Long-Term Energy Source**:
   - RTGs using Pu-238 provide power for decades without sunlight — critical for deep-space missions (e.g., Voyager, Curiosity, Perseverance).
2. **Scientific Advancement**:
   - Enables missions to distant or dark regions of the solar system, yielding valuable knowledge that can benefit humanity.
3. **Minimal Operational Risk**:
   - RTGs are designed to be rugged, and Pu-238 is in a ceramic form that reduces inhalation risks.

Potential Risks:

1. **Accidental Release**:
   - If the launch fails or the probe crashes, Pu-238 can contaminate soil or water, leading to **bioaccumulation** in organisms and chronic radiation exposure.
2. **Human Health Hazard**:
   - Alpha particles from Pu-238 are highly ionizing. While they don't penetrate skin, **inhalation or ingestion** can lead to long-term tissue damage and cancer.
3. **Environmental Impact**:
   - Persistent radioactive contamination could harm ecosystems for centuries.

Ethical Considerations:

- **Precautionary Principle**: Given the high risk, launch procedures must minimize all possible failures.
- **Informed Consent**: Populations potentially affected by a crash should be informed and involved in discussions.
- **Intergenerational Justice**: Decisions made today must consider impacts on future generations and environmental sustainability.
- **Transparency and Accountability**: Agencies like NASA must maintain open communication about risks, design safety, and emergency protocols.

Indicator 1: Scientific Explanation of Nuclear Stability, Decay & Half-Life Calculation *(9 scores)*

Criterion	Score 3	Score 2	Score 1
Relevance	Clearly explains both alpha and beta decay, and accurately connects them to nuclear stability and decay series.	Describes alpha and beta decay with limited or vague connection to nuclear stability.	Mentions decay types but doesn't link to nuclear stability; off-topic content present.
Accuracy	All decay equations, principles, and half-life calculations are scientifically accurate and correctly presented.	Minor calculation or concept errors; general understanding shown.	Major errors in decay explanation or half-life calculation; misconceptions present.
Coherence	Explanation is well-structured, showing a clear logical flow from decay type to stability and half-life.	Mostly clear and connected, but transitions or connections may be weak.	Unclear or disorganized argument; jumps in logic or lacks development.

Indicator 2: Ethical and Environmental Evaluation of RTG Use *(9 scores)*

Criterion	Score 3	Score 2	Score 1
Relevance	Thorough evaluation of both benefits and risks of RTG use directly related to the scenario.	Touches on both sides but may not fully explore or relate to the scenario.	Discusses only one aspect (e.g., only benefits or only risks); little relevance to the case.
Accuracy	Ethical and environmental impacts are accurately described, including health risks and contamination.	Minor inaccuracies or omissions, but basic understanding is evident.	Misrepresents facts or ethical implications; contains errors in environmental impact.
Coherence	Argument is logical, well-balanced, and smoothly presented.	Generally organized but may have uneven development or slight repetition.	Unclear or disorganized argument; jumps in logic or lacks development.
Excellence	**Score 1**		
	Provides thoughtful insight beyond the expected — e.g., deep ethical reasoning (like intergenerational justice), real-world comparisons, or connections to international policy or sustainable practice.		

MAXIMUM TOTAL SCORE = 19