PART 2

Read the text below and answer questions 14–26.

THE QUEST FOR MATERIALS IN EXTREME ENVIRONMENTS: THE CASE OF SPACE

Spacecraft materials engineering is defined by a “stacked” risk profile: hazards that are manageable in isolation can become destructive when they operate simultaneously. In orbit and beyond, vacuum promotes outgassing and cold-welding, ultraviolet light and ionising radiation break chemical bonds, electrostatic charging triggers arcing, and atomic oxygen in low Earth orbit chemically attacks exposed polymers. Added to this are hypervelocity impacts from micrometeoroids and debris, where even millimetre-sized particles carry enough kinetic energy to crater surfaces. The central design problem is therefore not merely selecting strong materials, but selecting systems that retain function when multiple degradation mechanisms act at once.

Thermal cycling provides a concrete example of that synergy. A structure can swing from about *-150°C* in shadow to roughly *+120°C* in direct sunlight, and these extremes are not rare events but routine transitions. Repeated expansion and contraction induce fatigue, loosen fasteners, and propagate microcracks through coatings and composites. Engineers mitigate this by selecting alloys with stable coefficients of thermal expansion, introducing compliant interfaces between dissimilar materials, and managing heat flow so sensitive instruments remain within permissible limits. The challenge is compounded by geometry: thin panels and antenna booms can develop thermal gradients across small distances, creating internal stresses even when average temperatures remain acceptable.

Thermal protection systems illustrate how performance is constrained by mass. For atmospheric entry or severe heating, ablative materials and high-temperature ceramics dissipate heat by controlled erosion and radiative loss, while reinforced carbon-carbon can tolerate high fluxes without catastrophic distortion. In more typical orbital conditions, insulation is often the limiting factor rather than a single peak temperature. Multi-layer insulation (MLI) blankets—stacks of thin, reflective polymer films separated by spacers—reduce heat transfer by limiting radiation and conduction pathways. Yet an apparently simple choice becomes a trade-off: robust protection may be heavy or mechanically complex, while lighter systems can be vulnerable to tearing, ageing, or performance losses at seams and penetrations. Because launch costs scale with kilograms, designers repeatedly confront the same dilemma: the safest thermal architecture may be economically prohibitive.

Radiation adds a distinct failure mode that accumulates silently. Outside the shielding effect of Earth’s magnetosphere, electronics and structures face galactic cosmic rays and

episodic solar particle events. Dense metals such as lead are often dismissed despite their stopping power because the weight penalty is unacceptable for most spacecraft architectures. Instead, engineers evaluate shielding efficacy per unit mass, which shifts attention toward hydrogen-bearing materials that can scatter high-energy particles effectively while remaining lightweight. Even then, shielding is never complete; it is a probabilistic reduction of dose, not a guarantee of immunity.

This is where material selection becomes both technical and strategic. Polymers and composites can be formulated to be *hydrogen-rich*, increasing their ability to moderate energetic particles, and they can be integrated into structural panels so shielding performs a dual function rather than becoming dead weight. However, radiation does not merely pass through; it can change the material itself. One persistent concern is *radiation-induced* embrittlement, in which prolonged exposure alters microstructure and reduces ductility, making components more brittle and more prone to crack growth under stress. Over long-duration missions, a material that initially passes strength tests can drift into a failure regime because its fracture toughness degrades, particularly when combined with thermal cycling and mechanical vibration.

Low Earth orbit introduces yet another chemical aggressor: atomic oxygen. At orbital velocities, oxygen molecules are dissociated by ultraviolet radiation and exist as highly reactive atoms that erode many polymers through surface oxidation. The result can be mass loss, roughening, and loss of optical or thermal properties, which is particularly damaging for MLI blankets, polymer films, and exposed adhesives. Engineers counter this with coatings—such as thin oxides or metallic layers—and by choosing polymer chemistries less susceptible to oxidation. Yet coatings can crack under thermal strain or be punctured by debris, allowing atomic oxygen to attack the underlying substrate. The environment therefore forces a layered defence strategy: chemistry, barrier design, and mechanical durability must align.

Space is also a laboratory that reveals behaviour Earth-based manufacturing can hide. On the International Space Station, facilities such as the Microgravity Science Glovebox allow researchers to process alloys, foams, and crystals in near-zero gravity. With buoyancy-driven convection largely absent, molten materials can solidify with different microstructures; segregation patterns change; and crystals can grow with fewer defects. These experiments are not academic curiosities: they inform how materials might be manufactured for high reliability, and they generate datasets about how surfaces weather when exposed to vacuum, radiation, and atomic oxygen. External exposure platforms provide long-duration evidence of degradation rates, helping engineers refine coatings and predict lifetime performance rather than relying on short terrestrial tests.

Looking ahead, the most disruptive shift may be manufacturing location rather than manufacturing method. In-situ resource utilisation (ISRU) proposes using off-world materials to build habitats and infrastructure, reducing dependence on Earth launches. Experiments already explore converting *lunar regolith* into solid blocks through sintering, microwave processing, or binder-assisted consolidation, producing concrete-like materials from local feedstock. If ISRU becomes reliable, it would not merely reduce logistics costs; it would force advances in autonomous manufacturing, robotics, and quality control under remote constraints. Those advances would likely feed back into terrestrial industry, where automated, low-waste production is increasingly valuable.

Questions 14–18

Complete the table below. Choose **ONE WORD AND/OR A NUMBER** from the text for each answer.

Environmental challenges and material solutions

Challenge / Goal	**Material or condition**	**Performance / Comment**
Thermal environment	Temperatures range from about **14** ..... in shadow to around **15** ..... in sunlight	Repeated expansion and contraction can cause fatigue and microcracks
	Multi-layer insulation (MLI)	Reflective polymer films reduce heat transfer, but protection involves mass and durability trade-offs
Radiation	**16** ..... polymers and composites	Scatter or moderate energetic particles while remaining relatively lightweight
	Prolonged exposure	May cause **17** ..... embrittlement and reduce fracture toughness
Atomic oxygen	Thin oxide or metallic coatings	Protect exposed polymers, although cracks may expose the underlying material

Challenge / Goal	Material or condition	Performance / Comment
Future construction	Lunar **18 .....**	Can be processed by sintering to produce concrete-like building blocks

Questions 19–22

Look at the following terms and the list of descriptions below. Choose the correct letter, **A, B, C, D, E or F**.

List of Descriptions

A A method of limiting heat transfer using thin reflective films

B A degradation process in which components become more brittle after prolonged radiation exposure

C Building habitats using local resources instead of launching everything from Earth

D Processing materials in near-zero gravity to change how they form

E A type of impact caused by particles travelling at extremely high speed

F A protective gas used to prevent atomic oxygen erosion

19 Multi-layer insulation (MLI)

20 Radiation-induced embrittlement

21 Microgravity Science Glovebox

22 In-situ resource utilization (ISRU)

Questions 23–26

Select the correct answer.

23 What is the main purpose of the first paragraph?

A To explain why space missions are no longer necessary
B To argue that polymers are unsuitable for spacecraft
C To outline the combination of hazards that space materials must withstand
D To describe the history of the International Space Station

24 What design trade-off is emphasised in the discussion of thermal protection?

A Greater protection can increase weight, while lighter systems may be less durable.
B Better insulation always increases fuel consumption.
C Ceramic materials are suitable only for use in low Earth orbit.
D Radiative heat loss occurs only when a spacecraft is in a vacuum.

25 Why are dense metals such as lead considered impractical for radiation shielding?

A They develop cracks whenever spacecraft undergo thermal cycling.
B Their weight creates an unacceptable penalty for most spacecraft designs.
C They are incapable of reducing exposure to high-energy particles.
D Their surfaces are rapidly destroyed by atomic oxygen in every orbit.

26 If ISRU becomes reliable, the passage suggests it could

A remove the need for testing materials on Earth
B stop radiation damage to spacecraft entirely
C guarantee that habitats can be built without human planning
D stimulate advances in autonomous manufacturing with uses beyond space

Answer Key

14. -150°C
15. +120°C
16. hydrogen-rich
17. radiation-induced
18. regolith
19. A
20. B
21. D
22. C
23. C
24. A
25. B
26. D