Reusable Rocket Technology

Mains: *GS III – Science and Technology*

Why in News?

Recently the reusable rocket technology has gained importance around the sustainable use of space.

What is the status of space technology?

- **Past scenario** – For nearly four decades, space exploration was dominated by government agencies, with missions driven largely by strategic, scientific, and prestige considerations.
- **Present status** – The space sector has entered a commercial phase, led by private companies that invest, innovate, and compete to reduce costs and increase launch frequency.
- Today, space is one of the fastest-growing industries in the world and is projected to exceed $1 trillion in value by 2030.
- **Transformative innovation** – At the heart of this transformation lies a single disruptive innovation: Reusable rocket technology, which is redefining sustainability and cost-effectiveness in access to space.
- **The economics of launch costs** – Traditionally, rockets were expendable, meaning each launch destroyed the launch vehicle after a single use.
- This made space access extremely expensive, with costs running into tens of thousands of dollars per kilogram of payload.
- **Low launch of costs** – The introduction of partial reusability by private players has reduced the cost of access to space by 5 to 20 times, fundamentally altering the economics of spaceflight.
- Lower launch costs have multiple downstream effects:
    - Increased launch frequency
    - Expansion of satellite constellations
    - Greater accessibility for developing countries and private firms
    - New commercial applications such as space tourism and in-orbit servicing
- This shift has moved the industry from a “disposable” model to a transportation model, similar to aviation.

Why spaceflight is technically challenging?

- **Physical barriers** – Launching a rocket into orbit requires overcoming two major physical barriers:

    - Gravity
    - Aerodynamic drag.
- Unlike aircraft, rockets cannot push against air or ground and must propel themselves forward by ejecting exhaust gases backward at supersonic speeds.
- The fundamental physics governing rocket motion is explained by the *Tsiolkovsky rocket equation*, which links a rocket's velocity to its mass and fuel consumption.
- This equation highlights a major limitation: *fuel itself is extremely heavy.*
- As a result, more than 90% of a rocket's mass at liftoff is typically propellant and tanks, while less than 4% is the actual payload.
- This "weight problem" is the core reason spaceflight is expensive.
- **Role of rocket staging –** To address the limitations, rockets are designed with multiple stages.
- Each stage is an independent propulsion unit that is discarded once its fuel is exhausted, allowing the rocket to shed dead weight mid-flight.
- This improves efficiency and makes orbital insertion possible.
- Traditional launch vehicles such as PSLV and LVM-3 use expendable staging, where discarded stages fall into the ocean and are never recovered.
- While effective, this approach locks in high recurring costs because each launch requires a completely new vehicle.
- **Reusability –** Reusable rockets aim to recover and reuse the most expensive components, particularly the first stage, which contains engines, avionics, and fuel tanks.
- SpaceX has pioneered this approach with its Falcon 9 rocket.
- After separation, the first stage performs a controlled descent using:
    - Engine re-ignition (retro-propulsion) to reduce speed
    - Aerodynamic drag during atmospheric re-entry
    - Precision guidance and autonomous landing on land or ocean platforms
- This innovation has dramatically reduced costs and increased launch cadence.
- SpaceX has successfully recovered Falcon 9 first stages over 520 times, with some boosters reused more than 30 times.
- **Fully Reusable Launch Vehicles –** While partial reusability is now proven, the next major leap is full reusability, where both stages of a rocket are recovered and reused.
- SpaceX's Starship represents this ambition.
- Designed as a fully reusable, heavy-lift vehicle, Starship is intended to carry crew and cargo not only to Earth orbit but also to the Moon and Mars.
- **Other global players**:
    - Blue Origin has demonstrated vertical booster recovery for its New Glenn rocket.
    - Chinese commercial space firms, such as LandSpace, are attempting recovery technologies for orbital-class rockets.
- These developments indicate that reusability is fast becoming an industry norm rather than an exception.

What are the limits to reusability?

- **Practical limitations** – Rocket stages are subjected to extreme stresses:
    - Cryogenic temperatures from propellants
    - Intense heat during combustion and re-entry

    - High pressure, vibration, and g-forces
- Over multiple flights, these conditions cause material fatigue and microfractures, especially in engines and fuel tanks.
- **Other concerns** – Beyond a point, the cost and time required for inspection, refurbishment, and replacement of components can outweigh the savings from reuse.
- Thus, the feasible number of reuses is determined not only by engineering durability but also by refurbishment economics and acceptable risk levels.

What is the human spaceflight vs satellite missions?

- **Human space missions** – These are significantly more expensive than uncrewed satellite launches, often costing three to five times more. This is due to stringent requirements for:
    - Life support systems
    - Crew safety and redundancy
    - Escape mechanisms and reliability standards
- **Satellite missions** – They are typically one-way, with simpler hardware and software architectures.
- Reusability helps reduce costs in both cases but is especially transformative for high-frequency satellite launches.
- **India's Position in the Reusable Space Race** – India, through ISRO, has recognised the strategic importance of reusability and is actively developing relevant technologies.
- Two major approaches are being pursued:
    - **Reusable Launch Vehicle (RLV)** – A winged, shuttle-like vehicle capable of re-entering the atmosphere and landing on a runway.
    - **Stage Recovery Systems** – Using aerodynamic drag and retro-propulsion to recover spent rocket stages on land or sea platforms.
- While India has traditionally focused on cost-effective expendable launch systems, the rapidly evolving global market makes reusability a necessity rather than a choice.

What lies ahead?

- Future launch vehicles must be designed with reuse as a non-negotiable design driver.
- Advances in propellant density and engine efficiency now allow two-stage systems to perform missions that once required three or more stages.
- Key focus areas should include:
    - Optimised stage energy distribution
    - High-performance, compact engines
    - Rapid and economical refurbishment
    - Increased launch cadence.
- Reusable rocket technology represents a paradigm shift in space access, making it more affordable, sustainable, and inclusive.
- As space becomes a critical domain for economic growth, national security, and technological leadership, countries that fail to adapt risk being left behind.
- For India, timely induction of disruptive technologies and policy support for reusable systems will be crucial to remaining competitive in the emerging global space

economy.

Reference

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