Integrated Logistics and Supportability Challenges of Sustained Human Lunar Exploration

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Introduction and Overview

- **Core strategic principle of Artemis architecture is to establish a sustainable human presence on the lunar surface**
  - Support lunar exploration and utilization
  - Serve as a testbed for future human exploration of Mars
- **Artemis Base Camp (ABC) plan includes ~30 d crewed missions on an annual basis, with ~335 d uncrewed dormant period between missions**
- **ABC will be more challenging than past experience with sustained Low Earth Orbit (LEO) operations (e.g., ISS) or lunar sortie missions (Apollo)**
- **This paper:**
  - Discussion of integrated logistics & supportability challenges of sustained human lunar exploration
  - Review of historical human spaceflight (HSF) experience in comparison to Artemis plans
  - Discussion of implications of Artemis activities for Mars mission planning
- **Future operating contexts will be different from past experience, and historical approaches to risk management should be reexamined in this new context**
- **Sustained lunar operations provide valuable proving ground for Mars planning**

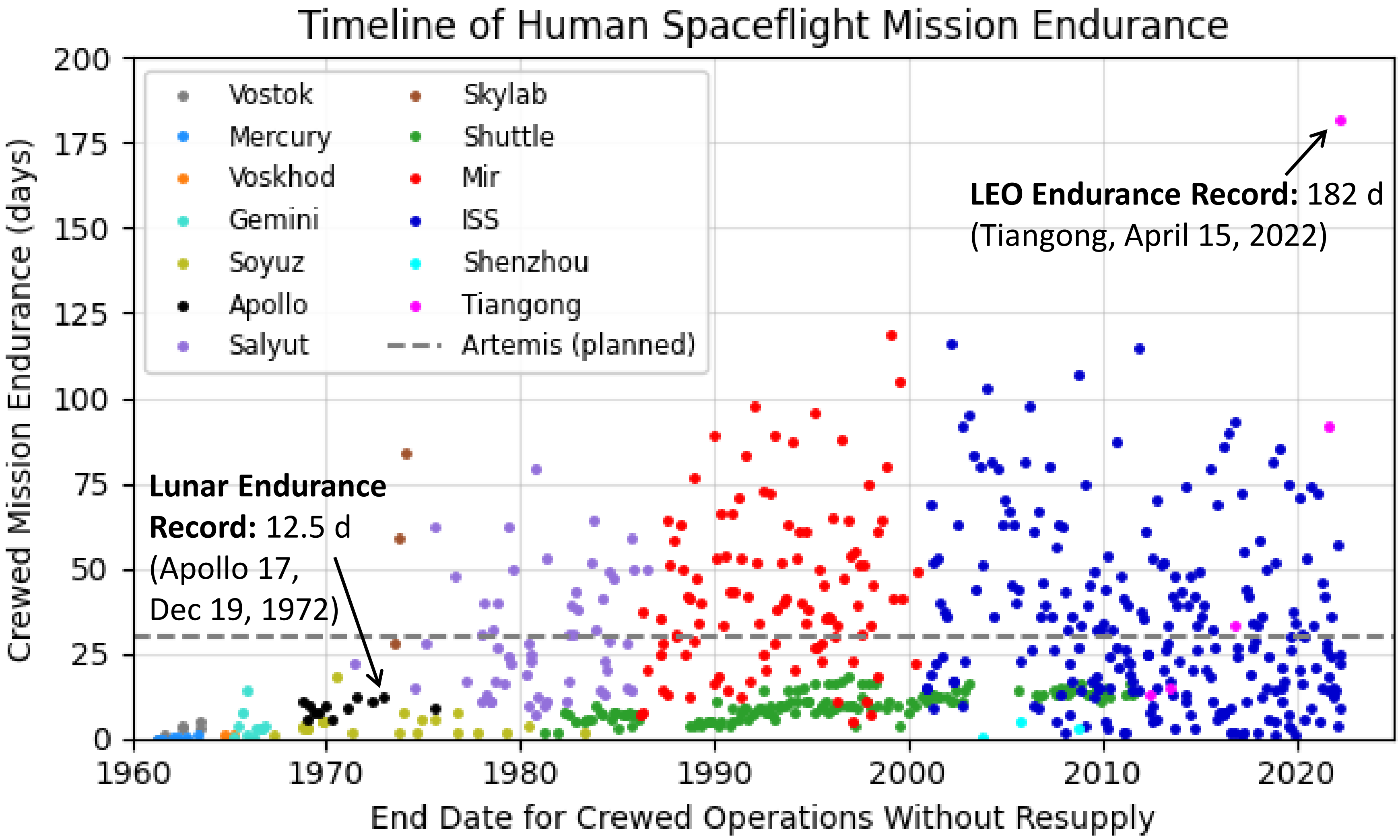
Four Key Metrics for Logistics, Supportability, & Risk

Crewed Mission Endurance	How long does the system have to operate and support the crew without resupply?
Uncrewed Duration	How long does the system have to operate (potentially in a dormant/standby mode) without crew present?
Transportation Overhead	How difficult is it to move crew and logistics from Earth to the exploration destination and back?
Access to Abort	How difficult is it to abort and return the crew to Earth if an anomaly occurs?

Crewed Mission Endurance

- **Crewed endurance is the amount of time that the system must operate and support the crew without resupply; defines logistics planning timeline**
- **Key driver of spares requirements:**
  Longer endurance → more uncertainty → more spares required to mitigate risk
- **LEO stations have demonstrated very long mission *durations*, but have relatively short *endurance* due to regular resupply**

Crewed Mission Endurance

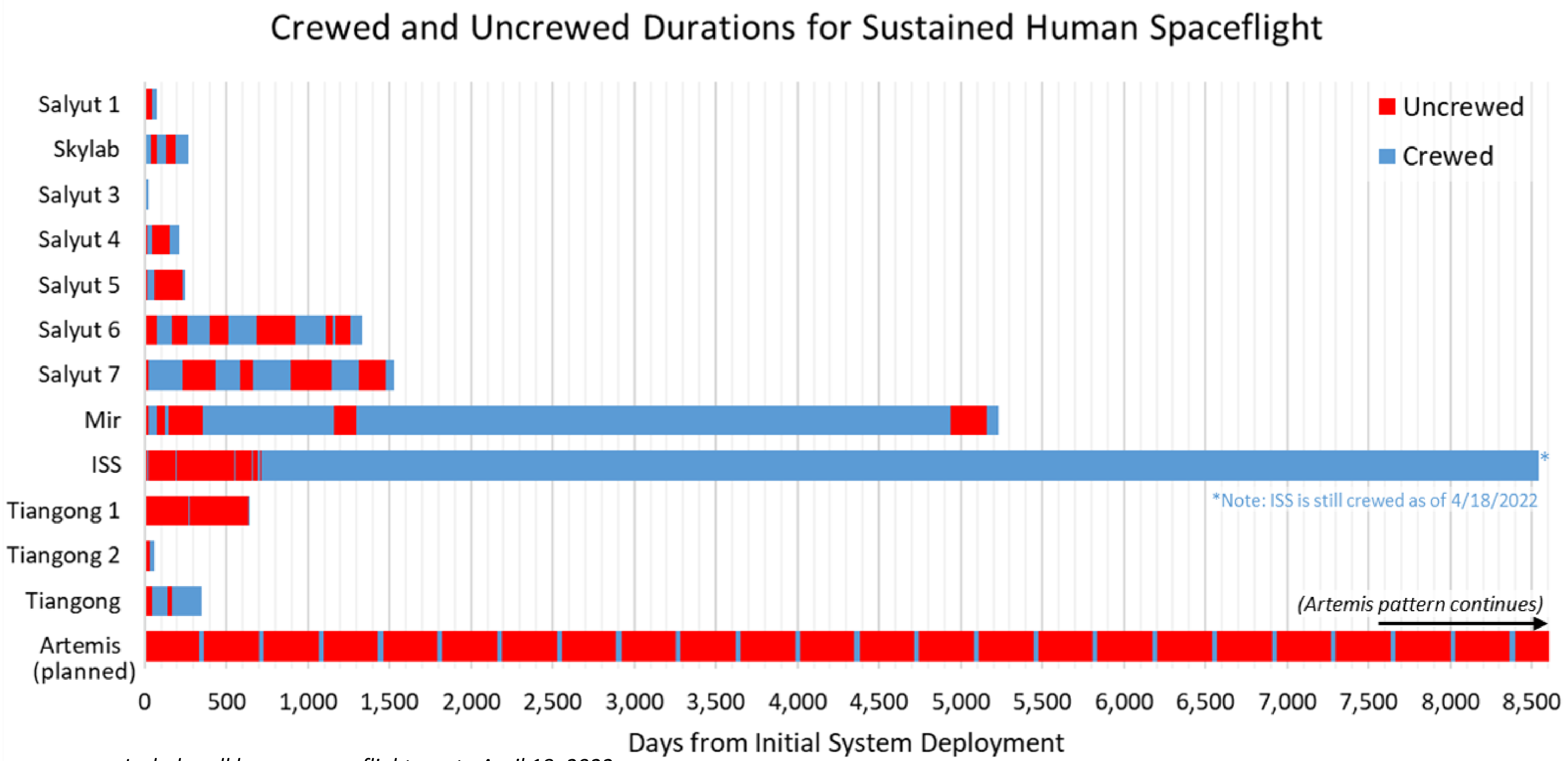


Includes all human spaceflights up to April 18, 2022.

- **ABC planned crewed endurance of ~30 d is similar to average ISS endurance**
- **LEO stations have regularly experienced crewed endurance longer than 30 d**
- **ABC crewed endurance is 2.4x longer than longest lunar mission to date**

Uncrewed Duration

- **Crew is not present to perform maintenance and manage operations during uncrewed periods; must use redundancy or robotic repair capability**



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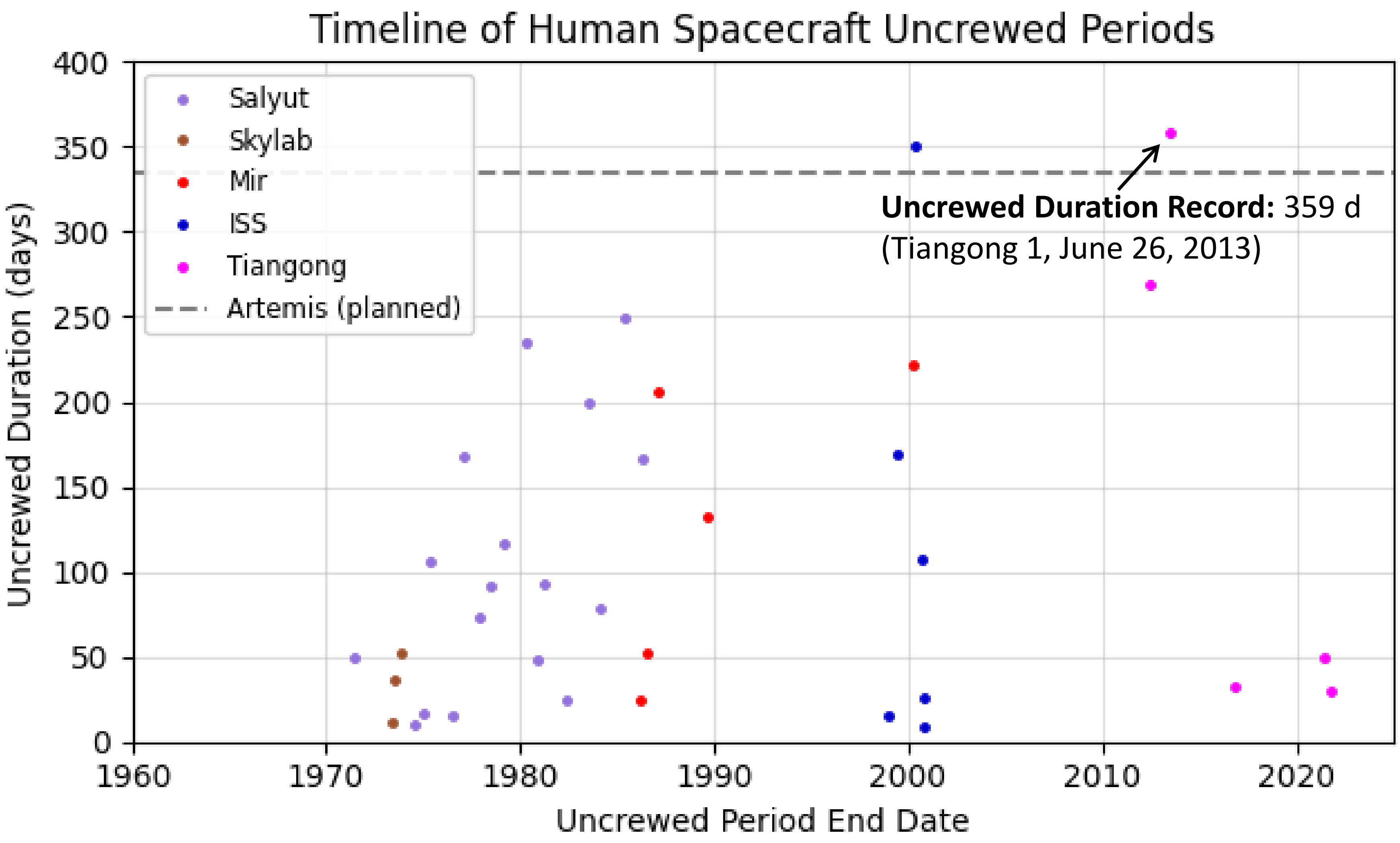
Uncrewed Duration



Includes uncrewed durations from all human spaceflights up to April 18, 2022.

- **ABC planned uncrewed duration of ~335 d is longer than all but two past uncrewed durations**
  - 359 d during Tiangong 1
  - 350 d during ISS assembly
  - Unclear what level of system complexity was implemented during those missions
- **Longest lunar uncrewed duration was a 7.5 hr EVA**
- **ABC will regularly have long uncrewed operations**

Transportation Overhead

	Distance	Transit Duration
ISS	400 km	Hours
Moon	363,000 – 405,500 km	Days

- **Transit to/from the Moon is more expensive and time-consuming than transit to/from LEO**
  - Full transportation architecture analysis beyond the scope of this paper, but as an illustrative example, SpaceX Falcon 9 capacity to Geostationary Transfer Orbit (GTO) is just 36% of capacity to LEO (8,300 kg vs 22,800 kg)
  - Once reaching GTO, a spacecraft would have to expend additional propellant to transit to the Moon and land on the surface
- **Logistics transfer more complex on lunar surface**
  - ***LEO:*** rendezvous and dock, then transfer logistics in microgravity
  - ***Lunar surface:*** land a safe distance away from existing infrastructure, use surface mobility elements to maneuver logistics in a partial gravity environment to the habitat

Access to Abort

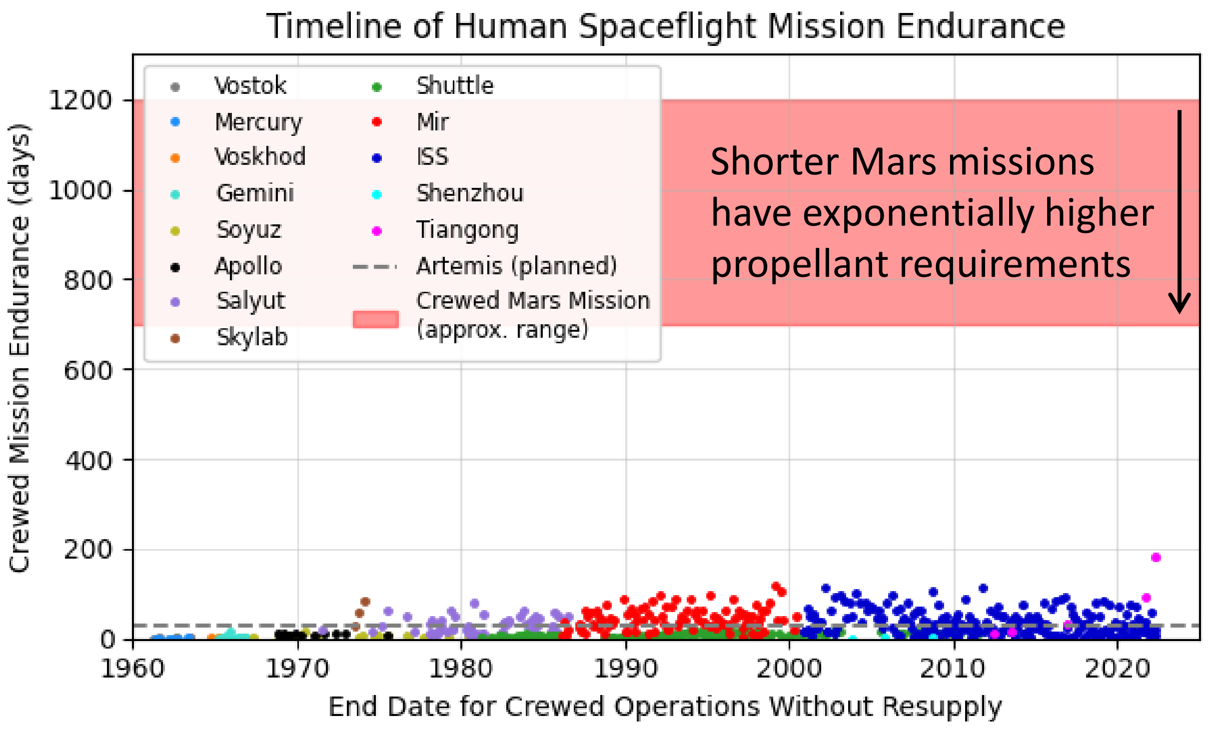
Date	Mission	Location	Cause
3/16/1966	Gemini 8	LEO	Fuel depletion due to stuck thruster
4/14/1970	Apollo 13	Cislunar	Oxygen tank explosion
4/24/1971	Soyuz 10	LEO	Docking system failure
8/28/1974	Soyuz 15	LEO	Docking system failure
4/5/1975	Soyuz 18a	Ascent	Stage separation failure
10/16/1976	Soyuz 23	LEO	Docking system failure
10/11/1977	Soyuz 25	LEO	Docking system failure
4/12/1979	Soyuz 33	LEO	Engine failure prevents docking
11/12/1981	STS-2	LEO	Fuel cell failure
4/22/1983	Soyuz-T 8	LEO	Failure to dock
7/29/1985	STS-51-F	Ascent	Sensor failure causes premature engine shutdown
11/21/1985	Soyuz-T 14	LEO	Medical evacuation
7/30/1987	Soyuz-TM 2	LEO	Medical evacuation
10/11/2018	Soyuz MS-10	Ascent	Launch vehicle failure

Includes all successful post-launch human spaceflight aborts up to April 18, 2022.

- **HSF missions have experienced 14 post-launch aborts**
  - 3 during ascent
  - 10 in LEO
  - 1 in cislunar space
- **Abort from the Moon will take longer and be more challenging than abort from LEO**
  - All transportation overhead considerations apply
  - Lunar surface abort requires successful ascent in addition to successful return

Implications for Mars Missions

- **Moon is more challenging than LEO; Mars is more challenging than Moon**
  - Higher transportation overhead and longer transit durations
  - Transit opportunities constrained by orbital mechanics; limited abort capability
- **One of ABC objectives is to prepare for Mars exploration**
  - Moon provides a relatively safe location to test new surface exploration capabilities
  - Artemis missions will provide first HSF operations experience in a dusty, partial-gravity, surface environment since 1972
- **To provide value for Mars missions, ABC activities need to use similar systems and techniques in a similar operating context**



	Distance	Transit Duration
ISS	400 km	Hours
Moon	363,000 – 405,500 km	Days
Mars	56,000,000 – 400,000,000 km	Months

Summary and Conclusions

Metric	Findings
Crewed Mission Endurance	Current endurance record is 182 d in LEO, 12.5d for lunar missions. ABC planned endurance is ~30 d on lunar surface.
Uncrewed Duration	Current record is 359 d in LEO. Only 2 missions have experienced uncrewed durations longer than ABC duration.
Transportation Overhead	Transit to/from Moon takes longer and requires more propellant than transit to/from LEO, and logistics transfer activities are more complex.
Access to Abort	Only 1 HSF mission has performed an abort from cislunar space. No missions have performed an abort from the lunar surface.

- **Sustainable lunar surface operations require a shift in design and operations mindset from LEO operations or lunar sortie missions**
- **An even greater shift will be required for Mars operations, and lunar activities provide a valuable testbed for Mars systems and techniques**
- **Past experience provides useful context for future plans, enabling data-driven assessment of gaps and challenges**

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