

Spacecraft Thermal Control in Crewed Lunar Missions: A Review from Apollo to Artemis

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Abstract: The global push for aviation decarbonization has elevated electric aircraft (EA) as a promising solution for short-On 20 July 1969, NASA's Apollo 11 mission achieved the historic first crewed landing on the moon, marking the dawn of human exploration beyond Earth. The Apollo program continued until 1972, dissolving an era of unprecedented scientific and engineering achievement in space exploration. Now, more than half a century later, humankind has once again accomplished the remarkable feat of journeying to the Moon and back, safely to Earth, rekindling global interest in lunar exploration. This review paper scrutinizes the spacecraft thermal control systems employed in the key crewed lunar mission vehicles, namely the Apollo Lunar Orbiter (Command Module), the Apollo Lunar Module, and the Artemis II Orion spacecraft. It further investigates the thermal challenges inherent to the lunar surface environment, presenting a comparative study of thermal control practices spanning from the pioneering Apollo missions to the futuristic designs of the Artemis program.

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1. Introduction

Since the historic launch of Sputnik-I in 1957 to the bold ambitions of the Artemis program today, space technology has undergone a noteworthy transformation, evolving from experimental rocketry into one of the most complex and multidisciplinary fields of modern engineering. At the heart of every successful crewed mission lies a suite of precisely engineered subsystems, none more quietly critical than the Thermal Control Subsystem (TCS). In the unsparingly harsh space environment, effective thermal management is not simply a design requirement, it is a matter of mission survival.

The historical record of crewed spaceflight bears sobering testimony to the consequences of thermal protection failures: The [Apollo 1 \(1967\)](#), [Soyuz 1 \(1967\)](#), [Soyuz 11\(1971\)](#), the [Space Shuttles Challenger \(1986\)](#) and [Columbia \(2003\)](#). Each of these tragedies not only caused the irreplaceable loss of human life, also inherently rebuilt the engineering philosophy and safety culture of human spaceflight programs worldwide.

This review paper provides a comprehensive examination of the thermal control systems employed in crewed lunar missions, encompassing the Apollo Command Module, the Apollo Lunar Module, and the Artemis II Orion spacecraft. It systematically investigates the passive and active thermal control strategies adopted across these vehicles, the severe thermal challenges of the lunar surface environment, and the significant advancements in thermal management that have emerged over more than five decades of lunar exploration.

2. Thermal Environment

A hospitable thermal environment is the only reliable option for a spacecraft, with its various components, to operate effectively. This is the exact function of the thermal Control Subsystem to provide a favourable thermal environment inside the spacecraft, for the operation of scientific instruments and other vital equipment for the success of the mission. The on-board thermal environment of a spacecraft can be determined by the

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- The magnitude and distributions of the input radiation, from the Sun and the planets
 - Heat from the electrical operations of the spacecraft
 - Heat from the internal sources, rockets, nuclear power sources and isotope heaters

The characteristics of heat transfer paths within the spacecraft and the external surface heat radiation affect the impact of the above-mentioned inputs.

Two main types of thermal control methods are used to maintain the environment in a spacecraft.

- Passive thermal control (PTC)
 - Surface Paints and Coatings
 - Multi-Layer Insulation (MLI)
 - Heat shields
 - Thermal tapes
- Active thermal control (ATC)
 - Heat pipes
 - Louvers
 - Radiators

2.1 In-orbit space environment

The space environment depends on the mission details, whether it is Earth-orbiting or deep space. For a spacecraft in orbit, the heat absorbed includes

- Solar Radiation
 - Direct Absorbed Sunlight
 - Albedo (Reflected Sunlight)
- Planetary Radiation
 - Infrared Energy (The radiation emitted by the planet itself) The heat that is produced internally is due to:
 - Power dissipated by the electronic and the electrical components.
 - Electric heaters
 - Radioisotopes
 - Chemical reactions

The heat is rejected by radiation to space from the spacecraft components.

Additionally, there are other in-orbit aspects of the space environment, the indirect heat sources that need to be considered in the design of the thermal control system. They include:

- Meteorite & Micrometeoroids
 - Space Debris
 - The Radiation fields outside of Earth's magnetic field
 - Galactic cosmic radiation
 - Solar particle events
-



- Trapped radiation field (Van Allen Belts)
- Secondary radiation

2.2 Lunar Thermal Environment

The lunar environment changes from location to location and from day to night rather drastically.

It takes approximately 28 Earth days to complete a lunar day with 14 days of sunlight and 14 days of darkness. The surface temperature of the moon can range from 374 K (100.85 °C) during the lunar noon (Earth day 7) to as low as 120 K (-153.15 °C) during the lunar night.

3. Case Studies: Past and Current Crewed Lunar Missions

NASA's final Apollo mission was nearly half a century ago. Even though there have been tremendous improvements in space technology since then, the underlying physics principles that dictated Apollo's structure & general design remain constant, leading to the striking resemblance of Apollo & Orion outwardly.

Table 1: Case Study Details

Mission Name	Mission Type	Launch Date	Mission Duration	Primary Mission Objectives	Crew	Key Achievements
Apollo 11	Crewed lunar landing	July 16, 1969	8 days, 3 hours, 18 minutes	1. Execute first human landing on the Moon 2. Walk on and observe lunar surface 3. Deploy instruments & conduct scientific experiments 4. Collect lunar soil/rock samples for Earth return 5. Return safely to Earth	Three Crew Members: • Astronaut Neil A. Armstrong • Astronaut Edwin E. Aldrin Jr. • Astronaut Michael Collins	• First human Moon landing • 26 hrs on lunar surface • Collected 21.5 kg samples
Artemis II	Crewed lunar flyby test	April 1, 2026	9 days, 1 hour, 32 minutes	1. Primary: Crewed test flight in lunar space 2. Confirm systems for deep space exploration 3. Test Orion life-support, propulsion, power, navigation 4. Evaluate crew performance in deep space 5. Prepare for sustained lunar presence	Four Crew Members: • Astronaut Reid Wiseman • Astronaut Victor Glover • Astronaut Christina Koch • Astronaut Jeremy Hansen	• First crewed mission beyond LEO in 50+ years • Flew farther than any human from Earth

Apollo & Orion spacecraft systems are analogous, comprising three major components:

- a. A launch abort system: It is responsible for the crew protection during launch & ascent stages.
- b. A crew module: Houses and sustains the crew by maintaining the environment of the module
- c. service module: Responsible for providing the main propulsive forces, power and life-sustaining commodities to the crew module.

Orion's significant advancements, building off from the Apollo program's lessons, allow NASA to extend the reach past the Moon to beyond. This helps in expanding the mission destination range and broadening the possibility to accommodate larger crews for longer missions.

Relatively, Orion's systems have been immensely upgraded to justify the effects of space radiation exposure. The electronic components within the computers are radiation hardened to survive the radiation hazard, something Apollo did not account for, as a period of minimum solar activity is chosen for the mission flight.

3.1 Crewed lunar orbiter

This section is for a detailed study of the thermal control design and methods used in the Apollo Command Module (CM), which stayed in the lunar orbit until the rendezvous and docking of the Lunar Module (LM).

The CM ended the Apollo mission with re-entry into the Earth's atmosphere and splashdown.

For the Apollo 11 mission, Astronaut Neil A. Armstrong served as the Commander, LM was piloted by Astronaut Edwin E. Aldrin Jr. and the CM was piloted by Astronaut Michael Collins.

Apollo Command Module

The main function of CM is to be the control centre and house the crew for most of the lunar mission. It is the only part that is recovered after the splashdown at the end of the mission.

The CM consists of two basic structures joined together with a layer of fibrous insulation as additional heat protection. The structures include:

- The inner structure (pressure shell) is basically the crew compartment, which is part of the module that is pressurized and contains an atmosphere.

The outer structure (heat shield) is made of stainless steel, with a brazed honeycomb sandwiched between steel alloy face sheets.

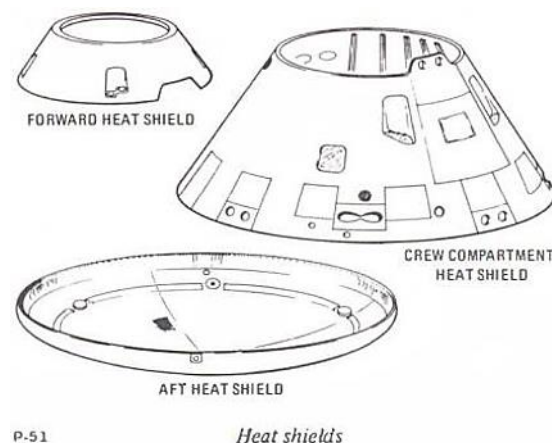


Figure 1: Heat Shields of Apollo Command Module [3] (Image courtesy: NASA Apollo Program Documentation, Command Module Overview [CSM06], NASA History Division. Public Domain.)

The CM is divided into three compartments (as seen in Figure 1):

- Forward Compartment (which is a small area at the apex of the module)
- Crew Compartment (occupied most of the centre section of the module)
- Aft Compartment (another relatively small area around the periphery of the module near the base)

Thermal protection (Heat shields)

The interior of the CM must be protected from the extreme environments encountered during the mission period. These extremes include:

- The heat of boost up to 1200°F (648.889 °C),
- The cold of space,
- the heat of the direct rays of the sun



- Most critical-the intense temperatures of entry, about 5000°F (2760 °C)

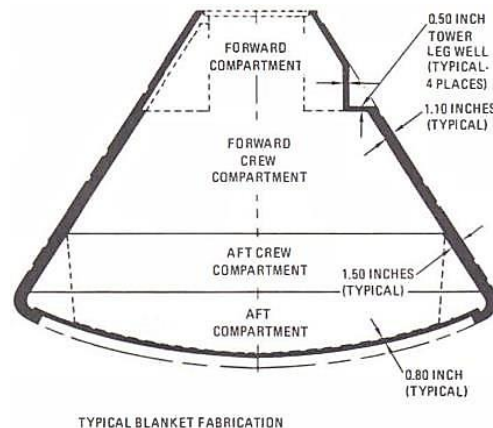


Figure 2: Typical Thermal Blanket Fabrication [3] (Image courtesy: NASA Apollo Program Documentation, Command Module Overview [CSM06], NASA History Division. Public Domain.)

Crew compartment heat shield

- The Boost Protective Cover (BPC) main function is to absorb the heat from the launch. It is a fiberglass structure that is covered with cork, fitted over the CM.
 - The BPC weighs about 317.514659 kg (700 lbs) and varies in thickness from about 3/10 of an inch to about 7/8 of an inch (at the top).
 - The cork is covered entirely with a reflective white coating.

This cover is permanently attached to the launch escape tower and is jettisoned with it at approximately 89916m (295,000 feet) during a normal mission.

The insulation between the inner & the outer shells, along with temperature control maintained by the Environmental Control Subsystem (ECS), protects the crew and the scientific equipment throughout the CM mission period.

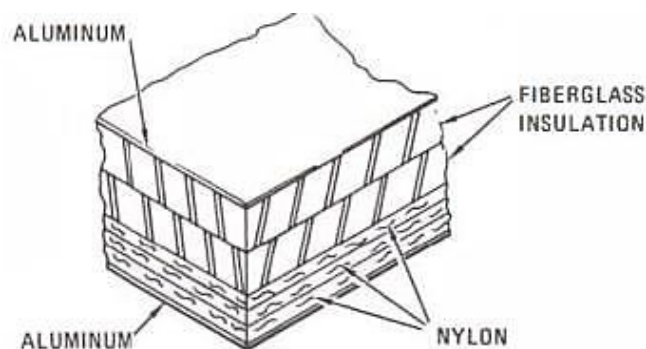


Figure 3: Insulation of Command Module (CM) [3] (Image courtesy: NASA Apollo Program Documentation, Command Module Overview [CSM06], NASA History Division. Public Domain.)

- The heat shield forms the outer structure of CM, weighing about 1360kg (3,000 lbs).

Its principal task is to protect the crew from the extreme heat during the re-entry phase. It varies in thickness:

- The aft portion is 0.0508 m (2 in)
- The crew compartment and forward portions are 0.0127m (½ in) each. It has numerous outer coverings:



- During the re-entry into the Earth's atmosphere, the ablative material controls the heat absorption rate either by charring or melting rapidly, dissipating the heat and preventing it from reaching the inner surface of the spacecraft.

This case study is about the thermal control in the recent Artemis II mission. The Orion Multi-Purpose Crew Vehicle (Orion MPCV) is a spacecraft of the Artemis program, which was the exploration vehicle carrying the crew of four astronauts to the moon and back.

Thermal control in the Artemis II mission

The flight path of the mission was designed in a way that carried humans farther into space than ever before.

The service module for the Orion spacecraft is the ESM, which acted as the primary power source and propulsion component to the CM until it was discarded at the end of the mission.

Additionally, the ESM supplies water, nitrogen and oxygen for a habitable environment, generates and stores electrical power, and regulates the temperature of the vehicle's systems and components.



- Structures, including Meteoroid and Debris Protection (MDPS)
 - Thermal Control Subsystem
 - Consumable Storage Subsystem
 - Propulsion Subsystem
 - Electrical Power
 - Service Module Avionics Equipment

In this paper, we focus on the thermal control system design, discussed in the section below.

ESM Thermal Control Design

The Thermal Control System (TCS), as mentioned in the previous sections, has two main subsystems: Passive Thermal Control System (PTCS) & Active Thermal Control System (ATCS). Additionally, the monitoring, control & power supply to the subsystems' active items (heaters, sensors, valves & pumps) is executed by two Thermal Control Units (TCU). These TCUs are commanded by the ODN /SNIC Network connection. The main temperature requirements are summarized in Table 2.

Table 2. Design Temperature Requirements [2]

Item	Min T	Max T
Avionics items	-20°C	50°C
Internal propulsion items	3°C	38°C
Propellants inside tanks	10°C	35°C
Water at delivery	13°C	28°C
Gas storage	0°C	50°C
ATCS fluid at IFHX inlet	4°C	21°C ⁵

Active Thermal Control System (ATCS)

The function of TCS is to collect thermal loads from the CM/ CMA & the ESM Avionics boxes and discard them into space. The architecture of the ATCS is based on two independent single-phase Fluid Loops working in hot redundancy. It uses the HFE-7200 series fluid as a coolant. The heat loads are collected from ESM avionics via cold plates and from CM/CMA via the Interface Heat Exchanger (IFHX), which are then transferred to the dedicated body-mounted radiators for a controlled heat rejection towards space. Represented in Figure 5

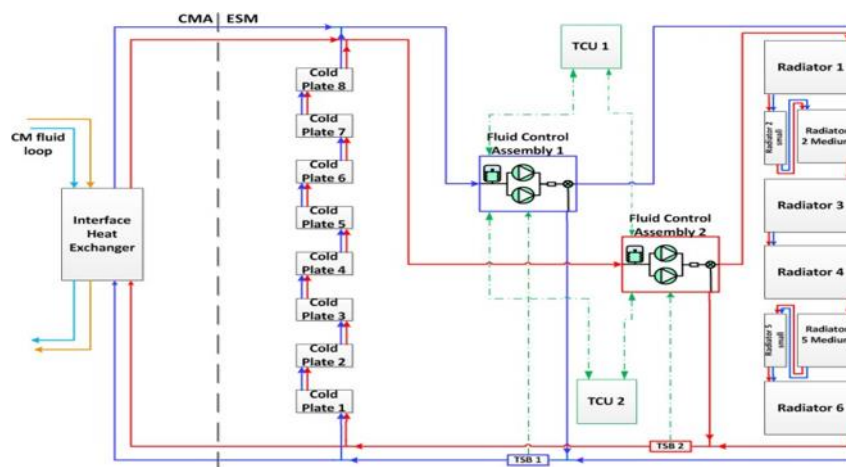


Figure 5 ATCS Schematic. Loop 1 in blue, Loop 2 in red [2] (Image courtesy: Berthe (2014), NASA Technical Report TR-20140008543. Public Domain.)

Along the ATCS, two dedicated restrictors are used:

- One on the bypass branch to balance the pressure drop between the radiator branch and the bypass branch
- One on the Cold Plates branch to ensure the correct coolant flow sharing between the cold plate branch and the IFHX branch

Passive Thermal Control System (PTCS)

The PTCS maintains the thermal control of propulsion, CSS, power and avionic items (ESM hardware). It also minimizes the temperature gradients and heat flow through the internal elements.

The PTCS is made up of two components:

1. Heaters

- **Heater lines**
 - They assure thermal control and the uniformity of temperature along the MPCV internals and for the local thermal control of the CSS Propulsion lines items and tanks,
 - Two of the Heater Lines work in cold redundancy, on each thermal homogeneous zone,
- Thermistors and Wire heaters

2. Insulation

- Multi-Layer Insulation (MLI) Thermal Blankets
 - It protects the internal parts of the spacecraft against the extreme external environment and heater lines to compensate for the heat leaks toward space.
- Flexible External Insulation (FEI) blankets (composed of silica felt embedded in Nextel fabric)
 - It provides thermal protection against high-temperature thruster plume impingement and engine nozzle thermal radiation
- Specific thermo-optical coatings
- Insulation washers

Thermal Control Units (TCU)

The TCU is designed to perform the management tasks of the TCS and of the CSS. For the ATCS,

- The TCU will acquire the various parameters from the ATCS sensors.
- It monitors and controls the valves ATCS,
- It issues commands to the Pump Package. For the PTCS,
- The TCU will control the heater chains and monitor the signals coming from the thermistors.
- It defines and modifies any independent heater chains activation and deactivation thresholds, while ensuring bus interface and power supply logic.

For the CSS,

- The TCU commands the valves and monitors their position, monitors the temperature levels on the tank for both the Water Delivery System & Gas Delivery System
 - It has a current/voltage monitoring to identify heater failures.
 - It also monitors pressure levels for the O2 and N2 distribution lines (high and low pressure) for the Gas Delivery System.
-



- For the Water Delivery System, it monitors the flow rate for the water distribution lines as well as turns on/off line heaters based on gas distribution request from CM and on the on-off valve position

Heat Shield

The heat shield is one of the most crucial components of the Orion spacecraft. Its main function is protecting Orion and the crew as they enter Earth's atmosphere, travelling about 40233.6 kmph (25,000 mph) and reaching temperatures of nearly 2760 °C (5,000 °F) It is the largest ablative heat shield in the world, standing at 5.0292m (16.5 feet) in diameter.

Avcoat, a reformulated version of the ablative material used on the Apollo capsules, is used for the Orion spacecraft.

- The Avcoat is first made into large blocks, then machined into 186 unique shapes before being applied onto the heat shield's underlying titanium skeleton and carbon fibre skin.
- Any gaps between the blocks are filled with an adhesive material and then reassessed.
- The entire outer surface is made up of blocks made with Avocat, which ablates during descent, transporting heat away from Orion.

As part of the final steps:

- The heat shield is painted with a coat of white epoxy paint.
- To dissipate electrical surface charges & maintain acceptable temperatures, aluminized tape is applied after the painted surface dries.
- Once all testing and verification are finished, the heat shield is then bolted to the crew module.

1.3 Crewed Lunar Lander Mission

This section is dedicated to discussing the thermal control for the Apollo LM, which reached the lunar surface, acted as a base for the astronauts and assisted in the launch of the ascent stage for rendezvous and docking into the CM in orbit.

Thermal control in the Apollo lunar module

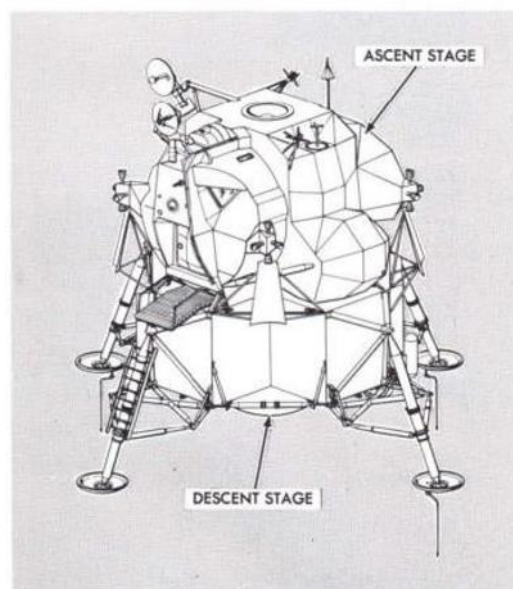


Figure 6: LM Configuration [4] (Image courtesy: NASA Apollo Program Documentation, Lunar Module [LM04], NASA History Division. Public Domain.)

The Apollo Lunar Module (LM), as in Figure 6, is made up of two main structures: an ascent stage and a descent stage. Both stages are joined together at four interstage fittings by explosive nuts and bolts and function as a single unit during separation from the Command Module (CM), lunar descent, and lunar stay.

LM is designed such that after descending to the lunar surface, it acts as a base from which the astronauts can explore the landing site. The descent stage serves as a launching platform from which the ascent stage lifts off from the lunar surface to rendezvous and dock with the Command & Service Module (CSM) in orbit. The ascent stage operates independently during the lunar ascent, rendezvous, and docking phase of the Apollo mission.

Thermal and Micrometeoroid Shield

The LM is exposed to micrometeoroids and solar radiation after it separates from the Spacecraft Lunar Module Adapter (SLA). To protect the LM, astronauts and the scientific equipment from the extreme temperatures, ATC and PTC systems are used. ATC is provided by the ECS. PTC isolates the vehicle interior structure and equipment from its external environment in order to sustain acceptable temperature limits throughout the lunar mission.

Ascent stage

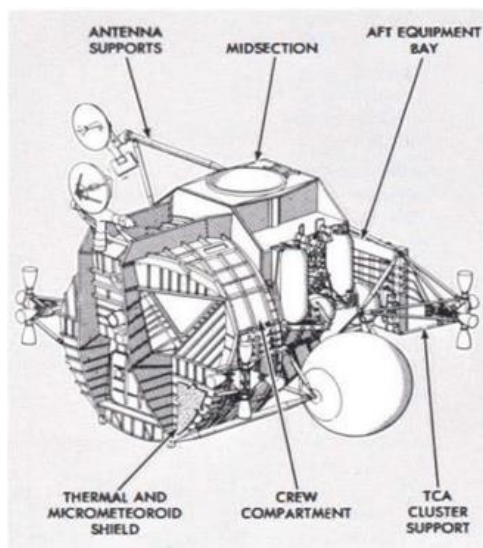


Figure 7: Ascent Stage Structure [4] (Image courtesy: NASA Apollo Program Documentation, Lunar Module [LM04], NASA History Division. Public Domain.)

The entire ascent stage structure (Figure 7) is enclosed within a thermal blanket and a micrometeoroid shield, as illustrated in Figure 8.

- Low thermal conductivity glass fibres standoff, hold the blanket away from the structural skin.
- The contact between the propellant tanks & the thermal blanket is prevented by the aluminium frames around the tanks.
- The **thermal blanket** is made up of a multiple-layered aluminized sheet. At least 25 layers of Mylar or H-film are used, each layer only 0.00015 inch thick and coated on one side with a micro-inch thickness of aluminium.
 - Mylar sheets are primarily used in areas where temperatures are under 300° F (~ 149°C).
 - H-film can endure temperatures up to 1000° F (~ 538°C). Since it is a heavier material, it is used only when it is indispensable.

For effective insulation, the polyimide sheets are hand crinkled before the blanket fabrication process, which provides a path for venting and minimizes contact conductance between the layers.

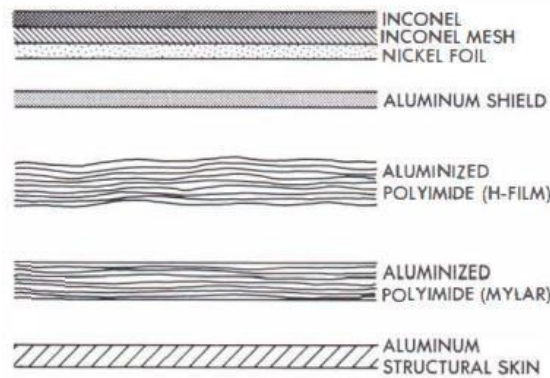


Figure 8: Typical Thermal Blanket & Micrometeoroid Shield [4] [Image Courtesy: NASA]

Individual structures like the antenna supports and landing gear equipment pass through the thermal blanket. They have high thermal conductivity, hence, a separate thermal protection.

Each of the blanket layers is overlapped and sealed tightly with a continuous strip of H-film tape. The blanket edges are sealed and stabilized with grommet-type fasteners. The seam is then folded and sealed with a constant strip of tape as illustrated in Figure 9.

Due to the plume impingement of CSM and LM Reaction Control System (RCS), certain areas of the ascent stage are exposed to temperatures as extreme as 982.2 °C (1800° F). To thermally control these areas, a sandwich material of thin nickel foil of 0.0000127 m (0.0005 inch) interleaved with Inconel wire mesh and Inconel sheet is used. To reduce the heat absorption for the front and docking windows, highly reflective surfaces of shades are used.

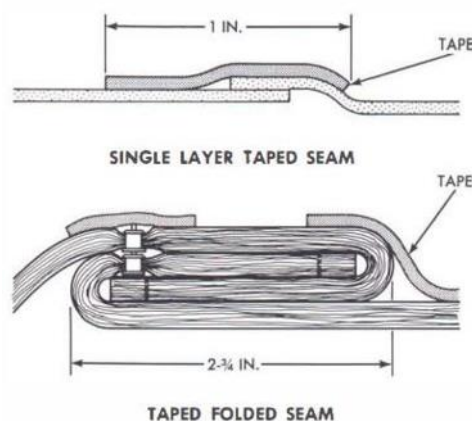


Figure 9: Thermal Blanket Joining Techniques [4] (Image courtesy: NASA Apollo Program Documentation, Lunar Module [LM04], NASA History Division. Public Domain.)

- The micrometeoroid shield (illustrated in Figure 3.10) is a sheet of aluminium, situated outside of the thermal blanket.

Its thickness varies from 0.0001016 to 0.0002032 m (0.004 to 0.008 inch), depending on the vulnerability of micrometeoroid penetration. The same standoffs used for thermal blankets are used to attach the micrometeoroid shield. Several coatings of thermal control are applied to the outer surface of the shield, which provides a secondary temperature boundary for the insulation of the space vehicle.

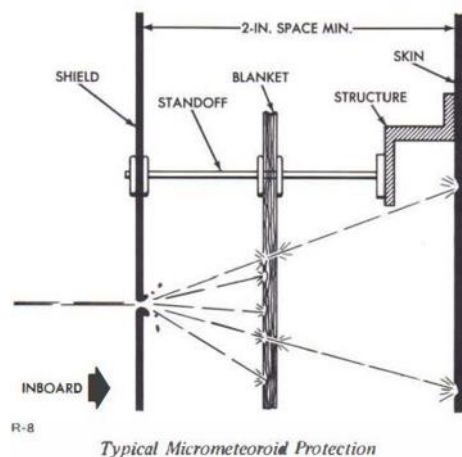


Figure 10: Typical Micrometeoroid Protection [4] (Image courtesy: NASA Apollo Program Documentation, Lunar Module [LM04], NASA History Division. Public Domain.)

Descent stage

Similar to the ascent stage, the entire descent stage structure is encompassed in a thermal and micrometeoroid shield, as shown in Figure 311. The top deck and side panels of the descent stage are vastly protected with a nickel Inconel mesh sandwich outboard of the H-fil & Mylar blankets, since they are exposed to engine exhaust.

The steps below are taken to protect the descent stage from the ascent stage's engine exhaust gases that are deflected outward, between the stages, during lift-off from the lunar surface:

- A Teflon-coated titanium blast is secured to the upper side of the compartment, below the thermal blanket.
- Several layers of H-film are joined to the blast deflector, which acts as an ablative layer protecting the descent stage structure from the engine exhaust gases

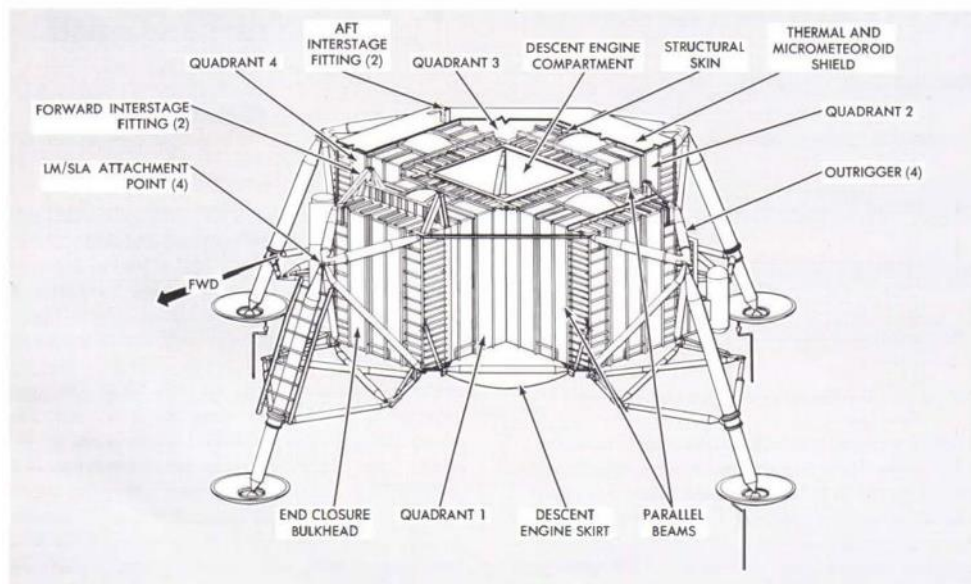


Figure 11: Descent Stage Structure [4] (Image courtesy: NASA Apollo Program Documentation, Lunar Module [LM04], NASA History Division. Public Domain.)

A special base heat shield made of titanium is attached to the descent stage structure to protect it from the excess heat of the descent engine. The heat shield supports a thermal blanket on each of its sides.



The thermal blanket that faces the engine nozzle comprises numerous layers of nickel foil, glass wool and an outer layer of H-film. This thermal blanket acts like a protective layer to survive:

- Engine exhaust gases,
- Back pressures at lunar touchdown
- Prevent the heat, which was absorbed by the lunar surface during the landing of LM, from radiating back into the descent stage structure.

The blanket on the other side of the titanium is made up of twenty-five layers of H-film.

A bellows arrangement, a flange-like ring of columbium backed with a fibrous (Min-K) insulation, is attached directly to the nozzle extension of the engine. This arrangement allows the gimbaling of the descent engine, but prevents the heat from the engine from leaking into the engine compartment.

However, very few minor changes were made to the command and service modules, the lunar module, of the Apollo 11 space vehicle from the Apollo 10 configuration.

- A change from Kapton to Kel-F was made to the descent stage base heat shield to preclude the possibility of interference with the landing radar.

Also, insulation was added to the landing gear and probes to accommodate the requirement for descent engine firing until touchdown.

4. Key Thermal Challenges on the Lunar Surface

Moon's surface thermal environment is much more severe than that of the Earth in both magnitude and variation, due to

- The rotational period of the Moon,
- The thermo-physical properties of lunar regolith
- The absence of an atmosphere

The lunar surface is characterized, depending upon location, by a layer of regolith of irregular thickness. This section looks into the thermal challenges that are faced by the spacecraft, lunar rovers and the crew on the lunar surface.

4.1 Core Environmental Challenges

- Extreme temperature swings
 - Surface temperatures on the Sun-lit side of the Moon can exceed 390 K (242°F) at the equator, whereas the dark side temperatures may plummet below 90 K (-298°F). The day and night cycles on the moon are approximately 28 Earth days
- Polar and eclipse conditions
- Non-uniform infrared environment
- Spacecraft orbiting in low lunar orbits, passing directly above or near the lunar sub-solar point (i.e. Sun directly overhead), are subjected to the impacts of infrared flux emitted from the surface upon thermal radiators.

4.2 Lunar Dust Contamination

- Regolith is generally categorised as "dust" if it is less than 20 μm (micrometre) in diameter.
- Lunar dust is a challenge because of its sharp, charged, toxic, insulating, erosive, absorptive and fine nature.
- Dust contamination of external thermal control surfaces and particulate introduction into crew spaces are significant concerns for lunar lander missions.

4.3 Systems-Level Challenges for Habitats, Landers, and Rovers

- One of the major issues for the Lunar Rover Vehicle (LRV) was battery overheating on both Apollo 16 and 17 missions, due to the accumulation of lunar dust on the LRV radiator.
- Waste heat rejection was accomplished via water evaporation or sublimation from on-board water stores due to the thermal environment constraints
 - The Apollo Lunar Excursion Module (LEM) on-board water supply of 415 lbs was distributed between multiple tanks in the descent and ascent stages of the LM.
- Lunar dust accumulation on optical surfaces such as camera lenses, helmet visors, photovoltaic (PV) cells, viewports, and windows
 - Removal of lunar dust from the optical surface was done with special brushes, which were designed and used to remove dust from camera lenses during the Apollo era.
 - This technique might prove to be impractical and unsuccessful for the longer duration Artemis missions and for larger surfaces of PV cells.
- The heat rejection subsystem (Radiators) of the Thermal Control System (TCS) is likely the most affected by lunar dust, chiefly due to potential direct exposure and the significant impact the dust has on the component performance.

4.4 Spacesuits challenges

- Fabrics are top assemblies of fibres that must continuously withstand tensile, abrasive, twisting, and bending forces.
- In the Dust Management Project ([Hyatt & Straka, 2011](#)), the authors highlight that regolith can affect the performance of Extravehicular Activities (EVA) due to its contamination of the spacesuit fabric and mechanisms.

Mitigation approach proposed to protect MLI surfaces, spacesuit visors, and other EVA materials and tools was a dust mitigation coating using the lotus effect. Ñ

5. Summary and Conclusion

Designing and implementing the spacecraft TCS for a crewed lunar mission represents one of the most arduous & consequential challenges in aerospace engineering. This review paper has examined the thermal control systems and methods applied across three monumental space vehicles, the Apollo Command Module, the Apollo Lunar Module, and the Artemis II Orion spacecraft. The Apollo CM relied on a combination of ablative heat shielding, MLI, and the ECA to protect its crew from the thermal extremes of the space environment, from the intense aerodynamic heating of launch and re-entry. The Apollo LM, which is exposed to micrometeoroids and intense solar radiation after the separation from the CM, utilized a PTC architecture of multi-layer aluminized Mylar and H-film blankets, micrometeoroid shields, and specialized coatings, complemented by ATC through the ECS. Specific arrangements were undertaken for areas subjected to extreme plume impingement temperatures, and the descent stage incorporated dedicated blast deflectors and titanium heat shields to survive the severe temperatures of lunar ascent engine exhaust. The Artemis II Orion spacecraft employs dual-loop ATCS, employing HFE-7200 coolant fluid, cold plates, and body-mounted radiators, which work harmoniously with an extensive PTCs comprising MLI blankets, FEI, and thermo-optical coatings. The TCU provides smart monitoring and management of both subsystems. The Orion heat shield employs a reformulated ablative material called Avcoat, capable of withstanding re-entry temperatures of 2760°C (5,000°F). Beyond the spacecraft themselves, the lunar surface environment presents formidable and still unanswered thermal challenges to some extent. Extreme temperature swings between the sunlit and shadowed lunar surface, combined with the insidious problem of lunar dust contamination, remain active areas of concern for the Artemis program's longer-duration surface missions. In conclusion, though the fundamental physics governing spacecraft thermal control have remained unchanged since the Apollo era, the engineering solutions have developed considerably more sophisticated, redundant, and intelligent. The lessons carved into human spaceflight history by both momentous milestones of Apollo 11, Artemis II and catastrophic tragedies of Apollo 1, Soyuz 1, Soyuz 11, Challenger, and Columbia have collectively encouraged a culture of rigorous thermal design, analysis, and testing that strengthens every human spaceflight mission today. As the aerospace and spaceflight community set its sights on sustained lunar presence and eventual manned missions to



Mars, the endless advancement of thermal control technologies will remain the backbone of safe and successful human space exploration.

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8. Data Availability Section

All data supporting the findings of this review are available from the publicly accessible sources cited in the References section. No new experimental data were generated during the course of the study.

9. Conflict of Interest

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10. Conflict of Interest

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