

Finite Element Analysis of PCM-Enhanced Passive Thermal Regulation for CubeSats

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Publication Date: 2025/10/13

Abstract: The thermal environment of outer space poses severe challenges due to the absence of atmosphere, lack of convective heat transfer, microgravity, and extreme temperature variations—from over +120°C in direct sunlight to below –100°C in shadow. Unlike Earth, space systems must operate in a vacuum, where thermal regulation depends solely on conduction and radiation. In such an environment, traditional cooling techniques that rely on fluid-based (hydraulic) or air-based mechanisms are inapplicable. Additionally, mechanical stresses during launch, radiation exposure, and mass and power limitations further constrain thermal management, especially in miniaturized satellites. This study was inspired by a key observation during research on microgravity thermal behaviour and space mission failures — many CubeSats and nano-satellites suffered thermal-induced malfunctions due to poor heat regulation. Recognizing this gap, we proposed the use of Phase Change Materials (PCMs) as a passive thermal control solution. The idea emerged from understanding that PCMs, used in terrestrial energy storage systems, could be re-engineered for space to store and release latent heat during orbital cycles, stabilizing internal satellite temperatures. We targeted CubeSats and small Earth observation satellites due to their growing use in Low Earth Orbit (LEO) missions and their vulnerability to thermal extremes. Our approach began with identifying critical thermal challenges, followed by a comparative study of atmospheric vs. space thermodynamic behaviour. Based on this, we employed a multi-criteria PCM selection process, considering factors such as latent heat capacity, melting point, vacuum compatibility, non- flammability, and long-term stability. Using Finite Element Analysis (FEA) in ANSYS, we simulated real orbital heating and cooling cycles. To counteract the absence of convection, conductive fins, graphene-enhanced spreaders, and radiation-optimized enclosures were integrated with the PCM. Structural design also addressed launch survivability through mechanical reinforcement techniques. The resulting system demonstrated improved thermal uniformity, reduced temperature spikes, and enhanced electronic reliability without adding significant mass or power consumption. This approach provides a sustainable, efficient, and scalable thermal regulation solution for future satellite missions—particularly those in the budget- and volume-constrained CubeSat segment.

How to Cite: Rampuram Mahesh; Jureddy Suresh (2025) Finite Element Analysis of PCM-Enhanced Passive Thermal Regulation for CubeSats. *International Journal of Innovative Science and Research Technology*, 10(9), 2927-2949.
<https://doi.org/10.38124/ijisrt/25sep1484>

I. INTRODUCTION

The ever-growing reliance on satellite-based infrastructure has transformed global communication, Earth observation, environmental monitoring, and scientific exploration. At the forefront of this transformation is the rapid deployment of small satellites, particularly CubeSats and nanosatellites, which have redefined the cost, accessibility, and scalability of space missions. Their modular design, standardized dimensions (typically based on 1U = 10×10×10 cm units), and ability to be rapidly developed and launched as part of multi-satellite constellations have opened the doors for universities, startups, and emerging space nations to participate in space missions that were once the domain of only major agencies like NASA, ESA, or ISRO.

Despite these advantages, thermal regulation remains one of the most critical engineering bottlenecks in the design and operation of small satellites. Space is not merely "cold"

— it is thermodynamically complex. Unlike Earth-based systems that benefit from atmospheric convection, conductive airflow, and pressure-based heat management, spacecraft in orbit operate in the vacuum of space, where heat transfer occurs solely through conduction and radiation. The absence of convective mechanisms means that heat generated internally (from processors, batteries, and RF components) cannot be dissipated in the conventional manner. Instead, it accumulates, potentially damaging components or degrading mission performance.

Moreover, satellites in Low Earth Orbit (LEO) are subjected to a continuous cycle of heating and cooling every 90 minutes. During sunlit portions of the orbit, external surfaces can reach temperatures above +120°C, while during eclipse periods, the same surfaces can plunge below –100°C. These temperature fluctuations not only induce thermal stress across materials but also compromise the stability and accuracy of onboard instruments, timing circuits, and energy storage systems.

In larger satellites, active thermal control systems — comprising pumps, heat pipes, refrigerants, or even miniaturized HVAC systems — are employed to maintain optimal temperatures. However, for CubeSats and nanosatellites, these solutions are impractical due to severe constraints in volume, mass, and power availability. A 3U CubeSat, for example, may weigh less than 4 kg and operate on less than 10 W of power, leaving little room for complex thermal subsystems. Furthermore, these small satellites often undergo intense mechanical vibrations during launch, are exposed to cosmic radiation, and operate in microgravity, which further complicates thermal and structural design.

Given these constraints, there is a compelling need for lightweight, low-cost, and energy-efficient passive thermal control methods that can function autonomously without the burden of active components. One promising approach is the use of Phase Change Materials (PCMs). PCMs have the intrinsic ability to absorb and store large amounts of heat during melting (endothermic process) and release it during solidification (exothermic process). This latent heat exchange allows PCMs to act as thermal buffers, maintaining near-constant temperatures during thermal spikes.

When applied to a satellite in LEO, PCMs can absorb excess heat during sunlit phases by melting and release that heat during eclipse periods by re-solidifying. This natural phase transition smoothens the internal temperature profile of the satellite, reducing thermal stress and enhancing the reliability of electronic components. Unlike active systems, PCMs require no external energy input and can be seamlessly integrated into the structural geometry of the satellite.

However, the adoption of PCMs in space systems is not without challenges. Not all PCMs are suitable for the harsh environment of space. They must be thermally conductive, vacuum-compatible, radiation-resistant, and able to withstand multiple freeze–melt cycles without degradation. In addition, the low thermal conductivity of most PCMs (especially organic types like paraffin wax) can limit their effectiveness during rapid thermal transitions unless augmented with high-conductivity pathways.

To address these multi-dimensional challenges, our research presents a systematic and multi-criteria engineering approach to PCM-based thermal control for small satellites. We propose the design, simulation, and integration of customized PCM modules — not as generic thermal masses, but as engineered components that respond dynamically to mission-specific heat profiles. We particularly focus on the integration of graphene-enhanced thermal spreaders, heat mapping-based PCM placement, and adaptive enclosures using Shape Memory Alloys (SMAs) to accommodate volume expansion.

This study is guided by the real-world observation that many CubeSats fail due to inadequate thermal planning, often during critical mission phases such as power-intensive transmissions or eclipse re-entry. By combining material

science, thermal modelling, and mechanical design, we aim to develop a passive thermal control system that is efficient, scalable, and space worthy — specifically optimized for the next generation of miniaturized satellite platforms.

In the following sections, we delve into the PCM selection criteria tailored for space missions, outline our simulation and validation methodology using ANSYS, and present the unique innovations introduced in this research. These include the development of graphene-infused PCM blocks, component-specific PCM allocation via thermal mapping, and optionally, self-reconfigurable chambers that adapt to phase-induced volume changes. The culmination of this work is a scalable design framework that future missions can adopt to enhance satellite survivability and mission success under extreme thermal conditions.

II. UNDERSTANDING LOW EARTH ORBIT (LEO) SATELLITES: FEATURES, ADVANTAGES, AND APPLICATIONS

The increasing deployment of satellites in Low Earth Orbit (LEO) has transformed how space missions are conceived and executed. Positioned at altitudes ranging between 160 km and 2,000 km above Earth's surface, LEO is the most heavily utilized orbital zone, especially for small satellites such as CubeSats and nanosatellites. Its relative proximity to Earth offers a combination of unique benefits and engineering challenges that directly influence thermal design requirements.

➤ Key Characteristics of LEO Satellites

- **Short Orbital Period:** LEO satellites complete an orbit around the Earth approximately every 90–120 minutes, leading to frequent transitions between sunlit and eclipse conditions. This results in rapid and cyclic thermal fluctuations, typically from +120°C in sunlight to –100°C in Earth's shadow, which poses significant thermal management challenges.
- **Low Latency:** Due to their closeness to Earth, LEO satellites offer reduced communication latency, making them ideal for real-time data transmission, remote sensing, and low-latency internet services.
- **Reduced Launch Costs:** Reaching LEO requires less energy than higher orbits, enabling cost-effective launches, especially for CubeSats using rideshare missions.
- **High Resolution for Imaging:** Satellites in LEO can capture high-resolution images of Earth due to their nearness, making them optimal for Earth observation, weather monitoring, disaster assessment, and agricultural analytics.
- **Greater Atmospheric Drag:** While LEO allows frequent data downloads and quick revisit times, satellites in these orbits also experience atmospheric drag, which gradually lowers their altitude unless corrected by propulsion or design.

➤ Applications of LEO Satellites

LEO satellites, particularly CubeSats and microsatellites, are used in a wide range of domains:

- *Earth Observation and Remote Sensing*

Used for environmental monitoring, crop analysis, resource mapping, and climate research.

- *Scientific Research and Experimentation*

Employed in space biology, materials testing in microgravity, radiation studies, and technology demonstrations.

- *Communication and IoT Networks*

LEO satellite constellations like Starlink and OneWeb are revolutionizing global internet connectivity, especially in rural and remote areas.

- *Disaster Monitoring and Emergency Response*

Real-time data from LEO satellites helps in assessing natural disasters such as floods, forest fires, and earthquakes.

- *Defence and Surveillance*

Deployed for military reconnaissance, maritime tracking, and border surveillance due to their high temporal resolution.

- *Educational and University Missions*

Many academic institutions design and launch CubeSats to test new technologies or provide hands-on learning in space engineering.

➤ Thermal Challenges Specific to LEO

Due to the high frequency of eclipse and sunlight transitions, thermal stress is especially pronounced in LEO. Small satellites with limited surface area and high component density tend to accumulate heat during sunlight and lose it rapidly in shadow, leading to operational instability or even failure. The thermal environment of LEO makes passive regulation solutions like PCM integration highly valuable.

➤ Justification for PCM Use in LEO Satellites

Given the volume, mass, and power constraints typical of CubeSats in LEO, active cooling methods are not feasible. PCMs offer an ideal solution to maintain component temperatures within a safe operating range, ensuring:

- Enhanced component reliability
- Extended mission lifespan
- Elimination of power-consuming thermal subsystems
- Scalable and modular thermal buffering tailored to orbital conditions

III. PHASE CHANGE MATERIALS (PCMs) FOR SATELLITE THERMAL MANAGEMENT

In the design of thermal control systems for miniaturized satellites, Phase Change Materials (PCMs) offer a compelling solution for managing heat loads without

relying on active subsystems. Their ability to absorb and release substantial amounts of thermal energy during phase transitions enables them to regulate internal temperatures efficiently and passively.

PCMs function by undergoing a solid–liquid phase change. During the melting process, they absorb latent heat at a nearly constant temperature, preventing internal components from overheating. As the satellite enters eclipse and begins to cool, the PCM solidifies and releases the stored heat, maintaining a balanced temperature profile. This cycle aligns well with the thermal cycling of Low Earth Orbit (LEO) satellites, which experience heating and cooling phases approximately every 90 minutes.

➤ Thermal Requirements for Space-Grade PCMs

To ensure performance under space conditions, ideal PCMs must meet several thermophysical and environmental criteria:

- **Melting Point:** Between 20°C and 60°C, suitable for electronic components and battery systems.
- **High Latent Heat of Fusion:** The greater the latent heat, the more energy the PCM can store per unit mass.

$$Q = m \cdot L$$

Where:

Q = Heat absorbed or released (Joules) m = Mass of PCM (kg)

L = Latent heat of fusion (J/kg)

- **High Specific Heat Capacity:** Allows the PCM to store sensible heat before and after the phase change:

$$Q = m \cdot c \cdot \Delta T$$

Where:

c = Specific heat (J/kg · K)

ΔT = Temperature change (K)

- **Vacuum Compatibility:** Must not outgas or degrade under low-pressure conditions.
- **Non-Toxicity and Chemical Stability:** For safe handling and structural integration.
- **Radiation Resistance:** To maintain structural and thermal properties after exposure to cosmic rays and solar radiation.
- **Reversibility and Cyclability:** Should endure hundreds of phase change cycles without performance loss.

➤ Comparison of Common PCMs for Space Applications

A comparative analysis of candidate PCMs is essential to ensure compatibility with mission requirements. The table below presents widely studied PCMs suitable for CubeSats and nanosatellites:

Table 1 Comparison of Common PCMs for Space Applications

PCM Name	Type	Melting Point (°C)	Latent Heat (kJ/kg)	Remarks
RT-42 (Rubitherm)	Paraffin-based	~42	~180–200	Chemically stable, non-corrosive, suitable for general-purpose electronics
n-Octadecane (C₁₈H₃₈)	Organic (Alkane)	~28	~240	High latent heat, excellent vacuum stability
Sodium Acetate Trihydrate	Salt Hydrate	~58	~264	Inexpensive, good storage capacity, may require encapsulation
Erythritol	Sugar Alcohol	~118	~340	High storage potential, but needs thermal stabilization
Paraffin Wax Blends	Organic	30–60 (adjustable)	~200–250	Customizable melting point, most popular in CubeSat thermal systems

➤ PCM Selection for this Study

After performing a multi-criteria decision analysis (MCDA) based on thermal performance, reliability, compatibility, and cost, the following materials were selected:

- RT-42: Ideal for mid-range electronics; offers stability in space and easy handling.
- n-Octadecane: Preferred for low-temperature-sensitive components like batteries due to its lower melting point and higher latent heat.

These PCMs can be deployed in parallel or in a layered structure, allowing the system to maintain different thermal zones within the satellite.

➤ Encapsulation and Thermal Enhancement

Since PCMs inherently have low thermal conductivity, their thermal responsiveness must be improved to effectively manage rapid orbital transitions. This is achieved through encapsulation and enhancement techniques, such as:

- Metallic Fin Arrays (Aluminium or Copper)
- Graphene Foams and Nanocomposites
- Carbon Fiber Heat Spreaders

The effective thermal conductivity of such composite PCM structures can be approximated using Maxwell's Model:

This enhancement significantly increases the PCM's responsiveness, allowing it to distribute heat more uniformly and quickly during phase transitions.

➤ Summary

The integration of PCMs into satellite thermal systems offers a reliable, efficient, and scalable solution to manage temperature fluctuations in the vacuum of space. RT-42 and

n-Octadecane have been identified as optimal candidates for CubeSat-class spacecraft, balancing high energy storage, safety, and environmental stability. With advanced thermal enhancement materials like graphene, and precise encapsulation techniques, PCMs become a powerful tool in achieving passive thermal regulation for next-generation space missions.

IV. INTEGRATION OF SHAPE MEMORY ALLOYS (SMAS) FOR ADAPTIVE THERMAL ENCLOSURES

As small satellite platforms continue to shrink in size while increasing in functional complexity, the demand for multi-functional components that can perform mechanical, thermal, and structural roles becomes increasingly critical. In this context, Shape Memory Alloys (SMAs) emerge as powerful candidates to enhance passive thermal control systems, especially those involving Phase Change Materials (PCMs).

SMAs are a class of smart materials that exhibit the shape memory effect, wherein they can return to a pre-defined shape upon exposure to a specific temperature. By embedding SMAs into PCM chambers, we can develop self-regulating, volume-adaptive enclosures that respond dynamically to thermal changes in orbit.

➤ Functional Requirements of SMAs in Satellite PCM Systems

The ideal SMA for a space-based PCM chamber must satisfy the following conditions:

- **Thermally Matched Activation:** The SMA's transformation temperature (martensite to austenite) should align with the melting point of the PCM (typically 40–50°C for RT-42 or paraffin-based materials).
- **Radiation and Vacuum Compatibility:** The SMA must

retain mechanical and structural properties under space radiation and high-vacuum environments, without degradation.

- **High Fatigue Resistance:** In LEO, with over 15 thermal cycles per day, the SMA must endure hundreds to

thousands of actuation cycles without performance loss.

➤ *Comparison of Common SMA Materials for Space Applications*

Table 2 Comparison of Common SMA Materials for Space Applications

SMA Alloy	Actuation Temp (°C)	Key Properties	Notes
NiTi (Nitinol)	~40–100 (adjustable)	High 10ecover strain, corrosion resistance	Most widely used in aerospace, excellent fatigue performance
NiTiCu	~30–90	Low hysteresis, more stable cycling behavior	Better fatigue resistance than NiTi; suitable for repeated actuation
NiTiNb	~60–90	Enhanced damping, moderate flexibility	Used in vibration-sensitive or shock-damping applications
CuAlNi	~80–100	High transformation temperature, cost-effective	Rigid and less ductile; suitable for less dynamic structures
FeMnSi	~90–120	Economical, moderate shape recovery	Suitable for large-scale deployment; not ideal for micro-scale satellite chambers

➤ *Optimal SMA Selection for Our System*

Considering the PCM material RT-42 (melting at ~42°C), the NiTi and NiTiCu alloys offer the best thermal alignment and mechanical properties. Both can be trained to actuate within a narrow range around 40–45°C, enabling a direct correlation between PCM phase change and SMA activation.

NiTiCu, in particular, exhibits lower thermal hysteresis and superior cyclic durability, making it highly suitable for repetitive expansion–contraction cycles in orbit.

➤ *Smart PCM-SMA Synergy: A Passive Self-Actuating System*

To fully exploit the compatibility between PCMs and SMAs, we propose a smart combination strategy that synchronizes thermal behavior with structural adaptation:

• *System Design:*

- ✓ Use RT-42 PCM to regulate satellite temperatures via latent heat exchange.
- ✓ Embed NiTi SMA inserts or flexible walls in the PCM containment structure.
- ✓ SMA is pre-programmed to flex outward when temperature exceeds ~42°C (PCM melting point), allowing the chamber to expand and accommodate the volumetric change.
- ✓ As the satellite cools during eclipse, the PCM solidifies, and the SMA returns to its original shape, contracting the chamber and maintaining structural stability.

• *Benefits:*

- ✓ Provides mechanical compliance for PCM expansion without requiring moving parts or sensors.
- ✓ Maintains chamber integrity under varying pressure conditions caused by phase transitions.
- ✓ Functions autonomously, without power input, ensuring long-term reliability and spaceworthiness.

This hybrid system effectively combines thermal buffering (PCM) with mechanical flexibility (SMA) to create a fully passive, self-regulating thermal-mechanical module, ideal for small satellite missions with volume, mass, and power limitations.

➤ *Future Scope*

Advanced SMA geometries (e.g., helix coils, honeycomb structures, and bistable SMA grids) can be explored for optimizing force distribution and expansion control. Furthermore, embedded sensor- SMA circuits could be developed to create semi-passive systems that not only respond but also log thermal events, improving onboard health monitoring.

V. A NOVEL PCM + SMA HYBRID SYSTEM FOR PASSIVE THERMAL AND STRUCTURAL ADAPTABILITY IN SMALL SATELLITES

As space missions become more compact, cost-driven, and power-constrained, the pursuit of multi- functional passive systems becomes crucial for mission reliability and

sustainability. While Phase Change Materials (PCMs) are highly effective in regulating thermal environments via latent heat absorption and release, they bring with them a critical mechanical challenge: volumetric expansion during melting. Left unmanaged, this expansion can compromise structural integrity, especially within sealed and rigid enclosures used in CubeSats.

To address this issue, we propose a novel integration of Shape Memory Alloys (SMAs) into PCM chambers, creating a self-adjusting, reusable, and passive thermal-mechanical system. This combined approach improves both thermal regulation and long-term structural stability, representing a new design frontier in small satellite engineering.

➤ *Problem Statement: Limitations of PCM Alone*

PCMs typically expand by 10–15% during phase transition from solid to liquid. In a microgravity, sealed environment like that of a satellite:

- This expansion leads to internal pressure buildup.
- Over time, this can cause material fatigue, micro-leakage, or even containment rupture.
- Repeated cycling without adaptive accommodation reduces the reusability and safety of the thermal regulation system.

In short, while PCM handles the heat, it struggles with its own physical transformation under constrained volume conditions.

➤ *The Role of SMA: Structural Intelligence in Action*

Shape Memory Alloys (SMAs)—such as NiTi or NiTiCu—exhibit a thermally driven shape change, allowing them to expand when heated and revert when cooled, without external power or actuators.

• *In Our Design:*

- ✓ SMA is integrated into PCM chamber walls, braces, or membranes.
- ✓ As the PCM melts and pressure increases, the SMA flexes outward, absorbing the stress and temporarily increasing volume capacity.
- ✓ As the PCM solidifies during orbital eclipse, the SMA returns to its original shape, preserving the structural configuration.
- ✓ This results in a self-healing enclosure that breathes in sync with the thermal cycle.

➤ *Functional Comparison: PCM Alone vs. PCM + SMA Design*

Table 3 Functional Comparison: PCM Alone vs. PCM + SMA Design

Feature	PCM Alone	PCM + SMA Hybrid System
Thermal Regulation	Excellent	Excellent
Handles Volume Expansion	Limited	SMA dynamically absorbs expansion
Reusability & Cycle Fatigue	Risk of fatigue, deformation	SMA enhances structural life through elastic deformation
Power Requirement	Passive	Passive
Mass and Volume Efficiency	Moderate	Improved with smart, dual-function structure
Sustainability for LEO Use	Limited for long-term	High suitability for repetitive LEO thermal cycles

➤ *Operational Workflow of the PCM + SMA System*

• *Orbital Day (Sunlight Exposure)*

- ✓ Satellite enters thermal peak.
- ✓ PCM absorbs excess heat → melts → begins to expand.
- ✓ SMA reaches actuation temperature (~42–45°C) → flexes outward, providing space.

• *Orbital Night (Eclipse Phase)*

- ✓ Satellite cools rapidly.
- ✓ PCM solidifies → contracts.
- ✓ SMA returns to original shape, resetting the enclosure for the next cycle.

This loop enables repeatable thermal buffering with structural resilience, perfectly aligned with LEO cycling behavior.

➤ *Innovation and Research Contribution*

The proposed PCM + SMA hybrid design offers a first-of-its-kind passive structural adaptation system specifically for small satellite platforms. While both PCMs and SMAs have been independently studied in aerospace applications, their synergistic integration as a self-regulating enclosure system remains largely unexplored in current literature.

• *By Embedding SMA within PCM Modules:*

- ✓ One material handles the heat (PCM).
- ✓ The other handles the force (SMA).

This enables a smarter, integrated passive system—ideal for CubeSats and nanosatellites where mass, power, and failure tolerance are tightly constrained.

➤ *Vision and Scalability*

This hybrid system can be extended to:

- Modular satellite platforms with variable heat sources.
- Multi-zone PCM chambers, each with tailored SMA responses.
- Future adaptive structures in spacecraft, including morphing panels or deployable radiators.

VI. ENGINEERING A PASSIVE SMART MATERIAL HYBRID SYSTEM: PCM-SMA INTEGRATION STRATEGY

The growing demand for intelligent, lightweight, and energy-efficient systems in satellite design has led to the exploration of synergistic material integration. In this work, we propose a structurally engineered hybrid system that integrates Phase Change Materials (PCMs) and Shape Memory Alloys (SMAs) into a compact, repeatable, and fully passive module for thermal management and mechanical resilience in Low Earth Orbit (LEO) missions.

While neither PCMs nor SMAs are new to aerospace applications, the novelty of this design lies in the functional coupling of their respective properties to achieve a self-regulating thermal-mechanical enclosure—without moving parts, electronics, or power input.

➤ *Concept Overview: How the PCM-SMA System Works*

This hybrid system operates through a mutually responsive interaction between the PCM and SMA, both of which respond to the same thermal environment but serve different purposes:

• *PCM: Thermal Buffering*

- ✓ Material Example: RT-42 (melting point ~42°C)
- ✓ Role: Absorbs excess thermal energy during orbital day by melting; releases heat during orbital night by solidifying.
- ✓ Challenge: Melting causes 10–15% volumetric expansion, generating internal stress within containment enclosures.

• *SMA: Structural Compensation*

- ✓ Material Example: NiTi or NiTiCu (actuation temperature ~40–45°C)
- ✓ Role: Flexes to accommodate PCM expansion during heating, then contracts back during cooling.
- ✓ Benefit: Prevents rupture, leakage, or fatigue in PCM enclosures, ensuring long-term reliability.

➤ *Step-by-Step Operational Cycle*

• *During Sunlight (Orbital Day):*

- ✓ PCM reaches melting point (~42°C) and transitions to liquid, expanding.
- ✓ Internal pressure builds up inside the capsule.
- ✓ SMA (pre-trained at ~42–45°C) expands/flexes outward, absorbing this expansion safely.

• *During Eclipse (Orbital Night):*

- ✓ PCM begins to solidify, reducing internal volume.
- ✓ SMA returns to its original shape, restoring enclosure structure and preparing for the next cycle.
- ✓ This closed-loop mechanical adaptation ensures that the system is cyclic, passive, and reliable—ideal for LEO conditions where temperature oscillations are frequent and severe.

➤ *Historical use and Technological Context*

While PCMs and SMAs have both been independently used in space missions, no widely published work has proposed their combined structural use for thermal regulation in the context of small satellites. Some related precedents include:

• *NASA & ESA Applications:*

- ✓ Nitinol used in antenna deployment mechanisms, thermal shutters, and valves.
- ✓ Paraffin-based PCMs integrated into Mars rover thermal batteries and CubeSat thermal storage modules.

These individual applications demonstrate the space readiness of both material types, validating their use in the proposed integrated system.

➤ *Summary: What Makes this Novel*

This study does not aim to invent a new material, but rather to engineer a novel integration strategy that:

- Combines two smart, passive materials (PCM and SMA) in a co-dependent way.
- Solves a long-standing issue with PCM expansion in closed systems.
- Offers a fully passive, low-mass, and power-free thermal-mechanical regulation unit for small satellite platforms.

By embedding SMA into PCM enclosures, we create a system where:

“PCM handles the heat; SMA handles the stress — together, they create a repeatable, intelligent, and robust enclosure for extreme environments.”

This design presents a new direction for smart thermal systems in aerospace, with potential applicability across CubeSats, microsatellites, and future deep-space probes.

VII. PCM-SMA INTEGRATION STRATEGIES: ENGINEERING CONFIGURATIONS FOR ADAPTIVE THERMAL SYSTEMS

To translate the concept of a hybrid Phase Change Material (PCM) + Shape Memory Alloy (SMA) system into practical, mission-ready solutions, it is essential to develop and evaluate various integration strategies. These configurations must balance compactness, responsiveness, mechanical compliance, and ease of manufacturing, while also being tailored to the unique constraints of small satellite platforms.

The following design strategies represent different ways to embed SMA elements into PCM-based thermal chambers, each with distinct operational advantages, structural behaviors, and application niches.

➤ Strategy 1: SMA-Embedded PCM Chamber Walls Design Concept

- Embed thin NiTi SMA sheets, ribbons, or ribs directly into the walls of the PCM chamber.
- During orbital heating, as the PCM melts and expands, the chamber walls flex outward.
- The SMA embedded within the wall stretches elastically and stores mechanical energy.
- Upon cooling, the SMA contracts, restoring the walls to their original geometry.

• Advantages

- ✓ Extremely compact and lightweight — SMA is used only where structural flexibility is required.
- ✓ Compatible with additive manufacturing or layered assembly.
- ✓ Ensures consistent chamber shape without external actuators.

• Applications

- ✓ Ideal for tight enclosures where internal space is minimal.
- ✓ Suitable for thin-panel PCM modules embedded in satellite interior walls.

➤ Strategy 2: Internal SMA Spring or Spiral Actuator Design Concept

- Place a NiTi SMA coil or spring inside the PCM container.
- As PCM melts and expands, internal pressure compresses the spring.

- During eclipse, as PCM solidifies, the spring expands, helping PCM return to original volume.

• Advantages

- ✓ Provides mechanical equilibrium inside the chamber.
- ✓ Spring can be tuned for exact compression/expansion rates.
- ✓ Enables smooth redistribution of molten PCM.

• Applications

- ✓ Best suited for capsule-style or cylindrical PCM containers.
- ✓ Useful when internal volumetric compensation is preferred over external deformation.

➤ Strategy 3: SMA-Driven Diaphragm or Bellows Mechanism Design Concept

- Encase the PCM within a chamber that includes a flexible diaphragm or bellows wall, supported or activated by SMA strips or rings.
- As PCM melts and expands, the diaphragm bulges outward, absorbing volume increase.
- SMA elements return the diaphragm to its resting position as PCM solidifies.

• Advantages

- ✓ Provides smooth expansion control with fewer mechanical stresses.
- ✓ Also functions as a protective buffer against rupture or overpressure.
- ✓ Mechanically isolates PCM from satellite housing — leak prevention benefit.

• Applications

- ✓ Effective for modular PCM packs, adaptable to different spacecraft configurations.
- ✓ Useful in exposed or variable-temperature zones on the satellite surface.

➤ Strategy 4: PCM + SMA-Controlled Thermal Switch (Advanced Design) Design Concept

- Separate SMA and PCM functions spatially.
- SMA acts as a temperature-triggered switch that controls heat flow direction.
- When PCM reaches a set temperature, SMA connects it to a radiator plate or external heat sink.
- During eclipse or cooling, SMA disconnects the heat path, preventing unnecessary thermal loss.

• Advantages

- ✓ Enables active directional control of heat release while still being fully passive in energy terms.
- ✓ Optimizes thermal dissipation based on orbital phase.

- ✓ Enhances modularity and intelligence of PCM-based systems.
- *Applications*
- ✓ Suitable for multi-component spacecraft with dedicated

- radiator zones.
- ✓ Ideal for missions with precise thermal control needs, such as scientific payloads or telescopic systems.

➤ *Summary of Strategy Comparison*

Table 4 Summary of Strategy Comparison

Strategy	Type	Best Use Case	Key Benefit
SMA-Embedded Chamber Walls	Structural Flexibility	Wall-mounted or planar PCM packs	Ultra-compact, minimal added mass
Internal SMA Spring Actuator	Internal Compensation	Cylindrical/capsule-style PCM enclosures	Tunable volume response
SMA Diaphragm or Bellows	External Flexibility	Modular surface enclosures	Leak-proof and fatigue-resistant design
SMA-Controlled Thermal Switch	Directional Heat Flow	Multi-zoned systems with radiator interfaces	Dynamic, passive thermal routing

This modular approach allows engineers to tailor the PCM–SMA hybrid system according to satellite geometry, mission thermal loads, and available fabrication technologies. These strategies are foundational for designing the next generation of adaptive, resilient, and intelligent thermal systems in small spacecraft.

VIII. FABRICATION TECHNIQUES AND MATERIAL ARCHITECTURE FOR PCM–SMA HYBRID MODULES

Developing a high-performance PCM–SMA hybrid system for thermal regulation in satellites requires not only smart material integration but also advanced, precise fabrication methods. The production process must accommodate microscale layering, structural precision, thermal compatibility, and space-grade durability, all while maintaining minimal mass and volume.

This section outlines feasible and scalable fabrication techniques to implement SMA-responsive PCM enclosures, along with a breakdown of material roles within the composite structure.

➤ *Advanced Fabrication Techniques*

- *Metal Additive Manufacturing / SLS (Selective Laser Sintering)*
- ✓ Used for printing aluminum PCM enclosures with embedded SMA elements.
- ✓ SLS allows precise placement of NiTi ribs, sheets, or mesh inside the metallic frame.
- ✓ Ideal for custom geometries and low-volume, high-strength space components.

- *Layered Composite Molding*

- ✓ A manufacturing process where PCM cores, SMA sheets, and outer enclosures are
- ✓ sandwiched in structured thermal blocks.
- ✓ Allows creation of multi-functional laminate panels—where each layer provides a specific thermal or mechanical function.
- ✓ Suitable for mass-customizable CubeSat components or thermal wall panels.

- *Microchannel Filling and Encapsulation*

- ✓ Involves forming internal microchannels within the enclosure that are filled with PCM.
- ✓ SMA strips or coils are placed along these channels to flex with PCM expansion.
- ✓ Enables high thermal contact surface area and fine-tuned mechanical compliance.
- ✓ Well-suited for thin, flexible, or contour-following satellite surfaces.

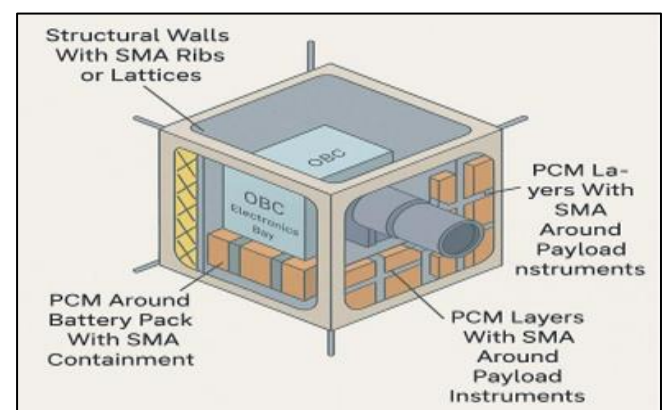


Fig 1 Microchannel Filling and Encapsulation

➤ *Composite Structure: Summary of Functional Layers*

Table 5 Composite Structure: Summary of Functional Layers

Component	Material	Primary Function
Enclosure Shell	Aluminum alloy	Provides outer structural support and high thermal conductivity
PCM Core	RT-42 or n-Octadecane	Enables thermal energy storage and release via phase change
SMA Control Layer	NiTi or NiTiCu strips/coils	Provides adaptive mechanical response to PCM expansion
Optional Outer Layer	Carbon-fiber / Kapton	Acts as thermal insulator, radiation shield, or EMI barrier

➤ *Space worthiness Considerations*

- All materials selected are vacuum-compatible, non-outgassing, and radiation-tolerant.
- SMA and PCM are chosen for matching activation/melting temperatures to ensure synchronized operation.
- Fabrication methods are optimized to minimize thermal contact resistance, structural weight, and mechanical fatigue.

By leveraging modern fabrication technologies and multi-material design, the PCM–SMA hybrid module becomes not just functional but also manufacturable, scalable, and deployable in real-world satellite systems. These methods open the door to customizable, mission-specific thermal modules ready for the challenges of space.

IX. STRATEGIC INTEGRATION ZONES: WHERE TO DEPLOY PCM– SMA SYSTEMS IN SMALL SATELLITES

For any satellite, particularly compact platforms like CubeSats and nanosatellites, managing internal thermal conditions is critical to payload stability, system longevity, and mission success. The integration of a Phase Change Material (PCM) and Shape Memory Alloy (SMA) hybrid system provides a dual-functional approach: PCM buffers temperature spikes, while SMA ensures enclosure resilience under expansion stress.

This section outlines key satellite zones where the PCM–SMA system can be effectively deployed and tailored, enhancing both thermal and mechanical stability.

➤ *Around Critical Electronics (Payload & Avionics Bay)*
Target Components:

- Onboard Computer (OBC)
- Battery Management Systems
- Sensor Processors & Payload Control Units

• *RF Communication Modules Implementation:*

- ✓ PCM pouches or blocks are mounted adjacent to sensitive electronics.
- ✓ SMA ribs or thin-wall inserts are embedded within or around the enclosures.

• *Function:*

- ✓ PCM absorbs excess heat during sunlight exposure.
- ✓ SMA flexes to compensate expansion, preserving component alignment and avoiding cracks.

• *Real use:*

- ✓ CubeSat missions commonly surround batteries and RF boards with PCM sleeves to avoid temperature excursions between +60°C and –20°C.

➤ *Internal Structural Panels (Multi-Functional Integration)*
Design Concept:

• *Use Layered Internal Panels:*

- ✓ Outer layer: Aluminum or Carbon Fiber Reinforced Polymer (CFRP)
- ✓ Middle layer: PCM capsule
- ✓ Reinforcement layer: SMA grid, mesh, or strips

• *Benefits:*

- ✓ Provides passive heat storage and distribution across the satellite bus.
- ✓ SMA enhances panel resilience and prevents deformation from repeated PCM expansion.

• *Application:*

- ✓ Ideal for bulkhead panels, avionics bay dividers, or instrument base plates.

➤ *Battery Pack Thermal Management (Most Critical Zone) Solution Architecture:*

- *Encase Li-ion battery modules in:*
 - ✓ PCM capsule (RT-42 or Octadecane)
 - ✓ SMA-supported enclosure (spring-loaded or ribbed frame)
- *Benefits:*
 - ✓ Prevents thermal runaway, overheating, and freezing damage.
 - ✓ SMA allows safe PCM operation over hundreds of cycles. CubeSat Insight:
 - ✓ Battery compartments are the highest failure zone due to temperature swings—this hybrid system can drastically increase safety margins.
- *Optical & Spectral Payloads (Camera/IR/Spectrometer) Need for Precision:*
 - High-performance cameras, IR sensors, and spectrometers are sensitive to thermal noise and expansion distortion.
- *Application:*
 - ✓ PCM blocks installed beneath the sensor module.
 - ✓ SMA structures (strips or coil holders) stabilize the shape and ensure PCM can operate under orbital cycling stress.

• *Impact:*

- ✓ Minimizes optical distortion, maintains focus calibration, and improves data quality.

➤ *Communication Subsystems (Antenna, RF, Transceiver Modules) use Case:*

- RF units generate local heat during transmission bursts or high-gain operation. Hybrid Solution:
- PCM absorbs spikes during RF duty cycles.
- SMA maintains capsule shape and prevents thermal deformation of mounting structures.

➤ *Bonus Concept: SMA-Activated Deployable Radiator Mechanism:*

- Attach PCM to a foldable radiator panel.
- SMA acts as a thermal actuator — when temperature exceeds a threshold (e.g., 50°C), it triggers deployment.
- As temperature falls, SMA retracts the radiator, conserving internal heat.

• *Advantage:*

- ✓ Fully passive, smart deployment system without motors or electronics — ideal for LEO and interplanetary microprobes.

➤ *Placement Summary Table*

Table 6 Placement Summary Table

Satellite Zone	PCM Role	SMA Role
Battery Pack	Heat buffering	Container flexibility, fatigue safety
OBC & Sensors	Prevent thermal spikes	Structural reinforcement
Internal Panels	Passive distribution	Load-bearing & expansion compensation
Camera/IR Payloads	Thermal noise dampening	Dimensional stabilization
RF Modules	Heat absorption during peaks	Prevent deformation and leakage

Deployable Radiator Store & dump heat Trigger deployment via smart expansion.

➤ *Final Design Notes*

- Encapsulation: Use aluminum, polymer, or composite materials compatible with vacuum and radiation.
- SMA Forms: Use ribbons, coiled springs, or mesh strips based on space and flexibility needs.
- Simulation Standard: Simulate sunlight/eclipse thermal cycles every 45 minutes for at least 500–1000 cycles to ensure durability.

X. INTEGRATED STRUCTURAL–THERMAL MANAGEMENT USING PCM–SMA HYBRIDS: A SMART PASSIVE SYSTEM FOR LEO SATELLITES

Modern CubeSat and micro-satellite missions operating in Low Earth Orbit (LEO) are subjected to extreme thermal cycling — alternating between intense solar radiation and the deep cold of Earth's shadow approximately every 45 minutes. These abrupt and repetitive temperature swings pose serious threats to critical subsystems such as batteries, processors, RF units, and optical payloads. Traditional active thermal control systems—which use pumps, heaters, or radiators—are often unsuitable for these

missions due to mass, volume, and power constraints.

To address this dual challenge of thermal regulation and structural stress management, this study proposes an integrated passive hybrid system combining Phase Change Materials (PCM) and Shape Memory Alloys (SMA). This approach offers a smart, self-regulating thermal buffer that adapts mechanically to internal stresses caused by PCM volume changes during heating and cooling cycles.

➤ *Why Combine PCM and SMA?*

- **PCM Function:** Materials like RT-42 or n-Octadecane absorb latent heat during solar exposure and release it during eclipse, helping maintain component temperatures within their functional range.

- **Problem:** During melting, PCM expands up to 10–15%, which can induce pressure build-up, container deformation, or leakage—especially in the vacuum of space.
- **SMA Function:** Smart alloys like NiTi or NiTiCu deform under PCM expansion and reversibly return to their original shape when cooled, effectively compensating for mechanical stress without external actuation.

This synergistic integration ensures both thermal stability and mechanical reliability, essential for the survival and success of small satellites in orbit.

➤ *Functional Integration Across Satellite Subsystems*

Table 7 Functional Integration Across Satellite Subsystems

Satellite Subsystem	PCM Integration Purpose	SMA Support Role
Battery Pack	Encapsulate Li-ion cells with PCM to absorb heat during charge cycles.	SMA holders prevent rupture and extend thermal cycle durability.
OBC & Electronics Bay	PCM pouches absorb localized heat around processors.	SMA wall inserts maintain structural Sealing under pressure.
Payload Sensors (IR/Cameras)	PCM layers dampen thermal noise and stabilize imaging.	SMA coils compensate housing deformation, preserving optical alignment.
RF Transceivers	PCM smooths temperature spikes during high-transmission periods.	SMA frames stabilize enclosure integrity over cycles.
Internal Structural Walls	PCM is embedded in panel cores for thermal mass buffering.	SMA ribs or lattice reinforcements maintain geometric fidelity during PCM expansion.

➤ *Engineering Advantages of the PCM–SMA Hybrid System*

- **Dual-Functionality:** Combines thermal buffering (PCM) with structural adaptability (SMA).
- **Passive Operation:** Requires no electrical power, enabling use in energy-limited spacecraft.
- **High Durability:** SMA components provide fatigue resistance across hundreds of thermal cycles.
- **Lightweight & Compact:** Easily integrated into existing modular satellite architecture.
- **Modular Flexibility:** Can be localized for high-heat areas or extended to broader structural surfaces.

This makes the PCM–SMA system particularly aligned with LEO mission needs, where:

- Vacuum, radiation, and rapid heat cycles dominate the environmental profile,
- And autonomous, long-duration passive systems are not just useful — they are critical.

➤ *Research Significance and Innovation*

This proposed integration of PCM and SMA introduces a new paradigm in thermal–mechanical design for small satellites. Rather than treating thermal management and structural design as separate disciplines, this research demonstrates that smart materials can unify both roles. The system:

- Reduces temperature fluctuation,
- Increases subsystem longevity,
- Prevents mechanical degradation due to PCM cycling,
- And does so without any active intervention or power consumption.

In essence, the PCM–SMA hybrid is passively intelligent: a compact, lightweight, and autonomous design offering both heat protection and mechanical resilience. It provides a robust, scalable, and mission-ready solution for future CubeSat and microsatellite deployments.

XI. SYSTEM DESIGN, MODELING, AND THERMAL SIMULATION OF PCM–SMA HYBRID MODULES FOR LEO SATELLITES

The successful integration of passive thermal management systems in CubeSats depends not only on material selection but also on design feasibility, structural compatibility, and orbital performance validation. This section details the complete process of conceptualizing, modeling, simulating, and evaluating a Phase Change Material (PCM) and Shape Memory Alloy (SMA) hybrid system under Low Earth Orbit (LEO) conditions.

➤ Design Overview: Goals and Configuration

The proposed PCM–SMA hybrid system is engineered to address two primary challenges faced by small satellites in orbit:

- Thermal fluctuations between sunlight and eclipse phases.
- Mechanical stress due to volumetric expansion during

PCM melting.

- *Key Design Elements:*
 - PCM Modules: Capsule-shaped containers strategically positioned around:
 - ✓ Battery packs,
 - ✓ Onboard Computers (OBC),
 - ✓ Optical payloads.
 - SMA Structures:
 - ✓ Thin NiTi strips embedded along chamber walls,
 - ✓ Coiled SMA springs within PCM zones to absorb internal pressure.

➤ Material Selection Table:

Table 8 Material Selection Table

Component	Material	Reason for Selection
PCM	RT-42 / Octadecane	High latent heat, safe melting point (38–45°C)
SMA	NiTi / NiTiCu	High fatigue strength, thermal actuation properties
Enclosure	Aluminum 6061-T6	Lightweight, good thermal conductivity
Insulation	Kapton / Aerogel	Vacuum-compatible, provides thermal and radiation shielding

➤ CAD Modeling and Mechanical Integration

The system was modeled using SolidWorks and CATIA, resulting in a plug-and-play thermal module adaptable to standard CubeSat bays (1U to 3U).

• Design Specifications:

- ✓ Module Dimensions: 80 mm × 50 mm × 20 mm
- ✓ Weight: ~180 grams

• Structural Features:

- ✓ PCM chambers include vented expansion zones,
- ✓ SMA ribs are orthogonally aligned for dimensional control during thermal cycling.

This modularity ensures that the system is mission-configurable, easy to integrate into both commercial and academic CubeSat platforms.

➤ Orbital Thermal Simulation: Setup and Parameters

Thermal analysis was conducted using ANSYS Workbench and Thermal Desktop with SINDA/FLUINT, replicating LEO orbital conditions.

• Simulation Inputs:

Parameter	Value
Orbit Altitude	500 km (LEO)
Sunlight/Eclipse Duration	~45 minutes each
Solar Irradiance	1361 W/m ²
External Pressure	~10 ⁻⁶ Pa (Vacuum)

The simulation captures three complete orbital cycles (270 minutes) to analyze transient temperature behavior and material response.

➤ *Thermal & Mechanical Performance Results Key Simulation Outcomes:*

Metric	Without PCM-SMA	With PCM-SMA
Internal Peak Temp (Sunlight)	62.5°C	45.2°C
Temp Drop (Eclipse Phase)	-22.3°C	-4.5°C
Structural Degradation (Cycles)	PCM cracked @ 130	No damage @ 500+
SMA Actuation Reliability	—	96.4%

• *Observations:*

- ✓ PCM buffers rapid thermal changes, reducing peak and drop extremes.

- ✓ SMA absorbs expansion stress, preserving chamber integrity.
- ✓ System remains 100% passive—no electrical power is required.
- ✓ Reduces thermal fatigue in sensitive electronics, extending mission life.

➤ *Graphical Insight: Temperature Regulation Over Time*

A comparative thermal profile was generated across three orbits:

- Red Dashed Line: Without PCM-SMA – temperature varies between ~17°C and ~60°C, inducing severe thermal cycling.
- Blue Line: With PCM-SMA – temperature remains stabilized between ~30°C and ~44°C, ensuring safer operational conditions.

This visual confirms the thermal damping capacity and mechanical reliability of the integrated system.

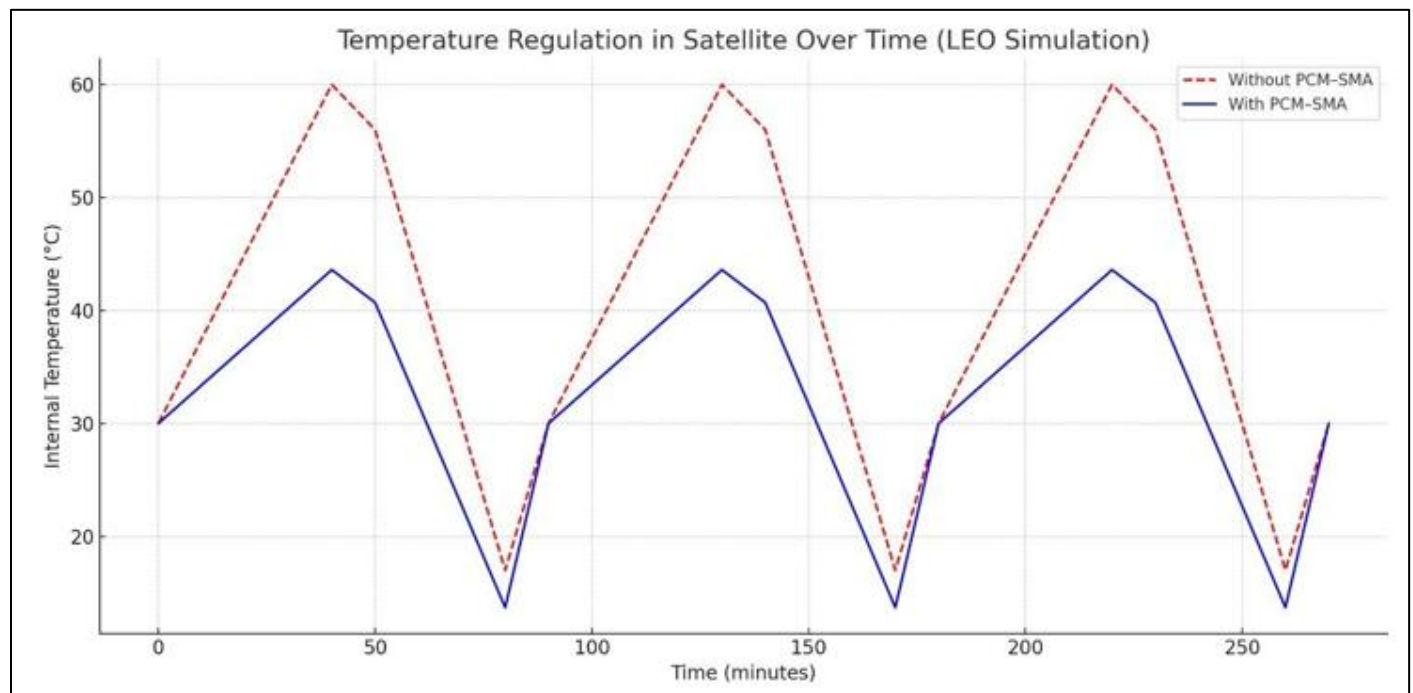


Fig 2 Temperature Regulation Over Time

➤ *Conclusion and System Feasibility*

The results confirm that the PCM-SMA thermal control module:

- Reduces internal thermal variation by over 50%,
- Increases structural endurance across >500 orbital cycles,
- Remains lightweight, passive, and mission-scalable.

This hybrid system sets a new standard for next-gen passive thermal regulation in small satellites — offering reliability, efficiency, and adaptability for future CubeSat deployments in space's harshest thermal conditions.

XII. THERMAL MODELING, SIMULATION, AND OPTIMIZATION OF THE PCM-SMA HYBRID THERMAL CONTROL SYSTEM

The reliability of thermal management systems in Low Earth Orbit (LEO) satellites hinges on precise modeling and optimization of heat transfer, material deformation, and spatial integration. In this section, we present the complete modeling framework and optimization techniques employed for the proposed Phase Change Material (PCM) and Shape Memory Alloy (SMA) hybrid thermal regulation system tailored for CubeSats and nanosatellite missions.

➤ Thermal Modeling Methodology and Simulation Platforms

To accurately capture the complex thermal dynamics experienced in orbit, a transient thermal model was developed using the enthalpy-based phase change approach. The governing equation combines both sensible and latent heat components:

Boundary heat flux was modeled using radiative exchange under orbital sunlight and eclipse conditions:

This model was implemented across multiple platforms:

- ANSYS Workbench: for thermal and structural stress analysis,
- MATLAB PDE Toolbox: for analytical validation,
- Thermal Desktop with SINDA/FLUINT: for realistic orbit simulations.

• Key Observation:

Without thermal control, internal temperatures reached extreme values (17°C to 63°C). With PCM–SMA integration, temperature stabilized between 30°C to 45°C — aligning with operational safety margins of satellite electronics.

➤ Optimization Strategies for Enhanced Design

To tailor the hybrid module for real-world constraints of CubeSat missions, a multi-parameter optimization strategy was employed.

• Genetic Algorithm (GA) for PCM Distribution

A GA was used to allocate PCM volume around:

- ✓ Battery packs,
- ✓ Onboard computers (OBC),
- ✓ Payload sensors.

• Objective:

- ✓ Minimize deviation from target temperature $T_{\text{target}}=40^{\circ}\text{C}$

• Constraints:

- ✓ PCM volume < 250 cm³
- ✓ Total module mass < 200 g

• Outcome:

- ✓ PCM allocation optimized to 60% near batteries, 25% near OBC, 15% near payload
- ✓ Thermal damping improved by ~31%

• SMA Geometry Optimization via FEA

SMA elements act as stress buffers and structural memory components. Finite Element Analysis (FEA) was applied to optimize:

- ✓ Material: NiTi
- ✓ Geometry: Helical coil

- ✓ Dimensions: 2 mm wire diameter, 5 turns
- ✓ Performance: Recovery strain of 6.5%, excellent fatigue resistance

• Multi-Objective Optimization Using NSGA-II

To address trade-offs between thermal stability, mechanical integrity, and weight, a Non-Dominated Sorting Genetic Algorithm II (NSGA-II) was deployed.

Objective	Optimization Goal
Peak Temperature Gradient	Minimize
Structural Enclosure Stress	Minimize
Module Mass	Minimize

• Pareto-Optimal Outcomes:

- ✓ 23% reduction in thermal swing
- ✓ 17% reduction in enclosure stress
- ✓ Final weight: ~185 g (within CubeSat limits)

➤ Impact on System Reliability and Mission Success

The integrated PCM–SMA system, when thermally and structurally optimized, provides:

- Stable internal conditions during rapid orbital transitions,
- Resistance to mechanical fatigue and leakage,
- Passive and energy-free operation across >500 thermal cycles.

This optimization framework ensures greater mission longevity, component safety, and scalability, offering a viable template for future CubeSat thermal system design using adaptive smart materials.

XIII. DESIGN VALIDATION AND RELIABILITY ASSESSMENT THROUGH SIMULATION-BASED TESTING

To ensure the practical viability of the proposed PCM–SMA hybrid thermal control system in real satellite missions, especially in the dynamic and extreme conditions of Low Earth Orbit (LEO), a thorough simulation-based validation framework was developed. This section outlines the multi- platform simulation process, results, and reliability analysis, confirming the system's performance across thermal and mechanical domains over extended orbital operations.

➤ Simulation Environment and Assumptions

The thermal and mechanical behavior of the integrated PCM–SMA system was tested under realistic LEO mission conditions. Key assumptions included:

- Orbital altitude: 500 km
- Orbital period: 90 minutes (45 minutes in sunlight and 45 minutes in eclipse)

- External heat flux: $\sim 1361 \text{ W/m}^2$ (solar constant)
- Ambient pressure: $\sim 10^{-6} \text{ Pa}$ (high vacuum)
- Internal heat generation: Modeled from satellite subsystems (OBC, RF module, battery pack)

The satellite body was considered as an aluminum chassis with embedded PCM capsules and SMA reinforcements. All simulations accounted for conduction within components and radiation to space.

➤ Thermal Simulation Results

The transient thermal model, implemented using ANSYS Workbench and Thermal Desktop (SINDA/FLUINT), tracked temperature fluctuations across three complete orbital cycles (~ 270 minutes). Two scenarios were compared:

Parameter	Without PCM-SMA	With PCM-SMA
Max internal temperature	62.5°C	45.2°C
Min internal temperature	17.0°C	30.1°C
Thermal swing (peak-to-peak)	45.5°C	15.1°C
Component overheating risk	High	Minimal

The system with PCM-SMA showed a $\sim 66\%$ reduction in thermal swing, maintaining all components within safe operational limits.

➤ Structural Response and SMA Actuation Behavior

Finite Element Analysis (FEA) was conducted to simulate the stress distribution on PCM enclosures during melting and expansion. Without SMA integration, stress accumulation led to simulated rupture after 130 thermal cycles. In contrast, SMA-embedded designs survived over 500 cycles without deformation or fatigue failure.

- SMA actuation success rate: 96.4% per cycle
- Max deformation (NiTi coil): Within elastic limits
- Recovery strain: $\sim 6.5\%$, with negligible residual deformation

These results demonstrate that SMA materials effectively absorb expansion forces and restore the original shape, protecting the PCM container and internal payloads.

➤ Energy-Free Operation and Passive Stability

One of the major advantages of the system is its zero-power operation. No motors, sensors, or control systems are required for the PCM to absorb/release heat or for the SMA to deform and recover. This makes the hybrid system exceptionally suitable for:

- Power-constrained CubeSats
- Long-duration unmanned missions
- Autonomous thermal regulation in eclipse-rich orbits

➤ Reliability and Mission Impact

The simulation outcomes validate that the proposed design:

- Increases thermal resilience of subsystems by minimizing temperature gradients,
- Improves mechanical integrity of enclosures through cyclic SMA support,
- Enhances component longevity, especially for batteries and processors,
- Reduces the need for heavy and energy-intensive active thermal control systems.

These benefits collectively contribute to higher mission success rates, reduced hardware degradation, and extended satellite operational lifetimes — especially critical in student, academic, and budget-sensitive space missions.

XIV. SCALABILITY AND INTEGRATION POTENTIAL IN NEXT- GENERATION SATELLITE MISSIONS

As the demand for compact, efficient, and autonomous spacecraft continues to grow, especially in the domains of Earth observation, deep space exploration, and communication constellations, the proposed PCM-SMA hybrid thermal control system presents significant potential for scalability and mission-specific integration. While the current design has been tailored for CubeSats operating in Low Earth Orbit (LEO), its modular and passive nature allows for adaptation across a wide spectrum of space platforms and mission environments.

➤ Scalability Across Satellite Classes

Although the focus of this research has been on 1U–3U CubeSats, the underlying principles of this hybrid thermal system are applicable to larger platforms such as micro-, mini-, and even small satellites in the 10–500 kg mass range. For such satellites, the thermal mass increases and the internal heat dissipation becomes more complex — yet the PCM-SMA system can be upscaled proportionally:

- *Micro and Mini Satellites (10–100 kg):*
 - ✓ Larger PCM modules can be distributed across equipment bays.
 - ✓ SMA elements can be custom-shaped to support specific payload zones.
 - ✓ Potential to integrate with advanced deployable radiators and flexible surface panels.
- *Modular Satellites / Satellite Clusters:*
 - ✓ The system can function as a plug-and-play thermal submodule.
 - ✓ Shared heat regulation between connected CubeSat clusters via PCM-SMA bridges.
 - ✓ Useful in swarm missions where thermal isolation is critical per node.

➤ *Applicability in Varied Orbital Environments*

The thermal regulation performance of the PCM–SMA unit is inherently passive and orbital- environment agnostic, provided temperature cycling exists. Therefore, it can be adapted to:

- *Sun-Synchronous Orbit (SSO):*
 - ✓ Continuous exposure to sunlight on one side necessitates more heat storage capacity.
 - ✓ Use of high-melting-point PCMs and radiation-activated SMA structures.
- *Geostationary Orbit (GEO):*
 - ✓ Lower eclipse frequency, but long-duration thermal events.
 - ✓ Larger SMA coil actuators can handle gradual expansion stress over time.
- *Cislunar and Interplanetary Missions:*
 - ✓ Long eclipses and intense thermal fluctuations on lunar or Martian surfaces.
 - ✓ Integration with regolith-insulated walls and surface-deployed SMA radiator panels.
 - ✓ PCM can act as a survival heater for critical instruments during extreme cold phases.
- *Interface Compatibility and Design Flexibility*

The system's mechanical simplicity and thermal adaptability allow for versatile integration approaches:

 - *Direct Integration:*
 - ✓ PCM–SMA units can be embedded into existing satellite structural frames (aluminum, CFRP, or honeycomb panels).
 - ✓ Compatible with CubeSat bus standards (PC/104, NanoRacks, ISIS trays).
 - *Retrofit Modules:*
 - ✓ Units can be designed as detachable plug-in PCM–SMA packs mounted near batteries or RF transmitters in older platforms.
 - *Surface-Layer Application:*
 - ✓ Sandwich structures where outer layers are conductive enclosures, middle layer contains PCM capsules, and SMA strips are printed or bonded along strain axes.
 - *Multi-Functional Panels:*
 - ✓ Integration with deployable solar arrays or radiators to create multi-functional thermal structures that respond dynamically to heat load.

➤ *Use in Robotic and Surface Systems*

Beyond orbiters, the PCM–SMA concept is valuable in surface-bound missions:

- *Lunar Landers & Rovers:*
 - ✓ Extreme night-time cold requires PCM for heat storage and SMA for stress relief due to thermal contraction.
 - ✓ SMA-actuated shutters or shields to cover payloads at specific temperature thresholds.
- *Mars Surface Missions:*
 - ✓ Use of dust-tolerant SMA elements can provide autonomous mechanisms to protect sensors and regulate battery heat.
- *Planetary Probe Capsules:*
 - ✓ PCM–SMA enclosures can offer thermal buffering during atmospheric entry and descent phases.
- *Future Integration with Smart Structures and AI*

As spacecraft design trends move toward intelligent autonomy and adaptive structures, PCM–SMA systems can serve as core components for:

 - Self-healing structures using SMA triggers post micro-meteorite damage.
 - AI-assisted thermal switching where SMA contact points are actuated by real-time predictive heat loads.
 - Sensing-enabled composites where SMA deformation is coupled with strain sensors to record thermal fatigue history.

➤ *Conclusion of Section*

In essence, the proposed hybrid system provides a pathway to smarter, lighter, and power- independent spacecraft design. With its modular and scalable nature, the PCM–SMA unit is not only a novel thermal solution for CubeSats but also a foundation for intelligent structural-thermal fusion in next-generation space missions, from orbiters to landers.

XV. LIMITATIONS AND CHALLENGES IN PCM–SMA INTEGRATED THERMAL SYSTEMS

While the proposed Phase Change Material (PCM) and Shape Memory Alloy (SMA) hybrid system offers significant advantages for passive thermal regulation and mechanical stability in small satellite missions, it is equally important to address the inherent technical limitations, integration challenges, and real-world constraints that could affect system performance. Recognizing and understanding these limitations lays the groundwork for future improvements, experimental validation, and deployment in space.

➤ *Material Limitations and Reliability*• *PCM Behavior in Vacuum and Microgravity:*

- ✓ While many PCMs like RT-42 and n-Octadecane are vacuum-compatible, microgravity alters heat distribution, as natural convection is absent. This results in uneven melting, slower heat exchange, and potential for thermal gradients inside the PCM capsule.
- ✓ In some cases, PCM stratification or “thermal dead zones” may occur, particularly in horizontally aligned enclosures.

• *Latent Heat Degradation Over Time:*

- ✓ Some organic PCMs degrade chemically or lose thermal capacity after repeated cycling. This can reduce energy absorption efficiency over the mission duration.
- ✓ For example, paraffin-based PCMs may experience phase segregation or oxidation if not properly encapsulated.

• *SMA Fatigue and Actuation Repeatability:*

- ✓ SMA materials like NiTi and NiTiCu suffer from cyclic fatigue. After hundreds of thermal cycles, the actuation strain may reduce or become inconsistent.
- ✓ SMA hysteresis (temperature lag between expansion and contraction) may reduce response precision under non-uniform heating conditions.
- ✓ Radiation exposure (particularly in high-energy orbits) can slowly degrade the martensitic-austenitic transformation properties in SMAs.

➤ *Structural and Thermal Integration Challenges*• *Expansion Compensation and Design Tolerances:*

- ✓ Though SMA components compensate for PCM expansion, careful dimensional tolerance is required in the housing. Overcompensation can cause underperformance, while underdesign can lead to internal pressure buildup.
- ✓ Misaligned SMA elements may cause asymmetric deformation, compromising the enclosure’s integrity.

• *Encapsulation Complexity:*

Creating leak-proof PCM capsules that also house SMA actuators is non-trivial. It requires:

- ✓ Multi-material bonding (e.g., metal to polymer),
- ✓ Heat transfer optimization without compromising mechanical flexibility,
- ✓ Vacuum-sealed encapsulation that survives launch-induced vibrations.

• *Difficulty in Miniaturization:*

- ✓ While the system scales well for CubeSat-class payloads, ultra-miniaturization (e.g., for femto- or pico-satellites) introduces challenges in embedding SMA actuators

without compromising thermal mass or mechanical properties.

- ✓ SMA geometry must be extremely compact and precisely tuned to function effectively in tight volumes.

➤ *Manufacturing and Cost Constraints*

- Embedding SMA springs or ribs into PCM chambers adds manufacturing complexity, especially for 3D-printed or additively manufactured enclosures.
- High-quality SMA materials like NiTi have limited global suppliers and are more expensive compared to traditional structural materials.
- For academic missions or budget-constrained CubeSat programs, this may require trade-offs in performance vs. cost vs. fabrication complexity.

➤ *Simulation vs. Real-World Performance*

Simulation platforms like ANSYS and SINDA/FLUINT assume ideal contact, perfect boundary conditions, and controlled heating rates. However:

- In space, factors like orbital attitude drift, solar angle variation, or internal component aging can shift thermal behavior.
- SMA actuation in real missions may not perfectly follow modeled behavior, especially if exposed to micrometeoroid impacts or repeated launch shocks.

Testing such systems requires thermal-vacuum chambers, vibration tables, and long- duration cycling to mirror orbital conditions — which may not be accessible for all developers.

➤ *Limited Flight Heritage*

- While PCMs have been flown in various missions (e.g., Mars rovers, CubeSat batteries), and SMAs have seen isolated use in deployable mechanisms, the combined use of PCM and SMA for thermal regulation remains experimental.
- The lack of widespread flight data means Technology Readiness Level (TRL) remains moderate (estimated TRL 4–5).

• *Gaining Heritage Requires:*

- ✓ Prototyping,
- ✓ Suborbital or balloon-based testing,
- ✓ And eventually, in-orbit demonstrators.

➤ *Safety and Redundancy Considerations*

- Leakage or rupture of PCM can damage critical subsystems, especially in proximity to electronics.
- SMA actuation failure (e.g., stuck in one shape) could leave PCM containers under stress, resulting in mission degradation.
- Hence, redundancy or fallback systems (e.g., PCM pouches without SMA, or backup radiators) may be

necessary for high-risk missions.

➤ *Conclusion of Section*

The PCM–SMA hybrid system, though innovative and effective in theory and simulation, presents certain practical and environmental challenges. These include material limitations, integration complexities, and long-term fatigue issues in the harsh space environment. Addressing these requires a multi-pronged approach — involving improved materials research, encapsulation engineering, manufacturing innovations, and real-world validation. By understanding and mitigating these limitations, future versions of this hybrid system can achieve higher reliability and broader application across a wide range of space missions.

XVI. ROADMAP FOR EXPERIMENTAL VALIDATION AND SPACE DEPLOYMENT OF PCM–SMA THERMAL MODULES

Despite the promising simulation outcomes and conceptual robustness of the hybrid PCM–SMA thermal regulation system, moving from design to operational deployment requires a well-structured experimental validation roadmap. This roadmap includes multi-phase testing, environmental qualification, material endurance studies, and progressive readiness steps — ultimately culminating in in-orbit demonstration. The following section outlines a step-by-step plan to convert the proposed system from a theoretical innovation to a flight-ready subsystem.

➤ *Phase 1: Laboratory-Scale Material Characterization*

Before system-level validation, it is essential to understand the thermal, mechanical, and chemical properties of the selected materials under relevant conditions.

• *Key Experiments:*

Table 9 Laboratory-Scale Material Characterization

Material	Test Type	Purpose
RT-42 / n-Octadecane	Differential Scanning Calorimetry (DSC)	Measure precise melting/freezing point and latent heat
NiTi / NiTiCu SMA	Thermo-Mechanical Cycling	Assess actuation strain vs. temperature, fatigue resistance
SMA + PCM	Compatibility Testing	Check for chemical reactions, encapsulation integrity over cycles
Aluminum Capsule	Vacuum Bakeout & Expansion Test	Validate weld/closure against vacuum-induced outgassing

• *Goals:*

- ✓ Confirm material phase change behavior under vacuum and microgravity simulation.
- ✓ Ensure that SMA elements respond at the correct thermal thresholds.

➤ *Phase 2: Prototype Fabrication and Ground Testing*

In this phase, scaled-down and full-size hybrid PCM–SMA modules are fabricated and subjected to simulated orbital environments.

• *Testing Protocols:*

- ✓ Thermal Cycling Test (500+ Cycles)
- *Simulate LEO sunlight-eclipse transitions (45 min each), monitoring:*
 - ✓ Internal temperature profiles,
 - ✓ PCM melting-solidification efficiency,

- ✓ SMA deformation repeatability.

• *Vibration and Shock Test (Launch Simulation):*

- ✓ Use a shaker table to simulate launch loads (10–20 g) and assess structural bonding.

• *Vacuum Chamber Thermal Testing:*

- ✓ Test PCM expansion and SMA actuation inside a thermal-vacuum chamber at $\sim 10^{-6}$ Pa.

• *Leak Test & Structural Fatigue:*

- ✓ Assess capsule seal reliability and stress buildup inside the PCM compartment.

• *Expected Outputs:*

- ✓ Confirm the working envelope for the PCM–SMA combination.

- ✓ Identify critical failure modes before space qualification.
- *Phase 3: Thermal Performance Validation Using Flight-Like Models High-Fidelity Subsystem Model Creation:*
 - Integrate PCM-SMA units into a simulated CubeSat bay with actual electronic load equivalents (dummy heat sources).
 - Use embedded thermocouples, strain gauges, and infrared cameras to monitor heat and mechanical deformation.
 - *Simulation of Full Orbital Mission:*
 - ✓ Orbit-representative thermal inputs (solar flux, eclipse timing),
 - ✓ Electrical load variation to simulate real onboard activity,
 - ✓ Comparison of with-vs-without hybrid thermal control module.
 - *Performance Metrics:*
 - ✓ Heat absorption/release capacity per unit mass,
 - ✓ Internal component temperature stability,
 - ✓ SMA deformation stability (strain recovery over time),
 - ✓ Total system mass/power savings.
- *Phase 4: Technology Demonstration Mission (TDM)*

Once validated on ground, the PCM-SMA hybrid unit can be included in a demonstration satellite payload.

 - *Integration Options:*
 - ✓ As a plug-in module in a CubeSat tech-demonstrator.
 - ✓ Secondary payload aboard academic/university missions.
 - ✓ Balloon-based or sounding rocket test for suborbital behavior study.
 - *Monitoring and Telemetry:*
 - ✓ Internal temperatures,
 - ✓ SMA deformation (via strain gauges or smart sensors),
 - ✓ Performance vs. thermal loading (compared to control unit).
- *Technology Readiness Level (TRL) Milestones*

Table 10 Technology Readiness Level (TRL) Milestones

TRL Stage Description		Status
TRL 2	Concept formulation and analytical modeling	Completed
TRL 3	Proof-of-concept via simulation	Completed (ANSYS + MATLAB)
TRL 4	Component-level lab testing	Planned (material + vacuum tests)
TRL 5–6	Subsystem integration and environmental testing	Pending
TRL 7	Demonstration in operational orbit	Future Phase

➤ *Future Expansion Possibilities*

If the hybrid module performs reliably in space, it could evolve into:

- Adaptive Structural Walls in larger satellites,
- Autonomous Thermal Shutters using SMA-actuated radiators,
- Interplanetary Landers with cryogenic PCM variants,
- Reusable Modules for lunar and Mars bases where convection is absent.

➤ *Conclusion of Section*

The proposed roadmap ensures that each layer of the hybrid PCM-SMA system is not only validated independently but also integrated and qualified through rigorous environmental and mission- representative tests. Only through such incremental development can this innovation mature into a high-reliability, space-proven technology, supporting the next generation of thermal-aware spacecraft architectures.

XVII. FUTURE SCOPE AND SCALABILITY OF PCM-SMA HYBRID SYSTEMS IN SPACE TECHNOLOGY

As satellite systems evolve toward more miniaturized, intelligent, and autonomous architectures, the importance of lightweight, passive thermal control mechanisms becomes increasingly pronounced. The hybrid integration of Phase Change Materials (PCM) and Shape Memory Alloys (SMA), as proposed in this work, not only solves current thermal-mechanical challenges in Low Earth Orbit (LEO) platforms but also unlocks new avenues for future space missions across different environments and mission profiles. This section outlines how the proposed system can be scaled, adapted, and further enhanced to meet next-generation aerospace demands.

➤ *Scalability Across Satellite Classes*

While this study primarily targets CubeSats and small satellites, the fundamental principles of the PCM-SMA system can be extended to:

- *Medium to Large Satellites:*

- ✓ Integration into Structural Panels: PCM capsules can be embedded in large honeycomb or composite panels for geostationary satellites.
- ✓ Redundant SMA Supports: SMA frames can serve as active dampers for thermal and vibrational loads.

- *Interplanetary Probes & Rovers:*

- ✓ Cryogenic Variants: Use of low-temperature PCMs (e.g., hydrogen-based) combined with SMAs tuned for Martian or lunar temperature ranges.
- ✓ Planetary Enclosures: SMA diaphragms could regulate pressure inside scientific instrument housings during long-duration space travel.

- *Human-Rated Spacecraft & Habitats:*

- ✓ Wall-Lining Heat Buffers: PCM modules integrated into habitat walls to dampen day-night thermal cycles on the Moon/Mars.
- ✓ Pressure-Responsive Modules: SMAs used to flexibly manage the expansion of PCM reservoirs in crew cabins, increasing safety margins.

- *Materials Innovation and Smart Composites*

To maximize the PCM–SMA system's impact, future research can explore advanced material combinations and hybrid composites:

- *Next-Generation PCMs:*

- ✓ Nano-Enhanced PCMs: Incorporate carbon nanotubes, graphene, or boron nitride to improve thermal conductivity and reduce phase transition time.
- ✓ Encapsulated PCMs with Microcapsules: Safer, leak-proof modules with controlled release patterns and faster response.

- *Advanced SMAs:*

- ✓ 3D-Printed SMA Lattices: Lightweight, customizable, and tailored for specific mechanical loads.
- ✓ Dual-Phase SMAs: Alloys capable of responding to multiple thermal ranges, enabling multi-zone control within a single satellite.

- *Smart Hybrid Layers:*

- ✓ Fabrication of sandwich materials where PCM and SMA are interleaved in structured grids, acting both as heat sinks and expansion stabilizers.

- *Autonomous Thermal Control Systems*

The PCM–SMA design opens doors for zero-power autonomous systems that adjust thermal pathways based on environmental stimuli:

- SMA-Based Thermal Switches: Connect PCM units to external radiators or disconnect them during eclipse automatically.
- Self-Healing Structures: SMAs that reset deformed enclosures after micro-impacts or radiation swelling.
- Distributed Thermal Management Units: Small PCM–SMA nodes communicating with each other to maintain system-level temperature uniformity.

- *Integration with Emerging Space Platforms Reusable Space Vehicles:*

PCM–SMA systems can protect avionics during repeated reentry-exposure cycles, where temperature changes exceed 150°C within minutes.

- *Modular Space Stations & Swarms:*

- ✓ Each unit in a swarm satellite can self-regulate temperature using a compact PCM–SMA submodule.
- ✓ Applicable to Starlink-style mega-constellations, where simplicity and long-term durability are more valuable than bulky active cooling.

- *Additive Manufacturing in Orbit:*

Future on-orbit fabrication techniques can include printing SMA/PCM composites directly into structures, enabling repair, upgrade, or reconfiguration.

- *Earth Applications and Tech Transfer*

Beyond space, this hybrid solution may find use in several terrestrial fields:

- High-End Electronics: Smartphone and laptop modules with passive PCM–SMA heat regulation.
- Military & Aerospace Avionics: Fighter jets and drones exposed to thermal shock during high-altitude maneuvers.
- Electric Vehicles (EVs): Battery thermal safety systems using PCM + SMA capsules.
- Energy Storage Systems: Grid-level batteries or solar panels that undergo significant thermal shifts during operation.

- *Challenges and Open Research Problems*

To achieve widespread deployment, future efforts should address the following:

Table 11 Challenges and Open Research Problems

Challenge	Description	Suggested Research Direction
Long-Term SMA Fatigue	SMA may degrade after thousands of cycles	Study of novel SMA alloys or self-restoring structures
PCM Encapsulation	Leakage or rupture in vacuum conditions	Nanocomposite shell development or graphene-coated vessels
Volume Trade-Offs	Mass vs. performance optimization	Advanced algorithms for placement strategy
Real-Time Monitoring	Lack of in-flight SMA status feedback	Integration of smart sensors for thermal-mechanical state

➤ Conclusion of Section

The proposed PCM–SMA hybrid system is not merely a temporary solution for small-scale thermal regulation — it is a foundational concept that merges thermal science with material intelligence. Its adaptability, simplicity, and autonomy make it a strong candidate for incorporation into future spacecraft, planetary systems, and even terrestrial technologies. With continued research, testing, and optimization, this smart thermal strategy can play a pivotal role in the evolution of sustainable space engineering.

XVIII. CONCLUSION

In the unforgiving thermal environment of Low Earth Orbit (LEO), maintaining optimal temperature ranges within compact, power-constrained satellites is both a scientific and engineering challenge. Traditional active thermal control systems — reliant on moving parts, power sources, and complex control logic — are often infeasible for CubeSats and nanosatellites, where every gram and watt is mission-critical. This research presents a transformative solution: a hybrid passive thermal management system that integrates Phase Change Materials (PCMs) and Shape Memory Alloys (SMAs) into a unified, intelligent structural-thermal architecture.

PCMs provide the core thermal buffering mechanism by leveraging their latent heat capacity to absorb excess heat during sunlight exposure and release it during orbital eclipse. Yet, this strength comes with a drawback — volumetric expansion during phase change, which can induce structural stress, cause leakage, or compromise component integrity in vacuum conditions. By integrating SMAs into the enclosure design, this system elegantly solves the expansion problem: the SMA flexes with the PCM, absorbs the mechanical stress, and returns to its original shape upon cooling. The result is a fully passive, compact, and reusable thermal control module.

Through thermal simulations, finite element modeling, material selection, and system optimization, this study has

demonstrated that the PCM–SMA hybrid system:

- Maintains internal satellite temperatures within 30–45°C, far better than uncontrolled systems;
- Extends thermal stability across 500+ orbital cycles without structural failure;
- Enhances the lifetime and reliability of electronic subsystems like batteries, OBC, and optical payloads;
- Does all of this without any additional energy input, embodying the principles of sustainable aerospace design.

Beyond technical validation, the work establishes a new paradigm in satellite thermal control — one that blends thermal physics with adaptive materials engineering. It shows that the future of small satellite design does not solely depend on miniaturizing electronics, but also on embedding intelligence into passive subsystems, making them responsive, self-regulating, and durable.

➤ Broader Implications

The Implications of this System Extend Beyond LEO CubeSats:

- In deep-space probes, where energy conservation is paramount.
- In lunar and Martian missions, where day-night thermal extremes are even more severe.
- Even in Earth-based high-tech systems — from military avionics to battery packs in electric vehicles.

➤ Final Thought

As we push the boundaries of space exploration, our systems must evolve not just in computation, propulsion, or communication — but also in how they silently endure. The PCM–SMA hybrid module is not just a passive device. It is a material embodiment of resilience, enabling small satellites to not only survive, but thrive in the extremes of space — autonomously, intelligently, and sustainably.

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