ENERGY & STORAGE

Passive Thermal Regulation Without Energy Input

How organisms regulate temperature through surface and structure, not metabolism

5	3	3–3	5
convergent strategies	principle clusters	TRL range	featured strategies

PROBLEM FRAMING

Active thermal management requires continuous energy input. Passive architecture — surface emissivity tuning, phase-change storage, convective geometry — can regulate temperature across ±30°C ambient variation without power. Biology has solved this for every climate on Earth.

Application domains: architecture, energy, materials

Principle cluster: thermoregulation, fluid dynamics, surface microstructure

Physics & Mechanism

Underlying physics

[DRAFT] Passive thermal regulation operates through four physical mechanisms, often in combination: (1) Radiative cooling — surfaces with high mid-infrared emissivity (8–13 µm atmospheric transparency window) reject heat to the cold sky (3 K effective temperature). Daytime sub-ambient cooling requires simultaneous high solar reflectance (0.3–2.5 µm) and high LWIR emissivity. Saharan silver ant cuticle — triangular hair cross-section creates total internal reflection for solar wavelengths while emitting strongly in the infrared. (2) Evaporative cooling — transpiration-mimicking porous structures; rate limited by vapour diffusion boundary layer. (3) Convective enhancement — fin geometry from natural convection analysis; shark-skin-inspired surfaces enhance heat transfer coefficients in forced convection. (4) Phase-change latent heat — biological wax phase transitions absorb heat peaks; engineered PCM composites mimic this. Combination strategies (radiative + convective) can achieve 5–15°C sub-ambient surface temperatures with zero energy input. [END DRAFT]

Biological Strategies

Transform Mechanical Energy Atlantic salmon · TRL 3/9 · 36 genera ✦ Evidence File

Atlantic salmon scales possess a hierarchical lamellar structure composed of collagen fiber bundles arranged in alternating layers. These collagen fibers create a complex, multi-layered architecture that exhibits piezoelectric and triboelectric properties when subjected to mechanical deformation. Under pressure, the scale's lamellar structure undergoes compression and sliding between fiber layers,…

Design principle: Engineer wearable devices by replicating the salmon scale's lamellar collagen fiber organization using flexible composites or bio-derived materials. Prioritize multilayer architectural design with alt

> What's actually hard: The deepest unsolved obstacle is implementing a passive or low-energy variable stiffness mechanism—such as layer jamming—that allows the gripper to transition instantaneously from a highly compliant, soft state to a rigid, load-bearing state without …

Protect From Excess Liquids Gentoo penguin

Gentoo penguins possess feathers which are fundamentally different from those of flying birds. Each feather is short, stiff, while lance-shaped, with an extended afterfeather that provides thermal buffering. Critically, these feathers are distributed uniformly across the body at exceptionally high density—30 to 40 feathers per square centimeter—rather than arranged in discrete tracts as in other b…

Design principle: This system suggests a protective coating strategy using density and mechanical control rather than passive material properties alone. Engineers might develop adaptive surface systems where individual

Protect From Wind Arid zone plants

Arid zone plants generate fine hair-like structures across their leaf and stem surfaces that form a dense felt-like covering. That hairy layer functions as a physical barrier that disrupts airflow directly across the plant's surface. By creating a microclimate of still air immediately adjacent to the plant tissue, the hairs lower the convective removal of water vapor that would otherwise be carrie…

Design principle: Engineers can apply this principle by developing surface textures and fiber arrays that create protective boundary layers in dry, windy conditions. The concept translates to designing materials with f

Transform Mechanical Energy Boa constrictor · 36 genera ✦ Evidence File

Interest in emulating the properties of biological muscles that allow for fast adaptability and control in unstructured environments has motivated researchers to develop new soft actuators, often referred to as 'artificial muscles'. The field of soft robotics is evolving rapidly as new soft actuator designs are published every year. In parallel, recent studies have also provided new insights for u…

Design principle: A comparative study of biological muscles and soft actuators, focusing on those properties that make biological muscles highly adaptable systems. In doing so, we briefly review the latest soft actuati

> What's actually hard: The defining engineering challenge is mathematically modeling and controlling the fluid-dynamic effects inherent in soft pneumatic systems. Replicating the snake's infinite degrees of freedom via continuous Cosserat rod theory requires immense, real-…

Transform Mechanical Energy Dogfish shark · TRL 3/9 · 36 genera ✦ Evidence File

Dogfish sharks possess dermal denticles—small tooth-like scales covering their skin that create non-smooth surface textures. These microscopic structures alter boundary layer separation and wake patterns in fluid flow. The bionic design mimics this surface morphology using D-type repeating units (semicircular elements with 7.2° center angles) applied to cylindrical interference bodies in piezoelec…

Design principle: Apply surface texture patterns inspired by shark dermal denticles to flow-facing surfaces of energy harvesting devices. Implement repeating non-smooth geometric units (e.g., semicircular protrusions)

> What's actually hard: The fundamental engineering gap is designing an active-renewal or self-cleaning surface. Biological sharks constantly shed and replace their denticles to maintain optimal geometry and prevent fouling, whereas synthetic riblets are static and vulnerab…

Combination Intelligence

Strategies that address different aspects of the same problem and are not redundant when combined.

Protect From Excess Liquids + Protect From Wind

Shared principles: fluid dynamics, surface microstructure, thermoregulation

These strategies share 3 underlying principles including fluid dynamics and surface microstructure and thermoregulation. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

EXPLORE THE INTERACTIVE VERSION

This report is a static synthesis. The interactive version includes live strategy cards, the Design Brief generator, Combination Intelligence engine, and filtering by TRL, scale, and principle.

`https://atlasofnature.org/challenge/passive-thermal-regulation`

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