

NanoArc RevB/RevC Phase-Change Material Development Proposal

Sodium Acetate Trihydrate Screening, Formulation, and Cartridge Validation

Project	NanoArc - Mira/Zoey/Rumi thermal development
Status	Draft proposal - not approved, frozen, or implemented
Date	2026-08-11
Scope	RevB and RevC PCM development; RevA remains unchanged
Authority	Tristan retains design, safety, freeze-break, and approval authority

Purpose. Establish a low-equipment, measurement-driven PCM programme that compares the original beeswax concept against sodium acetate trihydrate (SAT) and simple SAT composites before any RevB/RevC cartridge architecture is frozen.

Executive summary

NanoArc RevB and RevC require a compact thermal buffer, so phase-change material selection should be treated as an engineering development track rather than a one-time materials choice. Beeswax remains the baseline control because it is simple, accessible, and mechanically forgiving. SAT is the principal inorganic candidate because its phase transition is near 58 C and published work reports high latent-heat storage, but it has known supercooling and phase-separation problems.

This proposal formalizes three initial specimens: beeswax control, pure SAT control, and a literature-backed SAT/DHPD/CMC composite. For the third specimen, the starting composition is normalized to 97.5 wt% SAT, 2.0 wt% disodium hydrogen phosphate dodecahydrate (DHPD), and 0.5 wt% carboxymethyl cellulose (CMC). This supersedes the earlier informal 96/2/2 suggestion, which should not be treated as a validated literature formulation.

The programme is intentionally compatible with limited bench equipment. Initial screening requires only controlled low-temperature heating, weighing, mixing, temperature logging, small test vessels, and repeated cycling. Differential scanning calorimetry (DSC), vacuum impregnation, pressure vessels, nanomaterials, and custom PCBs are not prerequisites for Phase 1.

Decision principle: the winning PCM is not the material with the best literature number; it is the formulation that delivers the best repeatable usable heat absorption in the actual NanoArc cartridge geometry.

1. Development objectives

- Establish a repeatable thermal-storage baseline using beeswax, pure SAT, and one simple modified-SAT formulation.
- Measure supercooling, segregation, water loss, cycle drift, and dynamic heat absorption with NanoArc-relevant test geometry.
- Determine whether a salt-hydrate PCM provides enough practical benefit over beeswax to justify containment and cycling complexity.
- Keep the chemistry simple enough to prepare and iterate with existing or inexpensive bench equipment.
- Defer conductive fillers and exotic composites until baseline transport limits are measured.
- Produce cartridge requirements for RevB/RevC from measured data rather than assumptions.

2. Architectural context

This work is a RevB/RevC materials-development proposal. It does not authorize changes to frozen RevA hardware. It complements the broader ACE modular architecture by creating a future process-characterization workload that ACE can supervise: thermal profiles, logging, sensor validity, cycle counting, fault detection, and experiment records can remain in ACE, while heaters, thermal sensors, and power switching remain in a dedicated fixture or module.

3. Initial PCM candidate set

ID	Material	Role	Primary advantage	Primary uncertainty
PCM-A	Beeswax	Baseline control	Simple containment and predictable handling	Lower storage density and combustible organic working material
PCM-B	Pure SAT	Salt-hydrate control	High latent heat; transition near target thermal range	Large supercooling and possible phase separation
PCM-C	SAT + DHPD + CMC	Primary modified candidate	Nucleation aid plus thickening/segregation control	Mixing quality, long-term cycling, and real cartridge heat transfer
PCM-D	Alternative nucleator branch	Deferred screen	Newer nucleator research may outperform DHPD	Must not distract from establishing a baseline first

4. Baseline modified-SAT formulation

PCM-C screening composition (mass basis):

Component	Mass fraction	Function
Sodium acetate trihydrate (SAT)	97.5 wt%	Primary latent-heat storage medium
Disodium hydrogen phosphate dodecahydrate (DHPD)	2.0 wt%	Nucleating additive to reduce supercooling
Carboxymethyl cellulose (CMC)	0.5 wt%	Thickener/stabilizer to reduce phase segregation

Status of formula: screening baseline, not a NanoArc production formulation. Published studies report the DHPD/CMC combination as effective, but performance is formulation-, heating-, vessel-, and cycling-dependent. Newer nucleator screening also shows that other additives may outperform DHPD under some thermal histories.

5. Limited-equipment feasibility

The initial programme is deliberately designed around ordinary bench capability. No pressure chamber or specialized materials-processing equipment is required for the baseline composite screening.

- Mass measurement: a digital balance accurate enough to distinguish sub-gram additive quantities at the selected batch size.
- Heating: controlled hotplate or water-bath style heating sufficient to bring the specimen through the SAT phase transition without aggressive overheating.
- Mixing: heat-compatible vessel and simple mechanical stirring; the goal is reproducibility, not high-shear processing.
- Temperature measurement: thermocouple, thermistor, or other logged probe with repeatable placement.
- Containment: small sealed or semi-sealed development vessels that permit observation of segregation and mass loss; final cartridge design is deferred.
- Cycling: repeated melt/freeze tests with identical temperature endpoints and dwell times.

Important limitation. Bench screening can compare formulations and reveal obvious failure modes, but it cannot by itself provide DSC-grade latent heat or certify a production thermal design. Relative performance is the initial objective.

6. Cartridge implications

6.1 Heat transfer before chemistry complexity

SAT has attractive storage density but modest thermal conductivity. The first response should be geometric: thin PCM sections, a metal thermal spine, fins, or a high-area interface. Conductive powders should be added only after the baseline cartridge demonstrates that internal heat transport is the dominant limitation.

6.2 Containment and hydration

Salt-hydrate performance depends on retaining the intended water content. Development testing must therefore track specimen mass and visible separation. Cartridge development should assume that water loss and volume change matter, even when the chemistry itself remains stable.

6.3 Transition temperature as a system parameter

The roughly 58 C SAT transition is not automatically the correct NanoArc thermal clamp. The RevB/RevC thermal model must determine whether this plateau protects the components that matter while still allowing useful pulse throughput. A lower-temperature eutectic or a different PCM remains possible if system testing requires it.

7. Verification programme

Phase 0 - fixture and measurement sanity

- Use identical containers, specimen masses, probe placement, and external heating/cooling conditions.
- Run an empty-vessel or inert thermal-mass control to establish fixture lag.
- Verify that temperature logging is stable enough to distinguish melting/freezing plateaus and supercooling.

Phase 1 - three-way screening

- PCM-A: beeswax baseline.
- PCM-B: pure SAT.
- PCM-C: 97.5/2.0/0.5 SAT/DHPD/CMC.
- Record heating curve, cooling curve, phase-change plateau behavior, visible separation, and post-cycle mass.

Phase 2 - repeated cycling

- Cycle surviving candidates repeatedly under the same thermal endpoints.
- Track freeze onset, supercooling, peak/plateau temperature, melt/freeze time, mass change, and visual segregation.
- Flag any progressive drift rather than averaging it away.
- Retain samples after testing so physical changes can be compared with the original batch.

Phase 3 - NanoArc-like dynamic load

- Move the best candidates into a representative cartridge geometry with the intended metal thermal path.

- Apply repeatable burst heating rather than only slow bath heating.
- Measure peak temperature suppression, recovery time, and cumulative energy handling.
- Compare performance per gram and per cartridge volume against beeswax.

Phase 4 - long-cycle qualification

- Only after a candidate wins Phase 3, run extended cycling and orientation tests.
- Establish acceptable drift and end-of-life criteria.
- Freeze the RevB/RevC PCM chemistry only after cartridge-level behavior is repeatable.

8. Minimum dataset per specimen

Metric	Why it matters	Initial method
Specimen mass	Detects water/material loss	Mass before and after defined cycle groups
Melting/plateau behavior	Shows useful thermal clamp region	Logged temperature vs. time
Freeze onset / supercooling	Determines whether stored heat is released predictably	Cooling curve and crystallization event
Melt and freeze time	Reveals heat-transfer limits	Elapsed time between defined temperature points
Peak temperature under burst load	Directly relevant to NanoArc protection	Representative heater/cartridge test
Recovery time	Determines usable repetition rate	Time to return to ready state
Visible segregation	Identifies salt-hydrate instability	Photographic/visual inspection
Cycle drift	Determines service-life risk	Trend plots over repeated cycles

9. Decision gates

Gate A - Does modified SAT behave reproducibly?: PCM-C must crystallize consistently enough to be useful and must not show progressive separation or severe drift during short-cycle testing.

Gate B - Does SAT materially beat beeswax in the actual geometry?: The benefit must survive packaging, thermal-path, and recovery-time effects. Literature latent heat alone is insufficient.

Gate C - Can the cartridge remain simple?: If SAT requires excessive fluid management, maintenance, or thermal hardware, the system-level advantage may disappear.

Gate D - Is the transition temperature correct for NanoArc?: If the ~58 C plateau is too warm or too cool for the protected hardware, screen a different PCM/eutectic rather than forcing SAT into the design.

Gate E - Is long-cycle behavior acceptable?: Final chemistry is not frozen until extended cycle data show stable thermal behavior and containment.

10. Future ACE-driven PCM test fixture

Once basic manual screening proves worthwhile, PCM development is a strong candidate for an ACE application module. The process is slow, measurable, repetitive, and benefits from persistent records rather than fast closed-loop control in ACE itself.

- Profile-controlled heating and cooling cycles.
- Independent temperature channels for heater, thermal spine, PCM core, and ambient.
- Cycle counting and specimen identity.
- Automatic logging of melt/freeze events, supercooling, and recovery time.

- Detection of sensor faults or impossible thermal states.
- Exportable per-formulation datasets for direct comparison.

11. Open items before cartridge freeze

- Maximum acceptable component and enclosure temperatures in RevB and RevC.
- Target PCM transition/plateau temperature.
- Required absorbed energy per pulse burst and per duty-cycle window.
- Maximum PCM mass and volume allocation.
- Required recharge/recovery time between thermal events.
- Allowed cartridge orientation and motion.
- Whether RevB and RevC should share one PCM chemistry or optimize independently.
- Whether the PCM is field-replaceable, serviceable, or permanently sealed.

12. Current recommendation

Proceed with a three-specimen baseline: beeswax, pure SAT, and 97.5 wt% SAT / 2.0 wt% DHPD / 0.5 wt% CMC. Use the simplest repeatable melt/freeze fixture available and characterize relative behavior before buying or fabricating specialized PCM hardware.

Do not add graphite, nanoparticles, metal foams, or vacuum-impregnated supports in the first round. If the simple modified SAT is already unstable, conductivity enhancement is irrelevant. If it is stable but transfers heat too slowly, solve the measured transport problem in the cartridge before complicating the chemistry.

Treat newer nucleators as Phase 2 research, not as a reason to delay the baseline. A 2024 screening study identified calcium chloride dihydrate as a strong SAT nucleating agent, including at low loading, and found it more tolerant than DHPD under some high-temperature histories. That result is worth a later branch if DHPD performance is inconsistent in the NanoArc cycle envelope.

References and source basis

1. NanoArc ACE / future Apollo Applications extensions, "ACE RevB/RevC Modular Applications Architecture Proposal," draft, 2026-08-11. User project document.
2. L. Zhao, Y. Xing, X. Liu, and Y. Luo, "Thermal performance of sodium acetate trihydrate based composite phase change material for thermal energy storage," *Applied Thermal Engineering*, vol. 143, pp. 172-181, 2018.
3. J. Mao et al., "Preparation research of novel composite phase change materials based on sodium acetate trihydrate," *Applied Thermal Engineering*, vol. 118, pp. 817-825, 2017. DOI: 10.1016/j.applthermaleng.2017.02.102.
4. X. Jin et al., "Experimental investigation of the novel melting point modified Phase-Change material for heat pump latent heat thermal energy storage application," *Energy*, vol. 216, 119191, 2021.
5. J. Li, M. A. Parkes, and C. G. Salzmann, "Extensive Screening and Performance Testing of Nucleating Agents for the Sodium Acetate Trihydrate Phase-Change Material," *Crystal Growth & Design*, vol. 24, no. 20, pp. 8292-8300, 2024. DOI: 10.1021/acs.cgd.4c00691.
6. S. Heo et al., "Development of sodium acetate trihydrate-based composite phase change materials ...," *Applied Thermal Engineering*, 2025. Used as current evidence that DHPD and CMC remain active SAT modification approaches.

Document note: All numerical formulations and candidate rankings in this proposal are screening assumptions until reproduced on the NanoArc bench. Literature results are not treated as qualification data for RevB or RevC.